New Engine Block for Low Impact of CO_2 Emissions

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ABSTRACT

A significant presence of combustion engines is forecasted to passenger vehicles in the next decades due to the use of bio or synthetic fuels. Besides operational performance, it is also important to focus on improvements of engine manufacturing carbon footprint. For the last years, the focus on reducing weight enabled the move to Aluminium for engine blocks. However, this material requires significant levels of energy to be produced. This paper presents the development of a block made on cast iron with similar weight than Aluminium.

The weight reduction in cast iron is allowed by different innovations: improved mechanical resistance material, new casting techniques (additive manufactured sand cores and improved cooling speed), and casing cover on areas of no stress made of plastic. An actual demonstration is presented to illustrate this result based on series 1.2L turbo engine.

A dedicated analysis on CO2 emission is presented from literature and actual evaluations to illustrate the significant reduction of cast iron compared with Aluminium including the scenario of infinite recycling events. That reference indicates benefits beyond 50% reduction on CO2 emission during manufacturing for cast iron blocks compared to Aluminium. The benefit to combine this high strength technology with ethanol as fuel is also illustrated.

INTRODUCTION

In a worldwide perspective, the transformation in the automotive sector is leading to high level of uncertainty about market forecast. Many times, new predictions are published with high levels of electrification. However, it is very important to pay attention that many times when it is indicated electric vehicles it does not mean Battery Electric Vehicle (BEV) only, but Hybrids as well. In that sense, it is not correct to predict a complete ban of internal combustion engines. Anyhow the issue in concern is CO2 emission, which is linked to fossil fuel, that can easily be addressed using an internal combustion engine (ICE) with other fuels like biofuels or synthetic fuels. Ethanol experience in Brazil shows how that is perfectly possible. Even blends are considerable transition strategies to achieve low CO2 emission scenarios [1].

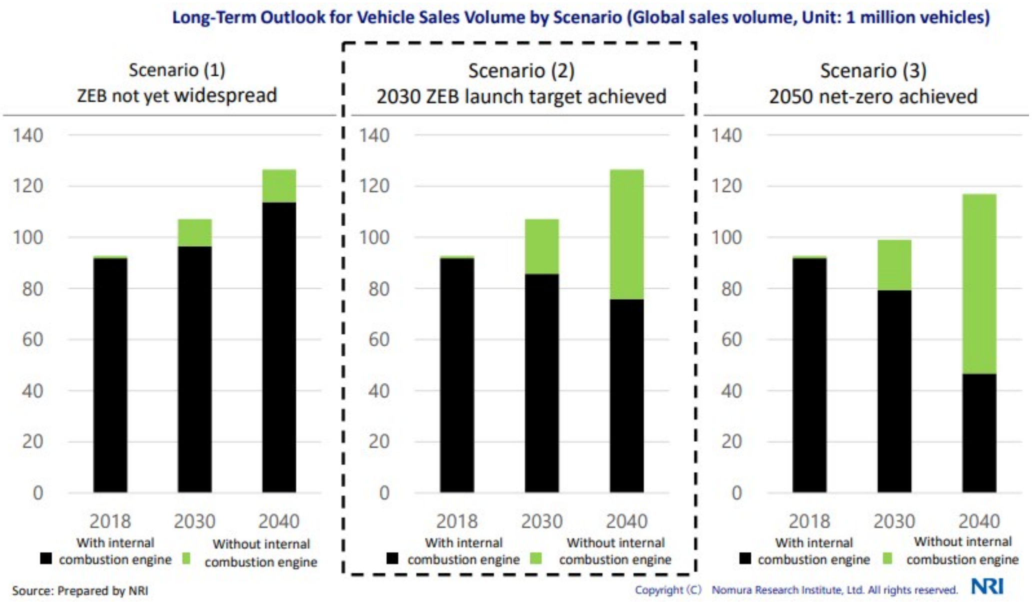

Figure 1: Scenarios for sales forecast of light vehicle for drivetrain type – extracted from [2]

As indicated by [2] in Figure 1, even on most aggressive scenario, internal combustion engines will be present in more than 40 million vehicles per year worldwide by 2040. In a realistic scenario, it is more than 70 million. In Brazil, ANFAVEA and BCG [3] presented a work in August 2021 indicating a similar picture even more conservative. In a realistic scenario 92% of vehicles would have an ICE by 2035, while in case of high electrification 77%. With these evaluations, internal combustion engines are important part of the transition, and its improvements are strategic.

