Bio-electrification - Development of an electric vehicle with Range Extender module based on a compact combustion ethanol engine

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Abstract

Electrical vehicles are experiencing a fast-paced demand worldwide driven by a quest for improved energy efficiency and Zero Emissions targets for vehicles mainly in cities. Nowadays, we are facing an increase of electrification in a short period of time, leading to a high demand for hybrid powertrains as well as battery electric vehicles (BEV). If there is not enough charging infrastructure available, actions for the BEV should be applied to avoid the user's "range anxiety", which can be an additional battery capacity, thus increasing the cost and weight in proportion to the requested range. An alternative to this matter is the so-called Range Extender (REx), a hybrid powertrain architecture that increases the range via an internal combustion engine (ICE), which also increases the cost and weight, but with higher energy density.

AVL South America in partnership with Aeronautics Institute of Technology (ITA) and companies FURNAS and SEFAC, presents in this paper the first plug-in hybrid vehicle developed in Brazil with an ethanol Range extender. This bio-electrification concept is under development with functional prototypes within the Project registered with the code PD-00394-1910 / 2019 which belongs to the R&D program regulated by ANEEL. In this present work it Casts light on the benefits in CO_2 emission reduction from an electric vehicle equipped with an ethanol ICE Range extender. The internal combustion engine is developed to have the optimum overall efficiency of the ethanol combustion, allowing the extension of the vehicle's range. Moreover, a significant reduction of carbon dioxide emissions of 73% was achieved when compared the E100 engine to the original petrol version range extender.

The ICE efficiency is improved through innovative technologies, which can be applied independently or in combination. The main motivation of this application is the use of energy sources with low environmental impact, among them the electric energy mostly coming from renewable sources in Brazil and the biofuel ethanol, which provides carbon dioxide absorption during the sugarcane cultivation cycle.

1. Introduction

Electrification is expected to have a major impact on the powertrain of passenger cars in the upcoming years. The application begins with simple start / stop systems, various types of hybridization, up to the purely electric vehicle (BEV). Although market share for battery-powered electric vehicles is still growing slowly, hybrid technology comes on a large scale in all vehicle segments.

For BEV vehicles a compromise must be overcome, which is the conflict between the required range and the weight of the batteries. In addition to the efficiency standpoint, it must be considered that electric vehicles require a certain excessive capacity to avoid the so-called "range anxiety" of the user who wants to complete his journey without any need for unexpected recharging.

In Figure 1 a production trend scenario is presented for each propulsion technology. It is observed that starting from 2020, a significant increase in the vehicles propelled by hybrid system (orange area) and a consequent reduction in the production of vehicles propelled solely with ICE is expected. There is still a trend of increasing range extender via fuel cell, but with low impact on the market due to complexity, feasibility and high cost.

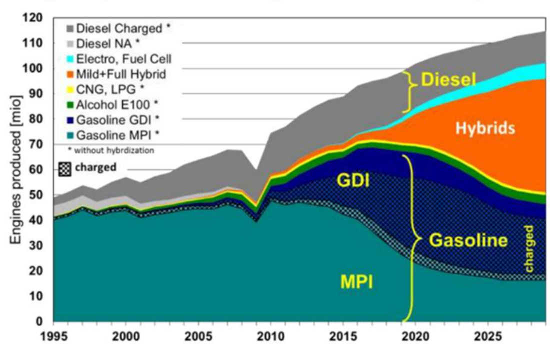

Figure 1. Production trend of passenger vehicles by propulsion technology. Source: Range Extender Technology for Electric Vehicles AVL-List (2018) [1]

The hybrid system is presented as a production ready and intelligent solution to overcome the conflict in the range extender through the internal combustion engine. The most effective technical solution for this range extender is largely determined by the ratio between pure battery operation and operation supported by an internal combustion engine.

