Development of range extender based on a BMW K75 engine

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Abstract. With growing electric mobility and its associated autonomy problems, the concept of range extender was born. A possibility for a range extender is to have an internal combustion engine producing the electric power when the battery is depleted by a certain level. It should be a highly efficient engine and this can be achieved by altering its thermodynamic cycle from the traditional Otto to an over-expanded one, by changing valve timings. The goals of this project are to test two operating modes for the range extender, one, at low speeds but extremely efficient, and another at higher speeds, with greater power output with less concern for efficiency.

Keywords. Range extender, internal combustion engine, over-expansion, efficiency

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Introduction

With a greater conscience on scarcity in available fossil fuels and a growing effort in finding better ways to exploit them, there is a need to develop increasingly more efficient technology, in order to prevent the end of these limited resources. The Environment and State Report [1] points out to a decrease in the consumption of oil and its byproducts in the last few years. Nonetheless, they still represent about 43% of the primary energy consumed in Portugal.

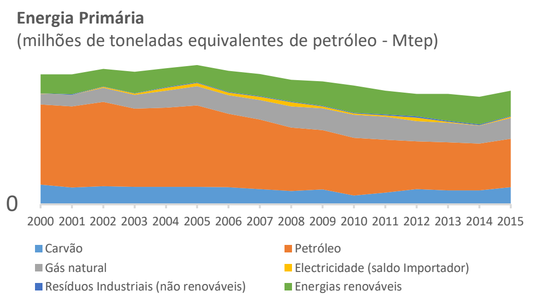

***Fig. 1** – Primary energy consumption in Portugal in 2015 ([2])*

It also points out that the transportation sector is one of the sectors with a bigger share in energy consumption and also in greenhouse effect gases emission, representing about 23% of the national emissions in 2014. This being said, the increase of energetic efficiency in the transportation sector is of primary importance, allowing, not only a decrease in greenhouse effect gases emissions but also a lower oil and byproducts consumption [1].

A good way to achieve this is to exchange the use of internal combustion engines powered vehicles with electric ones, since these usually have high efficiencies. However, two problems arise with this: their reduced autonomy, especially when compared to those of internal combustion engines, and the batteries required to power the electric motor, which are generally expensive and bulky and take a long time to charge. These two problems could be solved with a good network of charging stations around the country, but this raises other problems on its own. On the other hand, if the electric vehicles could be equipped with a range extender, the severity of the problem would be far lower.

A range extender is a device that allows for the autonomy of an electric vehicle to be increased for instance, a small internal combustion engine that produces electricity to charge the vehicle battery when it is needed. As electric motors have excellent efficiencies and usually internal combustion engines don't, it is required for the engine that would serve as a range extender to have an efficiency as high as possible and a good way to do that is to have the engine run with an over-expanded cycle, instead of the traditional Otto cycle. Over-expanded cycles have inherently bigger efficiencies than those of the Otto cycles, although they produce less power.

The range extender is to operate supplying the produced mainly to the electric motor. When the battery reaches below a certain defined state of charge, the range extender is activated to supply the electric power needed. Its output power could be variable, in order to supply only the needed power, as seen in **Fig. 2** (a), never actually charging the electric vehicle (EV) battery. Another alternative is for the range extender to have two fixed operating regimes, displaying only two fixed values of power, as represented in **Fig. 2** (b). With this last option, the excess power produced that is not needed by the electric motor could actually be used to charge the battery, which would eventually lead to its charge state being above the pre-defined state to active the range extender. When the power output of the first operating mode (ECO) is not sufficient, the range extender switches to a second one (BOOST), with power output as primary concern [3].

Considering this, it is proposed to develop a range extender with two operating modes: the ECO mode, running at low speeds with high efficiency and a BOOST mode, running at higher speeds and producing more power and with less concern for efficiency.