Once the discussion about electrification is related to CO2 emission, it is very important to have it considered as holistic as possible and no single sight only. In a AEA Symposium, Silva [4] presented an analysis considering the CO2 emission for producing a BEV and ICE vehicle and its emission along the life. It took as reference a C-Segment vehicle and 15.000 km use per year, see Figure 2.

On Figure 2, a BEV to be produced has a CO2 emission around 3 times higher than an ICE vehicle. This is negative result for the first perspective which needs to payback the CO2 emission by savings along the use of the vehicle. However, these savings depend on the source of electricity in the respective country. As seen in Figure 2, in Bolivia, there is no payback after 10 years use. Gasoline ICE was 4% lower accumulated emission than BEV. While in Brazil, it would represent 38% less CO2 emission after 10 years for BEV, even starting 3 times higher than ICE. Notice that there was no correction on electricity CO2 level that can change if demand increases. For example, in Brazil, the higher demands made the need to increase the use of thermal electric generators, which would increase the carbon intensity of the electricity. Another point not considered in the evaluation of Figure 2 is the need to replace the battery after 8 to 10 years. The main impact of higher CO2 emission in the production of electric vehicle is the battery, so its exchange before the final life of the vehicle would make a new increase on total emission making “pay back” not possible even when compared with Gasoline.

Conway 2019 [5] presented a similar analysis comparing the LCA for different vehicle autonomy range. That would make the “payback” for electrification more difficult once higher sized batteries are necessary and higher CO2 would be spent on production, see Figure 3.

A second important analysis presented at [5] is the importance of hybridization, that a small battery combined with simplified combustion engines can lead to a solution of low carbon footprint in production and lower inclination of operation curve once it is more efficient, see Figure 4.

But in Brazil, there is a long and huge experience on the use Ethanol as biofuel. Even the regular gasoline contains 27.5% of Ethanol blended to gasoline. More than 80% of new produced vehicles are flex fueled and allow the use up to 100% of hydrated Ethanol. In that regard, Silva [4] updated the picture in Figure 2 with the Ethanol curve generating the picture presented in Figure 5.

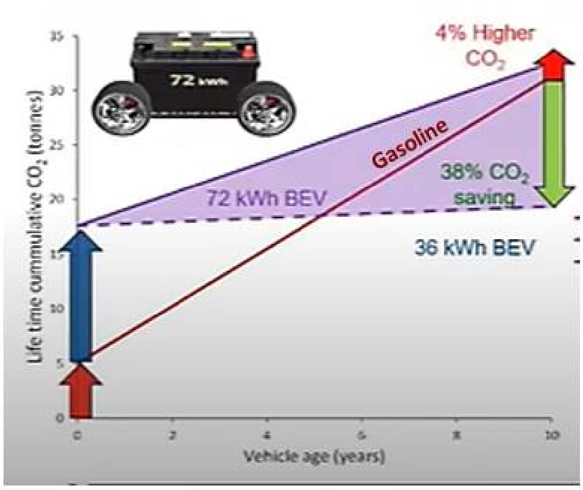

Figure 2: LCA analysis for a C-segment vehicle considering 15.000 km use per year. Extracted from [4]. Purple triangle is the range of electricity in Southamerica. Red arrow on the right side indicates Bolivia where BEV is worst than Gasoline after 10 years usage and Green arrow is the benefit of BEV compared to gasoline using Brazillian electricity.

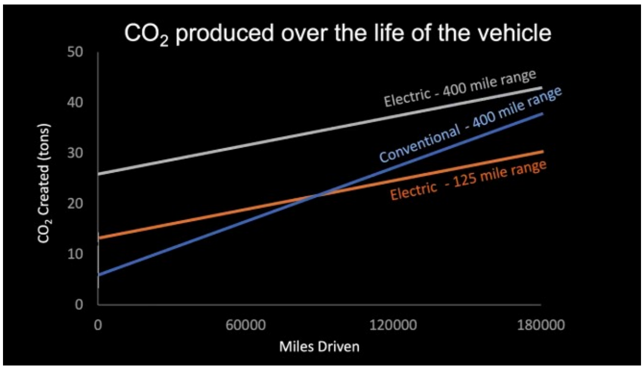

Figure 3: LCA comparison due to vehicle range. Extracted from [5].