As the operating range of the internal combustion engine in the range extender is limited to a few stationary points, it is possible to obtain a high degree of optimization, even with comparatively simple technology. With this increase in range for an electric vehicle, the combustion engine can be further simplified. Consequently, all engine changes necessary only for optimization outside the operating points can be reduced or removed, thereby reducing their cost.

From the standpoint of CO_2 emission, the electrical vehicle coupled with an Ethanol ICE range extender can present the lowest emission mainly due to the Brazilian electrical energy mix, which is approximately 87% clean and the ethanol, which present 73% less CO_2 emission compared to gasoline, contributing to reach the future emissions legislation levels, which requires reduction in emission of gCO_2/km.

2. Future trends

As previously mentioned, electric vehicles rely on batteries. These batteries have a fixed range, which after use requires recharging. To avoid constant recharging, range extenders are implemented in electrical vehicles to provide additional power to the batteries.

A better and more efficient range extender is required for electric vehicles to travel further. Several developments have been carried out by companies for the range extension via ICE and many other are still ongoing with alternative technologies, for example, fuel cell.

Factors such as the increase demand for extending the range of electric vehicles and engine downsizing complement the growth of the electric vehicle market with a range extender.

The main objective of sustainable mobility is the replacement of fossil fuels by carriers of renewable energy. This objective, however, results in an extensive diversification of technical approaches, as shown in the following figure.

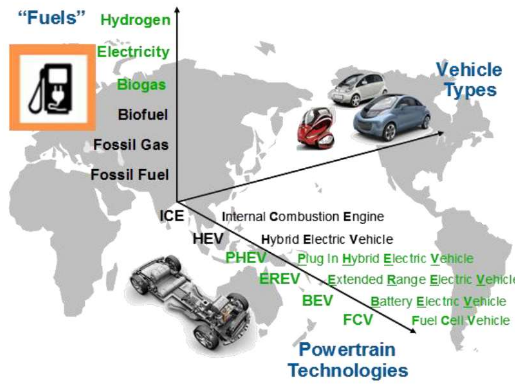

Figure 2. Diversification of propulsion systems. Source: AVL-List (2018) [1]

Electrification will substantially increase the diversity of powertrain technologies. Even though electric vehicles are more efficient and produce less carbon emissions, the low power density and high cost of batteries are still a problem to be addressed. Therefore, for a wider introduction in mobility, diverse solutions become necessary, such as battery vehicles, range extenders, plug-in hybrids and even fuel cell powered vehicles.

2.1. Ethanol as a renewable alternative

In 1975 the National Alcohol Program – Proálcool - was implemented in Brazil with the goal to reduce the foreign dependency for crude oil and create an additional market for the sugar producers, pushing the automotive industry into the development and manufacturing of purely ethanol fueled vehicles. In the first phase, the main goal of the program was to produce anhydrous ethanol to blend with gasoline. Efforts in research and development focused on ethanol fueled vehicles resulted in the creation of those vehicles in 1978. As a result of the second oil crisis in 1979, Brazilian government decided to increase the use of ethanol fuel, signing deals with the vehicle manufacturers and stimulating the creation of autonomous ethanol distilleries. This way, the large-scale ethanol fuel production in Brazil was started.

More than 4 million vehicles run with only hydrated ethanol in Brazil [6] and, moreover, petrol is blended with anhydrous ethanol (22 to 27% of ethanol content) extending the benefit of a lower carbon intense fuel to the remainder of the Brazilian fleet.

Brazil stands out by having the most advanced technology in the ethanol production. Worldwide production is in the order of 40 billion liters – Brazil is responsible for 15 billion liters. In the country, for each tone of sugar cane, 66 liters of ethanol and 700 to 800 liters of vinasse are produced [6].

One of the major challenges of the distilleries is to reduce the by-products (bagasse and vinasse) generated during the ethanol production. Some distilleries use the bagasse as fuel for the fermentation process. Another effective alternative is to perform continuous fermentation, reducing the vinasse production by almost 75%.