The main goals of this work is to develop a range extender based on an internal combustion engine, running on an over-expanded cycle, to be equipped in an electric vehicle intended to be used mainly in an urban environment, without the frequent need to make long journeys, that meets the following requirements:

- Use of ECO mode at 3000 rpm, when the autonomy of the battery isn't enough to cover the journey distance. It should reach at least 15 kW power and an efficiency as high as possible. It is intended that this mode will be about 95% of the range extender use.
- Use of BOOST mode at 7000 rpm, when a power peak is required, as in a long ascent or in case of overtaking. The minimum power required for this mode is 35 kW.

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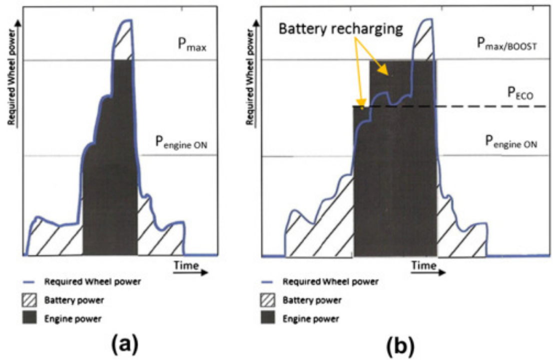


Fig. 2 *–Examples of operating modes for a range extender: (a) producing variable power; (b) two-mode operated range extender (adapted from [3])*

With this choice, it's possible to have a range extender highly efficient in the ECO mode and with good power peaks in the BOOST mode.

The choice for the engine to be adapted is from a BMW K75, running on gasoline. Since it is from a motorcycle, it is a small, compact engine. It's also a fast engine, capable of meeting the 7000 rpm mode requirement. This engine is under-squared, an uncommon feature on high efficiency engine, but this comes to prove helpful in the adaptation from the Otto cycle to the over-expanded cycle.

Context and State of the art

With the popularization of electric cars, the term "range anxiety" has come to be. "Range anxiety" is the fear that the vehicle's range will not be enough to reach the intended destination. In response to this, some companies provide the option to equip the electric vehicle with a range extender, the first being the Chevrolet Volt, although others exist, like the BMW i3. Some companies even offer the range extender as a standalone product, such as Mahle Powertrain or Duke Engine. It is extremely important that the efficiency of these range extenders be as high as possible, as the electric motors' are usually higher than those of an internal combustion engine (ICE)

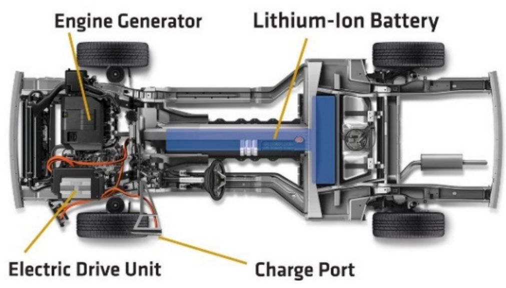


Fig. 3 - Chevrolet Volt layout (adapted from [4])

In order to determine the best strategy to increase the range extender's efficiency, some of these technics are here described.

In the engine optimization field, there has been much progress, and each company has its own technology. From variable compression ratio to variable valve timing, all this effort is being made in order to rise the efficiency of the internal combustion engine.

The compression ratio of an engine is directly connected with its efficiency and being able to manipulate it is a way used to increase efficiency or power, according to the situation. Some noteworthy engines with variable compression ratio (VCR) are the SAAB SVC (Saab Variable Compression), which is able to tilt the engine head in order to change the compression ratio from 8:1 to 14:1 or the Nissan Infiniti, which changes one the crankshaft supports, to alter the height the piston can reach, changing the compression ratio.