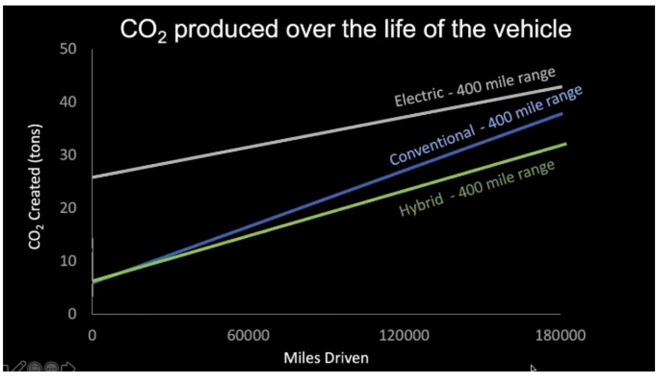

Figure 4: Hybridization benefit on LCA. Extracted from [5].

Figure 5 is clear that the lower carbon footprint to produce ICE and the excellent carbon footprint of Ethanol makes very advantageous the use of this mode for this kind of vehicle application in terms of accumulated CO2 emission even when compared with a very clean electricity source. The investigation on [6] shows that in Brazil average use of vehicle is 13.000 km per year, which indicates that evaluations presented in Figures 2 and 3 are well aligned or even more challenging for BEV on equivalent CO2 payback.

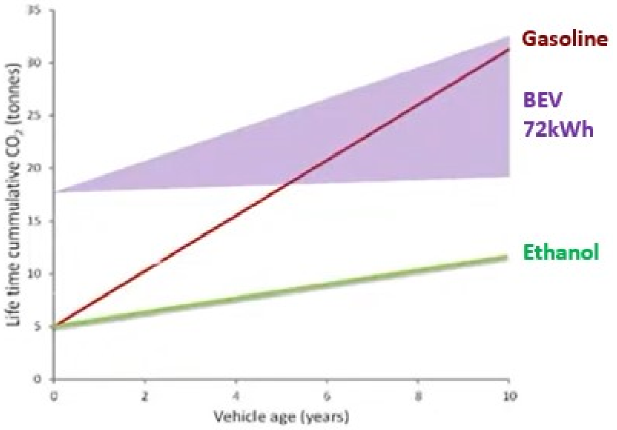

Figure 5: Ethanol comparison with Gasoline and BEV in therms of LCA for CO2 emission up to 10 years use. Extracted from [4].

In this paper, it is explored how ICE engines can continue to improve LCA and remain attractive to the energetic transition. Generally, the process of Aluminium is known to be intensive on energy consumption. However, its use on engine crankcase became so popular in the recent past due to the possibility to reduce weight saving fuel consumption. The authors decided to answer the question "what if cast iron crankcase could have the same weight than Aluminium?". From that it was selected a series engine as baseline and a demonstrator was built with partners from design, simulations and tests. This paper also presents future combinations with ethanol fueled crankcases and how the envelope of sustainable ICE will maintain a relevant position worldwide.

MANUFACTURING CARBON FOOTPRINT

Widely studied in previous research, the production of cast iron has significantly lower CO2 emissions than the production of Aluminium. In the specific case of passenger vehicle cylinder blocks, even with the favorable assumption of infinite recycling for Aluminium, the benefit of cast iron can save 40% to 70% of the manufacturing CO2 emissions compared to Aluminium, according to a publication at the 2017 Vienna Motor Symposium by Cranfield University [7]. See illustration from Figure 6.

The paper [7] uses a similar payback approach to identify that minimum 143 thousand km would be necessary to save enough fuel by weight reduction of Aluminium compared to cast iron to make the CO2 emission neutral by the disadvantage of Aluminium at manufacturing phase.

Now it needs to be updated that cast iron crankcase can have the same weight as Aluminium, making the savings on fuel consumption during engine operation by Aluminium not existent compared to cast iron and the emission of CO2 to produce cast iron even lower, around 30% less, which was the weight different considered in the paper.