As the ethanol share in gasoline increases, the share of lead in the Brazilian gasoline could be reduced, being completely banned in 1991. Aromatics hydrocarbons such as Benzine, which are seriously toxic, were also mitigated together with sulfur content. The simple tradeoff from lead to ethanol in the commercial gasoline reduced the carbon monoxide and sulfur emissions abruptly. Environmental lead concentrations in the State of São Paulo decreased from 1,4 $\mu g/m^3$ in 1978 to less than 0,10 $\mu g/m^3$ in 1991, according to CETESB (environmental company of the state of São Paulo), standing way lower than the maximum air quality standard of 1,5 $\mu g/m^3$.

Tail-pipe hydrocarbon emissions from alcohol fuels are less toxic when compared to commercial gasoline. They present less atmospheric reactivity and also a null balance of greenhouse gases considering tank to wheel (9,2 million tons of carbon dioxide were not released in the atmosphere in the year 2000 only by replacing gasoline for ethanol).

Figure 3 presents the carbon dioxide emissions in gram by kilometer, considering that the vehicle in question is a VW Golf with lifetime of 200.000 km. In red (*Vehicle manufacturer / Cradle to Grave*) it is indicated the carbon dioxide emissions since the production to its commercialization. For purely combustion engines vehicles (Otto or Diesel), the CO_2 emissions are quite similar. However, when we take into account the CO_2 emissions for the fuel production, considering the machinery in the harvest, transportation and processing, the diesel fuel emits less CO_2. Nevertheless, the major factor in the CO_2 emissions of ethanol, is its renewable impact, once every gram of CO_2 produced during the combustion of the fuel is absorbed during the sugar cane crops growth.

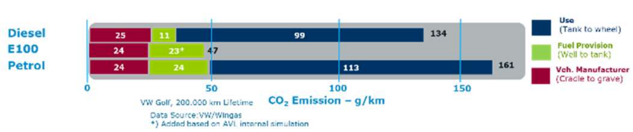

Figure 3. CO_2 emissions by kilometer for several fuels / Source: (Beste et al., 2009)

2.2. Brazilian Energy Mix

Energy mix represents the series of energy sources for electric energy production. A fair amount of the Brazilian electricity comes from hydropower plants, so we can imply that the Brazilian energy mix is mostly renewable, as shown is Figure 4.

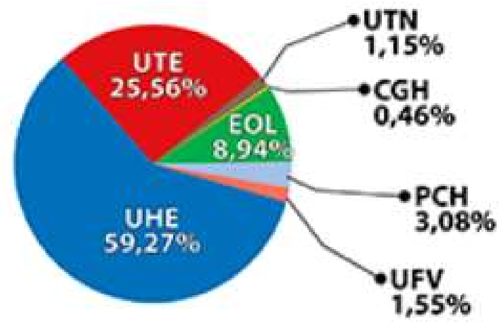

Figure 4. Brazilian Energy Mix. Source: ANEEL.GOV.BR, December 2020 * Acronyms in item 07

Figure 5 presents the global energy mix, which is composed mainly by non-renewable sources. There is an intense use worldwide of fossil fuels such as oil, coal, ever increasing the greenhouse effects.

Renewable sources such as solar power, wind power and geothermal represents approximately 4,5% of the global share in energy production. Together with hydropower energy, they represent just 11% of the global energy mix.

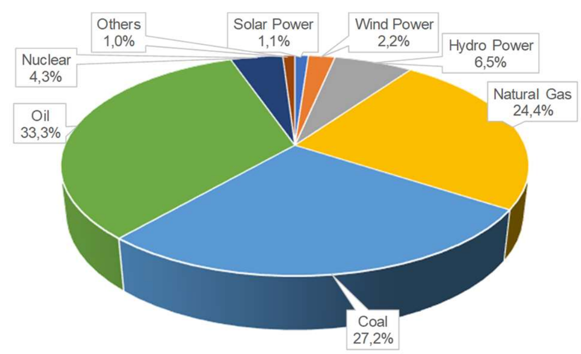

Figure 5. Global Energy Mix. Source: Our World in Data, 2018

An energy source is classified as renewable when it does not cause harm in the atmosphere and in their surroundings. Hydroelectric power plants do not release harmful gases into the ecosystem, nor cause soil degradation in the energy production.