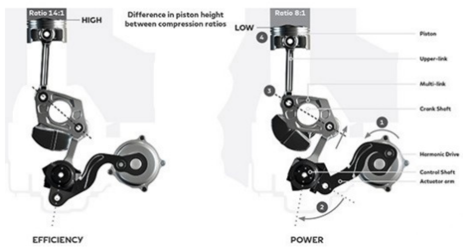


Fig. 4 - Nissan VCR system (adapted from [5])

Being able to change valve timing is also a frequently used way to optimize an engine, whether it is to increase brake power or reduce consumption. At lower speeds it's advantageous to have the valves open and close as close as possible to the corresponding dead centers. As the engine's rotation speed is increased, the timings should be altered, allowing to take advantage of inertial dynamic effects, so that it's possible to have mixture entering the cylinder even though the piston is already travelling upwards, that leads to an optimal filling of the cylinder, rising the engine's volumetric efficiency. Systems like BMW's VANOS [6] or Honda's VTEC [7] are capable of achieving such things. A peculiar system is the FreeValve [8], in which each valve, whether is it an intake or exhaust valve, is controlled independently by a hydraulic actuator, without the need of a camshaft.

As previously discussed, a way to rise the engine's efficiency is having it run in a slightly different cycle than usual, the over-expanded cycle. The Honda EXlink engine is an over-expanded that relies on a special crankshaft, causing the piston to have different intake and explosion strokes [9]. Others rely on valve timing to achieve the over-expansion, usually by closing the intake valve much earlier than the bottom dead center (BDC) or much later. Mazda has been known for having over-expanded engines, such as the Mazda Millennia or the Mazda2 [10] but with the introduction of high efficiency hybrids in the market, other companies have also used this technic, like the Toyota Prius or the Ford Fusion Hybrid.

Experimental Installation

The engine to be used in the project is a BMW K75, 750 cm^3, 3 cylinder inline, spark ignition engine. The adaptation to over-expanded cycle had already been done when this project started and it involved changing the camshaft (to a new one called Dwell 50, previously tested) and lowering the engine block by a total of 3.5 mm. The Engine Control Unit (ECU) used is a MegaSquirt II, due to its high flexibility and easiness in reading and changing the required injection and ignition maps.

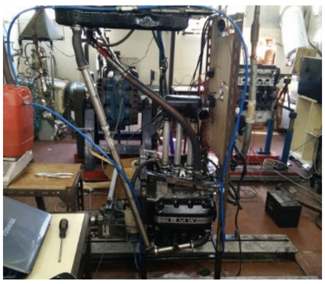


Fig. 5 - The BMW K75 used during the project

The gasoline is supplied to the engine by a pump located inside the deposit at a 3 bar pressure. The feeding system also has available a pressure valve and a return line. The engine's consumption is measured by weighing the deposit throughout time with a KERN scale, which registers in a text file the weight of the deposit every second.

Fig. 6 - Deposit and scale

To cool the engine there is a line of pipes transporting coolant liquid, pumped by the engine and cooled in a radiator and a temperature sensor is installed to let the user know when to turn on the radiator, since the cooling systems has no thermostatic valve.

The exhaust system is composed of an exhaust manifold that gathers the combustions gases in a single line and releases them to the atmosphere outdoors. A lambda probe is located after the exhaust manifold that shows the AFR ratio.

Fig. 7 - Exhaust line and pan

To power the starter, the injection system, ignition, the sensors and the ECU a 12 V DC battery is used. To protect all the wiring from eventual over-loads or short-circuits, a fuse box is used.

The current adaptation to over-expanded cycle was made by means of a new camshaft, the Dwell 45. This new camshaft begins opening the intake valve 15° later than the original and, when the valve reaches maximum lift, instead of starting to close, the valve remains open for 30°, resulting in an intake valve closure 45° later, hence the name Dwell 45. A new exhaust camshaft had also already been manufactured, in order to reduce valve cross-over, which allows to further the exhaust gases expansion. The current and original intake valve lift profiles and valve timing diagrams can be seen bellow:

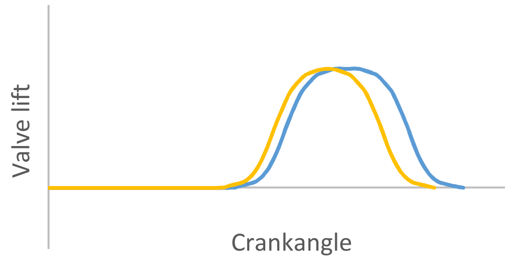


Fig. 8 - Profile for the original cam (yellow) and the Dwell 45 (blue)

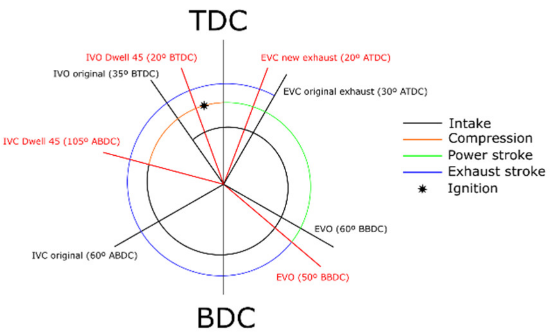


Fig. 9 – Current and original valve timing diagrams

With the ECU it is possible to fine tune many parameters, such as the injection or ignition maps (these two by trial and error), target AFR values, cranking, warm-up curves, and a lot more.

To measure the produced torque there is a hydraulic dynamometer available *(Go Power Systems Dynamometer D-100* [11]) equipped with a load cell. The torque curves of this brake are higher than those of the BMW K75, so that this dynamometer can actually brake the engine. To get accurate results from the load cell, it should be calibrated, in order to know the relation between the output cell voltage and the torque associated with it. By hanging some weights at 0.5 m away from the brake, the calibration curve was obtained. There is software that registers the output voltage values produced by the cell, which can easily converted to torque.

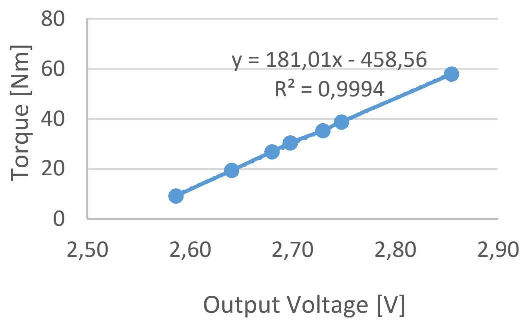


Fig. 10 –Calibration curve for the load cell

Experimental Procedures

Before testing the engine, there are a few steps to take. It should be checked if there is enough oil in the engine, as there are a few damaged threads and sometimes there can be oil leaks. It should also be checked if there is gasoline in the fuel deposit and if there is enough coolant. The exhaust system should be turned on as well as the pump that feeds the necessary water to the hydraulic brake. The ECU should be connected to a laptop in order to monitor the engine behavior. After verifying that there are no strange objects around the engine and the dyno, connect the battery cables and start the engine.

Once the engine is running, it should be kept at low rotation speeds (2000-2500 rpm) with the help of both the throttle and the brake until it reaches optimal temperature for testing, between 85 and 90 ºC, read on the laptop with the ECU. If the temperature is higher than 90 ºC, the radiator should be turned on. When the engine is running, the user should be alert at all times to strange noises, in the case of abnormal behavior, such as misfires, the appearance of knock, or any other problem.

After the engine is warmed up, the dynamometer is used to control the engine speed at any given throttle value, by means of two valves that control the water flow rate and, consequently, the braking force of the dynamometer. When the engine is successfully stabilized at the desired speed, it's possible to start logging the torque produced and fuel consumed during the test.

Fig. 11 - Water valves to control the braking force

Computational simulations

Some computational simulations were done before testing, allowing to know what to expect from the experimental results. The first used software was a Simulink model developed in the Universidade do Minho by Bernardo Ribeiro. It allows to simulation spark-ignition engines, controlling several geometrical parameters the air-fuel ratio. It should be noted that this model only accepts lean or stoichiometric mixture, as the rich mixture was never modelled. After modelling piston and valve movement, the simulink makes an analysis based on the 1st Law of Thermodynamics, followed by the combustion calculations, using a Wiebe function, and gas properties and exchange. The heat transfer is calculated using the Annand methodology and the Heywood and Sandoval correlation is used to model the engine friction. With all this data calculated, the final parameters are then computed such as torque, power, thermal efficiency or volumetric efficiency.