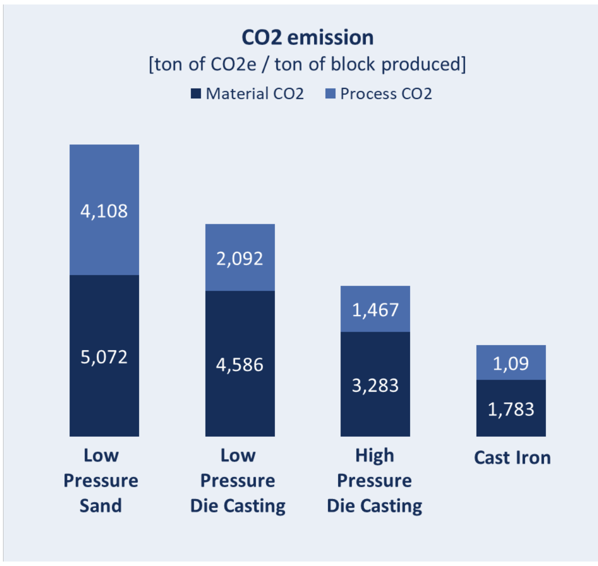

Figure 6: CO2 emission for the manufacturing of engine blocks. Comparison between Aluminium and cast iron. Adapted from [7].

Another important item to be taken in consideration is the CO2 emission reference of Tupy. As described in the sustainability report from 2021 [8], Tupy has a CO2 emission 30% lower than world average considering scopes 1 (direct emission) and 2 (indirect by electricity consumption). It is also indicated at [8] that Tupy had an average of 97% of iron used from recycled source against 91% used in the study presented at [7].

Concentrating the comparison with Aluminium only on the most efficient version of it, Figure 7 indicates potential correction of values for Tupy reference on CO2 comparison with Aluminium crankcase. Once Figure 6 was already an emission per mass, the correction applied presented at Figure 7 was only regarding the lower emission from Tupy compared to global average.

As can be seen in Figure 7, applied the corrections to the new conditions of the developed technology, cast iron increases its advantage for CO2 emission during manufacturing compared to the most efficient process of Aluminium from 40% benefit to 58% benefit.

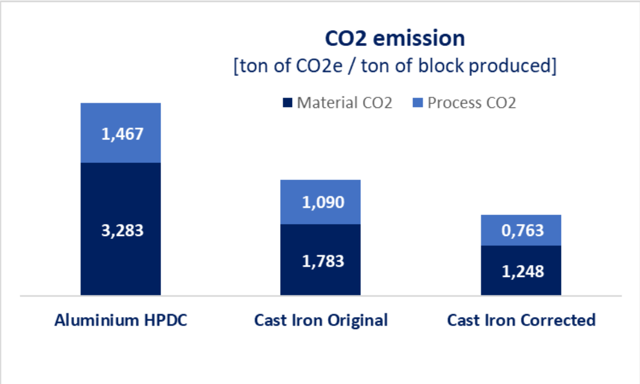

Figure 7: Corrected values for cast iron from [7] using data from [8]

Considering a production rate of 100 thousand vehicles a year for a 3-cylinder engine, which would have a weight between block, bad plate and caps around 20 kg, the total CO2 emission savings by the use of cast iron can represent 5,400 ton CO2 equivalent per year. Given the costs on carbon market, it can leverage resources to speed up projects for the transition from Aluminium to cast iron blocks supporting the global targets on CO2 reduction.

CAST IRON SAME WEIGHT AS ALUMINIUM

It was presented at [9] the development of a new compact graphited iron (CGI) material with superior mechanical resistance, which in combination with advanced casting techniques to control cooling velocity enabled thin walls resulting on redesign of crankcase. This redesign allowed the block to achieve the same weight than Aluminium on series application.

Table 1 and Figure 8 summarize the new material CGI500, and its properties compared with regular materials. Notice that on small blocks there is even the possibility to achieve higher resistance levels as 550 MPa minimum. This was the case on the demonstration presented at [9].

Table 1: Qualitative comparison between Aluminium and cast iron alloys.

Features	Aluminium	Gray Cast Iron	CGI450	CGI500/550
Mechanical Strength	+	+	+++	++++
Thermal Conductivity	+++	++	+	+
Thermal Fatigue Strength	+	++	+++	++++

It is important to observe that properties presented on Table 1 are related to the materials, e.g. for the final product, the thermal conductivity is the combination of material property and the wall thickness. That is why on actual application the performance of thermal conductivity is equivalent between Aluminium and cast iron due to the wall thickness much reduced of cast iron.