However, the installation of a hydroelectric power plant modifies the course of the river and the scenario of its surroundings, by flooding large areas, harming wildlife as well as communities nearby.

Hydroelectric energy is a cost-effective solution in Brazil, considering that the average value for 1 MWh of energy produced and distributed was of R$ 225/MWh from 2010 to 2017 [20]. In addition, it has a long-life energy production, once it can produce energy for over 80 years with the appropriate maintenance, according to geological studies presented in the thesis “Análise sinérgica da vida útil de um complexo hidroelétrico, 2005” [20]

Hydroelectric power plants produce energy 24/7, with a certain level of flexibility in energy storage throughout the day, differing from a solar power plant or a wind farm. Furthermore, the newest power plants have smaller reservoirs, reducing local environmental impacts.

3. Feasible Technologies Applicable to an ICE

As mentioned before, ethanol can have several advantages over fossil fuels. The major stake of CO2 released during its production and combustion is reabsorbed by the sugar cane crops. The exception is the CO2 released by diesel burn in machinery using in cultivation, transport, and harvest

Another advantage is its high-octane number, which is the capacity of the fuel to resist to knock, therefore improving thermal efficiency with a higher engine compression ratio. In addition, a lower vapor pressure when compared with gasoline results in less evaporative emissions.

Regarding all those advantages of using ethanol as fuel in internal combustion engines, it was selected a few technologies that could be implemented in a range extender in order to maximize its efficiency taking profit of the ethanol fuel and as consequence, improve the vehicle range.

Figure 6 presents a graph of feasible technologies to improve engine efficiency and reduce fuel consumption based on specific engine operating regions. It is noticeable that at part-load to the upper part of the engine load map, dethrottling strategies as well as heat rejection approaches appear to be the most prominent.

According to previous developments from AVL South America, the most feasible technologies to be implemented focusing on fuel consumption, emissions reduction and thermal efficiency improvement to the first ethanol range extender worldwide would be the following:

a. High Compression Ratio (Low cost / Low complexity)
b. Miller Cycle (Low cost / Medium complexity)
c. External EGR (High cost / High complexity)

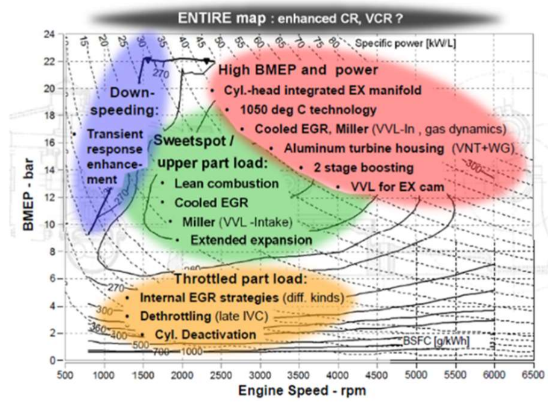

Figure 6. Feasible Technologies for fuel consumption reduction. Source: (AVL database, 2020)

3.1. High Compression Ratio

Regarding the capacity of bearing the high pressures and temperatures before autoignition, ethanol has a large advantage over gasoline. Theoretically, increasing the compression ratio of an engine improves its thermal efficiency, consuming less fuel to the same power output. The Otto air-standard cycle, over which spark ignition engines rely, has its theoretical efficiency directly correlated with the increase in compression ratio, and it is given by:

$$\eta T = 1 - \frac{1}{rc^{\mu-1}}$$

Equation 1. Theoretical thermal efficiency

ηT = Global Thermal Efficiency

rc = Compression Ratio

μ = Ratio of Specific Heats of Air = 1,4

The higher compression of the air fuel mixture leads to an increase in temperature and therefore a better fuel evaporation, improving mixture quality. It is also noted a better combustion efficiency from increasing compression ratio. That means an optimized conversion of the fuel into carbon dioxide and water, leading to less emissions of unburned hydrocarbons, increase heat release and power output with the same amount of fuel.