To use this simulink model, it should first be calibrated. This calibration is done using to parameters that control the discharge coefficient of the intake valve and the intake pressure. Manipulating these two coefficients, the model was calibrated to correspond with the manufacturer's torque curve.

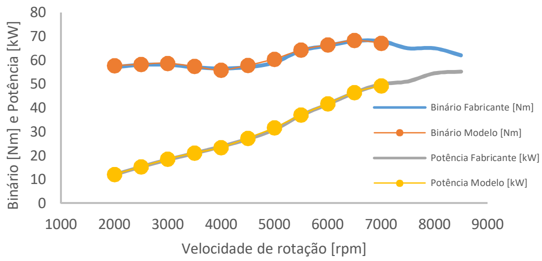


Fig. 12 - Calibrated results for the simulink model

Changing the needed parameters, like valve timing and geometric compression ratio, the over-expanded BMW K75 with the new Dwell 45 installed is simulated:

Table 1 - Numerical results from the simulink model

	Cons. [g/s]	Torque [Nm]	Power [kW]	BSFC [g/kWh]	η_t [-]	η_v [-]
ECO	1.007	51.9	16.3	222	36.5	75
BOOST	2.511	50.6	37.1	243	33.3	84

Another software was used for running simulations, the AVL Boost. It's an advanced software designed specifically to simulate internal combustion engines. In the AVL Boost, each component should de added individually as block representing different parts of the engine and afterwards connected with other by pipelines, making a path for the mixture to travel from the starting to the finishing point. Examples of these components are air cleaners, junctions, throttle valves, the injectors and the cylinders.

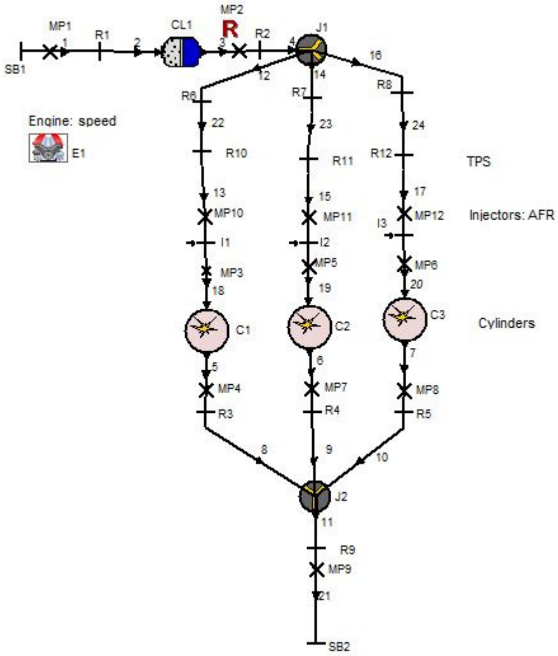


Fig. 13 - K75 model in the AVL Boost

The K75 model was made in way to be as equal as possible as the one modelled in simulink. The AVL Boost has many available correlations for each phenomenon that need modelling and the so the Annand correlation was used for heat transfer, the Heywood-Sandoval correlation for friction and a Wiebe model for combustion. The results obtained for the Dwell 45 camshaft in the intended ECO and BOOST mode are as follows:

Table 2 – Numerical results from the AVL Boost model

	Cons. [g/s]	Torque [Nm]	Power [kW]	BSFC [g/kWh]	η_t [%]	η_v [%]
ECO	0.989	49.8	15.3	227	36.0	67
BOOST	2.567	51.3	37.6	246	33.3	69

These results are, in first sight, very similar with the ones obtained with the simulink model, inspiring some confidence in their accuracy.