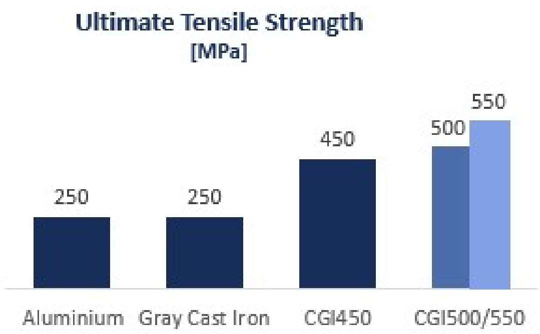

Figure 8: Ultimate tensile strength comparision for different material applied for engine blocks.

All the manufacturing was done inside Tupy's volume production environment. The individual cores were assembled to form fully enclosed core packages. Metal filters and running systems incorporated directly in the core packages were placed into green sand flasks on the standard production line. Figure 9 gives an overview of the box formation.

Adaptations of sand cores design and technology depends on the degree of freedom of each project. On certain restricted cases the use of printed cores is necessary, which are well known to the team and clear prepared to face industrial validation steps for mass production.

Using a series 3-cylinders 1.2L gasoline turbo European engine, it was possible to redesign its crankcase in cast iron CGI550 using the same engine head and same piston kit. While the series engine, considering block, bad plate and caps, weights 21.06kg, the redesigned version in cast iron, consisting of block, ladderframe, casings and caps, weights 20.06 kg. So, cast iron can have the same weight than Aluminium for crankcase applications.

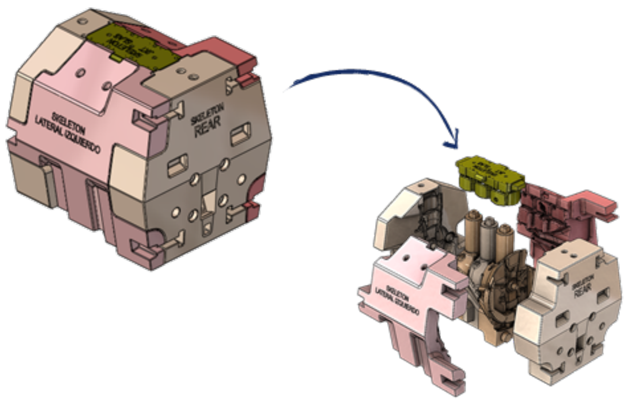

Figure 9: Exploded view of the cylinder block core package. Extracted from [9].

DEMONSTRATION ON ACTUAL APPLICATION

The demonstration on an actual application presented on [9] followed the main steps presented in Figure 10 ahead.

Table 2: Summary of cylinder block and fully assembled engine weights (kg). Extracted from [9].

Component	Aluminium (Original)	Aluminium (48-Volt)	CGI (48-Volt)
Cylinder Block*	14,05	13,46	15,68
Bearing Caps and Fasteners	2,54	2,54	-
Ladderframe and Fasteners	-	-	2,04
Outer Casings (Including Rear Cover, Gaskets and Fasteners)	-	-	2,34
Upper Oil Pan and Fasteners	3,45	3,45	-
Lower Oil Pan and Fasteners	1,02	1,02	-
Total Cylinder Block Weight	21,06	20,47	20,06
Assembled Engine Weight (Dry)	92,00	91,41	91,00