Figure 7 presents a study demonstrating the impact in brake thermal efficiency as the compression ratio is increased [19].

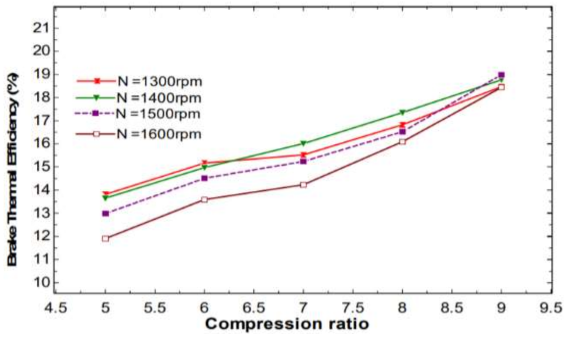

Figure 7. Brake thermal efficiency with the increase in compression ratio. Source: (Aina et al., 2012) [19]

As brake thermal efficiency is proportional to the inverse of brake specific fuel consumption (BSFC) it is possible to infer that, in the same operating condition, the BSFC follows a trend of reduction as the compression ratio is increased, as shown in the Figure 8.

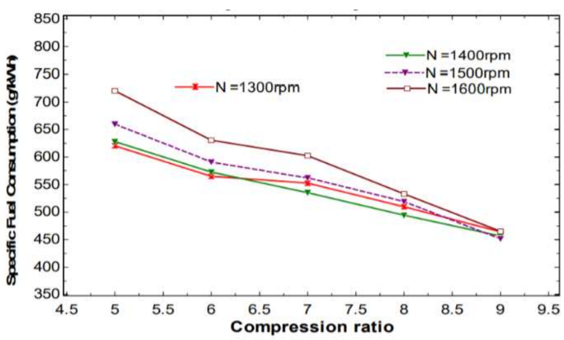

Figure 8. Specific fuel consumption with the increase in compression ratio. Source: (Aina et al., 2012) [19]

The effect of increasing the compression ratio in a cycle can be observed in Figure 9. A higher compression ratio produces a higher peak pressure during combustion resulting in more work from the gases to the piston and therefore more power.

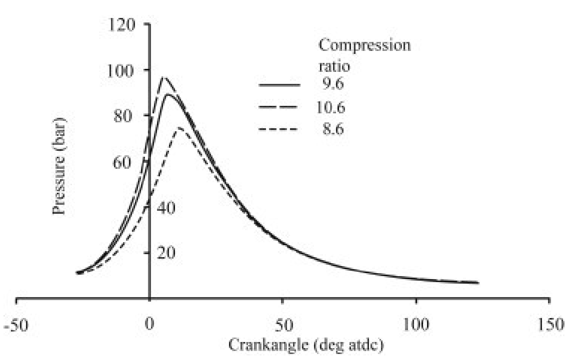

Figure 9. Peak cylinder pressure vs crank angle. Source: (Winterbone & Turan, 2015). [15]

3.2. Miller Cycle

Miller cycle is a modification of the over expanded cycle, which offers a higher expansion ratio than the compression ratio. The advantage of miller cycle over an ordinary Otto-cycle is that it can produce a higher thermal efficiency, as mentioned by Naber & Johnson (2014).