Afterwards, another simulation was done, comparing the thermal efficiencies of the previously tested Dwell 50, the Dwell 45 and a hypothetical Dwell 40. This was done in order to predict which one would be the best camshaft for the range extender at wide open throttle. The results are the following:

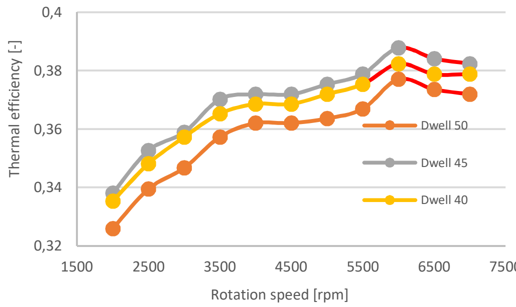
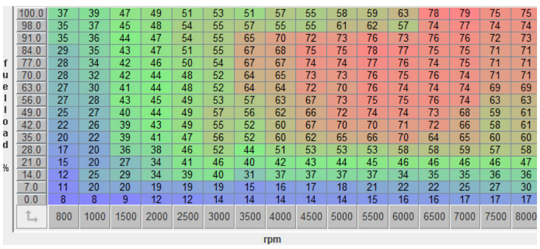


Fig. 14 - Simulated efficiencies for the over-expanded range extender (in red, predicted knock occurrence)

This suggests that the current camshaft being tested is the one who proves to be the best candidate for use in the range extender, as it seems that it's in the optimal point with the right amount of compression and over-expansion, without compromising efficiency.

Results and discussion

The tests to the engine are made after guarantying that the AFR values are the ones desired for each operating mode of the range extender. To the ECO mode, lean mixture is intended, with an AFR of around 16.7, or λ≈1.15, which is considered as a hand rule value that provides the biggest efficiency. On the other hand, for the BOOST mode 13.5 or λ≈0.9 is desired to give maximum power. And so, the injection map present in Fig. 15 was used in the ECU:



fuel load %	800	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500	8000
100.0	37	39	47	49	51	53	51	57	55	58	59	63	78	79	75	75
98.0	35	37	45	48	54	55	57	55	55	61	62	57	74	77	74	74
91.0	35	36	44	47	54	55	65	70	72	73	76	73	76	76	72	73
84.0	29	35	43	47	51	55	67	68	75	75	78	77	75	75	71	71
77.0	28	34	42	46	50	54	67	67	74	74	77	76	74	75	71	71
70.0	28	32	42	44	48	52	64	65	73	73	76	75	76	74	71	71
63.0	27	30	41	44	48	52	64	64	72	70	76	74	74	74	69	69
56.0	27	28	43	45	49	53	57	63	67	73	75	75	76	74	63	63
49.0	25	27	40	44	49	57	56	62	66	72	74	74	73	68	59	61
42.0	22	26	39	43	49	55	52	60	67	70	70	71	72	66	58	61
35.0	20	22	39	41	47	56	52	60	62	65	66	70	64	65	60	60
28.0	17	20	36	38	46	52	44	51	53	53	53	58	58	59	57	58
21.0	15	20	27	34	41	46	40	42	43	44	45	46	46	46	46	47
14.0	12	25	29	34	39	40	31	37	37	37	37	34	35	35	36	36
7.0	11	20	20	19	19	19	15	16	17	18	21	22	22	25	27	30
0.0	8	8	9	12	12	14	14	14	14	14	15	16	16	17	17	17

rpm

Fig. 15 –Injection map used while testing the K75 engine

After tuning the richness of the mixture, the optimal spark ignition advance (SIA) must be discovered. To do this, the engine must be tested several times, increasing the spark ignition advance one degree at a time, until the produced torque starts decreasing or knock is reached. For the ECO mode, the obtained results were the following:

Table 3 - Experimental results for the ECO mode (3000 rpm)

SIA (°)	Cons. [g/s]	Torque [Nm]	Power [kW]	BSFC [g/kWh]	Eff. [%]
18	0.9187	49.1	15.4	214	38.2
19	.9183	50.2	15.8	210	39.0
20	**.9223**	**52.7**	**16.4**	**202**	**40.5**

Unfortunately, due to scheduling conflicts and the need to remove the engine from its location to start installing a new dynamometer, necessary to increase test repeatability and reliability, it wasn't possible to run the BOOST mode experimental tests and so, there is no experimental data available for this operating mode.