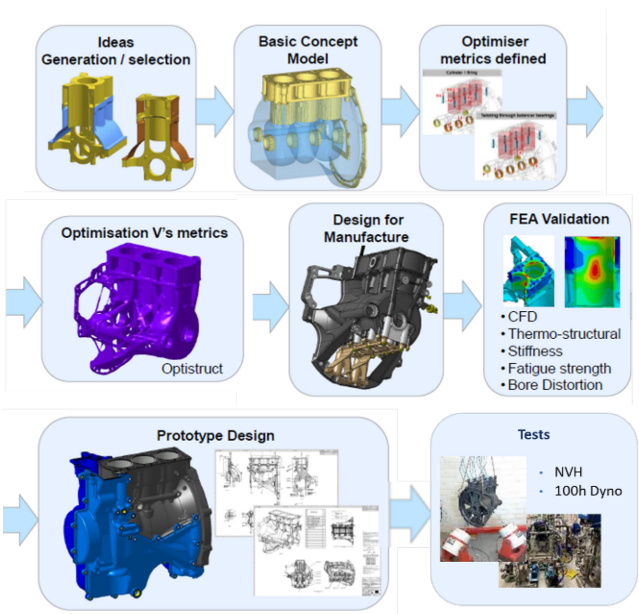

Figure 10: Stages of development for demonstration project

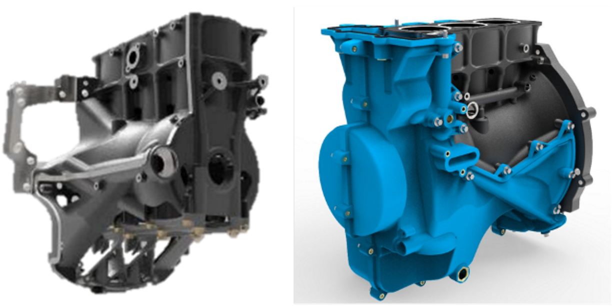

Figure 11: Demonstration engine. Extracted from [9].

In addition to the weight similarity, cast iron block presented 54% less material, enabling up to 2.25 times more area for breathing. These advantages could be returned back to design loops for further engine optimizations regarding operational performance.

In complement to the weight performance, the project was always validated by simulation and later by tests. In simulation The block design was iteratively modified to produce an architecture that provided the same stiffness as the original Aluminium block. The initial OptiStruct design was analyzed for bore distortion and ring conformability, head mounting stresses and local stress concentrations.

After simulation rounds, prototypes were produced to validate the production route for casting and machinability. All were approved and according to volume production experience of Tupy. For machinability the use of cast iron material enabled the use of fracture-split technology for main bearing caps. Such technology provides superior connection of the half parts enabling superior NVH results, see Figure 12.

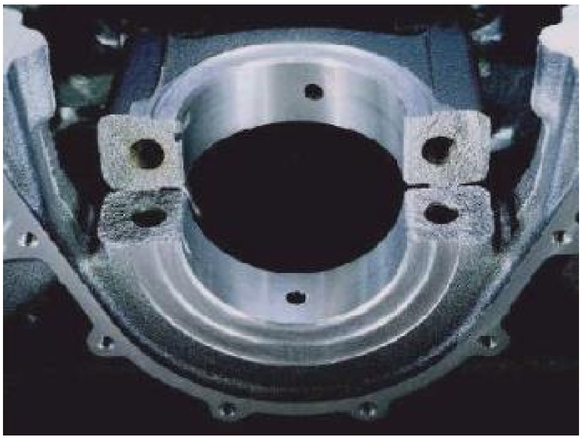

Figure 12: Fracture-split technology.

The blocks were investigated for frequencies enabling a NVH evaluation. Major modes are compared between materials showing that the global flexural modes of the CGI cylinder block assembly are approximately 4% higher than the original aluminium engine, which is a positive contribution to engine NHV. This benefit is due to the combined effects of the block architecture and the higher elastic modulus (material stiffness) of CGI (~2x Aluminium). Bearing cap main frequency modes were 200 to 600 Hz (18 to 46%) higher than the baseline Aluminium, indicating a significant increase in the stiffness of the bearing caps, despite the thinner profile and reduced weight. This improved stiffness is due to the combined effect of the unique ability of CGI to employ fracture-split main bearings and the adoption of the CGI ladderframe.

Table 3: NVH evalution between series Aluminium and cast iron development. Adapted from [9].

Mode Description	CGI (Hz)	Aluminium (Hz)	CGI Increase
Block Torsion	952	908	4.8%
Torsion - Bell Housing Lower	978	939	4.2%

Mode Description	CGI (Hz)	Aluminium (Hz)	CGI Increase
Bearing Cap 1 – Front End	1,969	1,398	40.8%
Bearing Cap 2	1,967	1,347	46.0%
Bearing Cap 3	1,763	1,346	31.0%
Bearing Cap 4 – Flywheel End	1,441	1,222	17.9%

The engine was also tested in a dyno cell for 100h, which proved the functionality of the new block. The tests showed same performance and fuel consumption of the base engine. Same engine head and piston kit from series engine were used on the tests. Details can be found at [9].