In fact, this difference in expansion ratio can be obtained from a compression stroke with a late closing of the intake valve or an early closing of the intake valve. This way, the effective compression ratio is reduced while maintaining the same combustion process and the same expansion stroke, allowing a better use of the gas expansion and, hence increasing efficiency. Despite the increase in efficiency, there is a reduction in power density, once a part of the air-fuel mixture returns to the intake manifold before the intake valve fully closes, being necessary the use of some form of boost to maintain the same engine load and still take advantage of the miller cycle.

This engine cycle also helps to mitigate the knock problem in spark ignition engines by cooling the air-fuel mixture by the longer opening of the intake valve, according to Wu et al., (2003) [18].

Figure 10 presents an example of the Miller cycle on a logarithmical pressure by volume diagram. On the left, with an early intake valve opening and on the right side with a late intake valve closure. Both seek the same effect, to reduce the effective compression ratio, thus resulting in an increase in the expansion ratio and in the thermal efficiency.

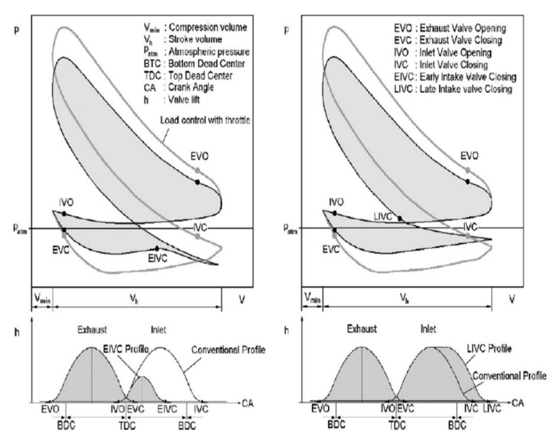

Figure 10. Miller cycle example. Source : (Kutlar et al., 2005) [12]

3.3. External EGR

Exhaust gas recirculation is widely used to reduce the trend of NOx formation in internal combustion engines. It does so by reducing the availability of oxygen inside the combustion and reducing the combustion temperature once it is composed mainly by carbon dioxide, which has a higher heat capacity than the air, thus mitigating the oxidation of the nitrogen at high temperatures.

In an Otto-cycle engine, this inert gas replaces a fraction of the air-fuel mixture within the cylinder, also contributing to reduce pumping losses at part load engine operation.

The recirculated exhaust gases from the EGR system will also have fractions of NOx and CO, but the formation of more pollutant will be mitigated, and the net emissions will have a lower concentration of those pollutants in the tail pipe.

Benefits of external EGR in a glance:

a. Reduction of pumping losses: A higher intake density becomes necessary to overcome the air mass flow reduction. The engine still reaches the same load which can be done by de-throttling or boosting.
b. Reduction of thermal losses: Reducing the peak temperatures during combustion, not only the formation of NOx is mitigated but also the heat transfer to the cylinder wall is lowered, thus allowing the converted fuel energy to produce more work instead of rejecting heat.

4. Well-to-Wheel Analysis

When comparing fuel consumption and carbon emissions of ICE vehicles with Hybrid or Full electric ones, the impression at first sight is always that plug-in vehicles have far better emissions stands and a much smaller fuel consumption, as the marketing for those vehicles do not consider the carbon footprint of the electricity.

Nowadays, many studies are considering a depth overview of the energy chain necessary to power plug-in vehicles. Instead of analyzing solely the carbon emissions of the fuel consumed from the tank of the vehicle, we must look to the whole energy cycle.

A Well-to-wheel analysis, as the name says, requires many processes since the energy production or mining, processing, transporting, storage and finally consumption in the vehicle be included in the footprint analysis. Therefore, when looking through this approach, carbon emissions from Plug-in HEV or BEV may be the same or even higher than an ICE, depending largely on the energy mix production of the country it is driven, as demonstrated by Woo et al. (2017).