According to the experimental results presented in Table 3, the optimal spark ignition advance to operate the BMW K75 range extender is 20^0, producing 16.4 kW with a 40.5% efficiency. It is possible now to compare these results with the results obtained from previous tests to the engine in its original state and with the previously tested camshaft, the Dwell 50.

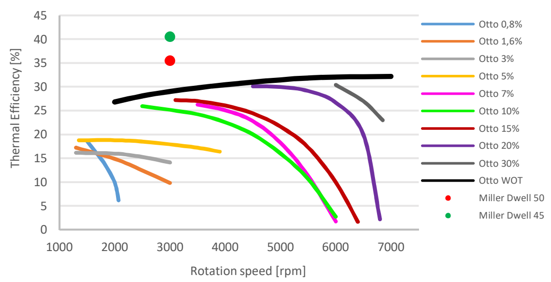


Fig. 16 – Comparison between original engine efficiencies and the efficiencies of over-expanded cycle in ECO mode (with results from [12])

To make a good comparison, one should fix torque and rotation speed (and not speed and throttle position) and compare the engine efficiency for those same fixed parameters. For the data with the original, two possible points are eligible: at 3000 rpm and 30% throttle or Wide Open Throttle (WOT), since at 3000 rpm, after 30% load, the throttle doesn't restrict the air flow anymore. The following table presents all the data gathered so far for the ECO mode:

Table 4 – Comparison for the ECO mode (with results from [12]

	TPS [%]	Speed [rpm]	Cons. [g/s]	Torque [Nm]	Power [kW]	BSFC [g/kWh]	Eff. [%]
Original	30	3000	1.22	54.0	17.0	258	31.7
Engine	WOT	2950	1.38	54.9	17.0	292	28.0
Dwell 50	WOT	3000	1.01	49.9	15.7	231	35.4
Dwell 45	**WOT**	**3000**	**0.92**	**52.72**	**16.42**	**202**	**40.5**

According to the previous obtained results it's possible to affirm the advantages of using the over-expanded cycle, as it allows to reduce the fuel consumption for the same torque at the same speed. The Dwell 45 proved to be the best camshaft for use in the range extender running at ECO mode. Although there is no experimental data to validate this, both computational models predicts that it's also better than the Dwell 50 for the BOOST mode, as it has more compression, which means more power. Also, both the simulink model and the AVL Boost model conclude the same thing, as can be verified bellow in Table 5.

Table 5 - Comparison for the BOOST mode (with results from [12])

	Speed [rpm]	Cons. [g/s]	Torque [Nm]	Power [kW]	BSFC [g/kWh]	Eff. [%]
Original	7000	2.69	49.7	36.4	266	30.8
Dwell 50	7000	2.67	48.2	35.3	272	30.1
Simulink Dwell 45	7000	2.51	50.6	37.1	243	33.3
AVL Boost Dwell 45	7000	2.57	51.3	37.6	246	33.3

Conclusions

From both the computational models and the tests ran during both this project and the previous one, the engine displayed its best efficiency operating in the low speed ECO mode, when equipped with the Dwell 45, as already presented, reaching an efficiency of 40.5% for this operating mode.

Although not tested, from the validated computational models, it is predicted that the BOOST mode for the Dwell 45-equipped engine will show a larger power output than its older counterpart, the Dwell 50, as its dwell is smaller, resulting in a larger effective compression stroke.

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