This demonstration engine was built with the concept to use same engine head and piston kit than original engine. In a situation of a complete freedom of design, even other design options could be tried with the superior properties from cast iron, e.g. distance between cylinders could be reorganized allowing more weight reduction and better heat control.

ETHANOL FUELLED CAST IRON CRANKCASE

Ethanol is known as the most important decarbonization option for gasoline. The emission of CO2 during vehicle operation is compensated by the sequestration of the biomass. However, different sources and processes of ethanol can lead to different levels of carbon intensity as presented in Figure 13 from [10].

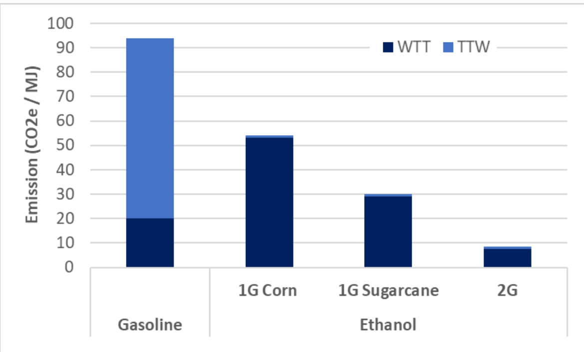

Figure 13: Well-to-wheel results in terms of CO2 equivalent for gasoline and bioethanol options (WTT = weel-to-tank; TTW = tank-to-wheel). Addapted from [10].

Even the carbon intensity of Ethanol can be benefited in the future from different decarbonization activities as land use strategies, substitution of Diesel by Hydrogen, more use of biofertilizers etc.

To enhance engine performance taking the advantage of higher knocking limit of ethanol, the path is to increase power density and increase compression ratio. The use of turbo system can help to lead to higher compression levels at combustion chamber. This will lead on higher peak cylinder pressure and consequently a higher mechanical resistance is needed by the crankcase. Being cast iron, it is in the correct direction to support engine improvement. It is also possible to design improvements on bore distortion that tends to be increased with engine load. The better control of bore distortion with a more stable material can also allow the combination of lower tension piston ring pack and higher clearances on pistons. The higher clearances on pistons tend to be critical for NVH, which was shown to be improved with cast iron crankcase.

Finally, the use of ethanol can be critical to the lubrication on bearings, especially main bearings, due to potential contamination of oil. However, it is reduced in the case of cast iron crankcase once the use of fracture-split technology enables a perfect fit of the cap's half sustaining good oil film, providing lower levels of exposition of the base material to any corrosion phenomena.

It is clear that a cast iron ICE fueled with ethanol is a solution for long term decarbonization once it brings even further improvements on the LCA presented in Figure 3 indicating no advantage in any timeframe for BEV. The only possibility for a situation where BEV can come closer would be in an intensive new energy scenario to produce electric vehicle and use of green electricity, which is not closer than 2040-2050 timeframe worldwide.

CONCLUSIONS

The CO2 solution is broader than a simple analysis on the operation of the vehicle only. It is very important to also understand the life cycle from the vehicle parts and the fuel/energy production to assure we are advancing to the correct direction.

As presented in this paper, Tupy developed with partners a crankcase on cast iron with same weight than Aluminium and this design approach is possible to be replicated to all pass car vehicles. This enables not only the chance to reduce costs, but also reduce the carbon foot print up to 58% when compared with Aluminium processed by High Pressure Die Cast technology, which is the most efficient one for Aluminium. There is also the extra benefit on recyclability of cast iron block due to material homogeneity. Further engine optimizations are also possible with cast iron crankcases due to its superior performance results like strength, NVH, breathing and bore distortion.

Hybridization shows to be one of the best strategies to cope with a compromise solution on low carbon footprint to propulsion system production and energy spent during vehicle operation.

The use of Ethanol makes the combination best for LCA while production energy sources are not totally clean. The possibility of getting extra performance from Ethanol due to its higher knocking resistance are also leveraged by higher resistance material like cast iron crankcases. The decarbonization of ethanol production is also playing an important role to show how such fuel has a clear path not only as transition but a permanent solution for decarbonization on transportation.

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