According to the study presented in the paper "*Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: A global perspective, (2017)*", for a compact class of BEV, the carbon emissions considering the energy mix for each country may vary significantly. For instance, countries relying mainly in fossil fuel such as coal or oil. China and India, present a value of carbon emissions when charging battery vehicles than the correspondent class of vehicles fueled with petrol or diesel, as presented in Figure 11.

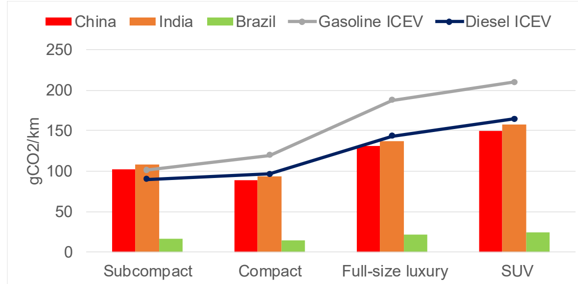

Figure 11. – Carbon emissions for BEV considering the mean emission factor of the country's energy generation mix. Source: (Woo et al., 2017) [16].

In addition, countries like Brazil, which have a large percentage of renewable sources of energy production, take advantage of well-to-wheel carbon emissions when comparing to petrol- or diesel-powered vehicles.

5. Advantages of an Ethanol Range Extender

For the purpose of this study, a plug-in hybrid vehicle coupled with a petrol range extender is analyzed for a fuel consumption improvement by converting it to an ethanol range extender and the addition of further technologies in order to maintain the range of the petrol model as well as significantly reducing the carbon emissions.

Based on a well-to-wheel analysis, carbon emissions with ethanol are reasonably lower than petrol fuel, mainly by the carbon absorption in the growth of the sugar-cane crops. However, there is still a carbon downside due to the transportation and production, which relies on diesel and the country energy mix, respectively.

Nevertheless, a preliminary study was performed comparing the carbon emissions and range of a commercial petrol range extender BEV against a converted range extender to operate with ethanol. Based on the AVL knowledge of carbon emissions regarding fuel consumption, the raw carbon emissions for both fuels could be estimated. In addition, the carbon emissions for the energy consumed by charging the batteries is estimated using the annual average emissions (gCO_2/kWh) of the energy mix, according to data from the Brazilian government.

To perform this analysis, some boundary conditions were considered. Using as a starting point the fuel consumption of the E.P.A ratings for the petrol range extender, a fuel consumption for an ethanol range extender could be estimated based on the ratio of the LHV (lower heating value) of the fuels. Moreover, to compare all option on the same basis of range, the additional weight of the batteries for the BEV to reach the range extender versions was not considered.

Heywood (2018) presents a relationship between the increase in the research octane number (RON) of the fuel with the allowable increase in compression ratio, considering optimal ignition advance in all cases. Therefore, the compression ratio could be increased by 3 percentage points for the conversion of the petrol range extender to an ethanol range extender, thus increasing the brake thermal efficiency by up to 5%, as presented in Figure 12. AVL expertise based on previous developments shows that the implementation of miller-cycle can reduce the specific fuel consumption up to 2%. Furthermore, the use of cooled EGR may further reduce the specific fuel consumption of up 3%.

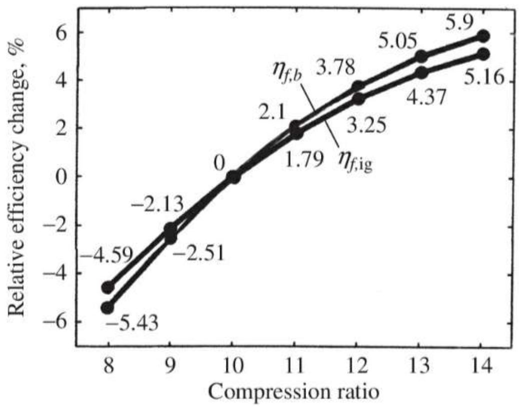

Figure 12. Relative efficiency changes with the increase in compression ratio. Source: (Heywood, 2018)

Table 1 shows a comparison in WLTC emission cycle of the specific and total carbon emissions for the total range of the vehicle on BEV mode, for a petrol range extender version and an ethanol converted range extender version.

Table 1. Energy consumption and carbon emissions for BEV and Range Extender versions

	Energy Consumption	WTW CO_2 Emissions	Total CO_2 Emissions
BEV	5,0 km/kWh	14,9 gCO_2/km	4930 gCO_2
REx E10	13,2 km/l	166,7 gCO_2/km	22906 gCO_2
REx E100	8,5 km/l	37,9 gCO_2/km	6478 gCO_2
Rex E100 (RC+EGR+Miller)	9,3 km/l	33,7 gCO_2/km	6111 gCO_2

It is noteworthy the large difference in carbon emissions from the original range extender version fueled with E10 to the BEV using the carbon emissions of the Brazilian energy mix, being 465% higher than the BEV version on the same range basis. Even though the E100 range extender presented a 24% higher CO_2 emission when compared to the electric version, mainly due to the low well-to-wheel ethanol carbon footprint, it is a small increase once the range could be extended by 56% compared to a BEV without the drawbacks of adding larger batteries and weight to the vehicle, further increasing carbon emissions of the electric version.

6. Conclusion

The growing demand for fuel consumption reduction and more efficient engines requires more complex powertrains with a higher level of electrification. The solution from AVL South America is to implement a range extender internal combustion engine fueled with ethanol into a BEV for a range extension, which provides low gCO_2/km emission based on the Brazilian energy mix. By having the ICE optimized for charging the battery at the sweet spot, lowest fuel consumption operating point, an even better vehicle range can be provided. The project and implementation of the range extender is being developed completely by Brazilian engineering, enabled by the investment of two power generation companies following the ANEEL regulations.

Such development might represent a reference for future studies and to ground future regulation of the electricity sector, allowing Brazil to enter new markets surging for the electric vehicles. In this scenario, the introduction of a range extender fueled with ethanol represents a pioneer work in Brazil which also contributes to the evolution of the flex-fuel market. The development of vehicles with range extenders opens opportunities to new smart energy, Enhancing the attractiveness of the zero emission vehicles and the BEV's for the customers.

The next steps of the ongoing development are: efficiency improvements of the ethanol range extender by the implementation of other technology such as thermal recovery, direct fuel injection, boosting, flexible valve actuation, coupled with a cost-effectiveness analysis. And a study of advanced technologies in order to replace the internal combustion engine range extender with a solid oxide fuel cell (also powered by ethanol).

7. Acronyms

Acronyms	Meaning
ANEEL	Agência nacional de energia elétrica
BEV	Battery Electric Vehicle
CETESB	Companhia Ambiental do Estado de São Paulo
Denatran	Departamento Nacional de Trânsito
ECE	Status of United Nations Regulation (Normative)
EGR	Exhaust Gas Recirculation
EPA	United States Environmental Protection Agency
EREV	Extended Range Electric Vehicle
FCV	Fuel Cell Vehicle
FTP-75	Federal Test Procedure - Number 75
HEV	Hybrid Electric Vehicle

Ibama	Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis
ICE	Internal Combustion engine
Inmetro	Instituto Nacional de Metrologia, Qualidade e Tecnologia
LHV	Lower Heat Value
MWh	Mega Watt hour
NVH	Noise, Vibration, Harshness
PHEV	Plug-in Hybrid Electric Vehicle
rc	Compression Ratio
REx	Range Extender
s	Second
THC	Total Hydrocarbon
WTW	Well-to-wheel
μ	Ratio of Specific Heats of Air
UTE	Thermoelectric Energy Unit
UHE	Hydroelectric Energy Uni
EOL	Wind Power Plant
UTN	Thermonuclear Unit
CGH	Hydroelectric Power Plant
PCH	Small Hydroelectric Power Plant
UFV	Photovoltaic Power Station

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