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NUMERICAL ANALYSIS OF THE PERFORMANCE AND SUBSEQUENT UPGRADE OF A RACING 3.0 L PORSCHE 911 ENGINE

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Abstract. The 1D software package Lotus Engine Simulation was used to numerically evaluate the performance of the atmospheric 3.0 L engine of a 1974 Porsche RSR racing car. The software construction of the engine took into consideration all the original dimensions of the different components of the engine. Changes in the original atmospheric engine configuration were done in order to improve its performance and a maximum power of 242.73 kW and a maximum torque of 306.17 Nm were obtained, and compared with the expected values of 232 kW and 313 Nm, being the differences meaningless in practical terms. Subsequently a KKK turbocharger, model K36 was applied to the engine, as per the 1976 3.0 L Porsche 934, and after several adjustments, and engine tuning, a maximum power of 468.05 kW and torque of 1027 Nm were obtained, and compared with the available reference values of 362 kW and 588 Nm. This last upgrade, for the supercharged engine, lead to a stronger performance improvement because the reference was a road car whereas the obtained performance results are for a racing car configuration.

Keywords: Lotus Engine Simulation, Engine performance, Racing car

1. INTRODUCTION

The use of 1D software packages for study of internal combustion engines performance has been the object of several research studies. The Lotus Engine Simulation (LES) software package has been the choice of several of them (Lotus, 2001). Lukács and Polóni (2011) evaluated the improvement of the Mazda B6 combustion engine performance to further carry out its tuning for sport competitions use. Chan et al. (2013) made a comparison of two software packages (Ricardo Wave and Lotus Engine Simulation) for the development of combustion engine control systems, and the numerical experiments they did showed that, both software packages predicted similar engine performances. The LES was also the software chosen for prediction of the performance of a Suzuki GSXR600 K5 engine using ethanol (E85) (Serrano et al. 2016). Mohamad and Rasid (2016) described an improvement of full-load performance of an internal combustion engine using Adaptive Valve Lift and Timing Mechanism (AVLT). Basaran and Ozsoysal (2017) studied, by means of LES, the modulation of intake valve closing time in a diesel engine to achieve an exhaust temperature rise in order to enhance exhaust gas after treatment performance.

A numerical evaluation of the performance of a 1974 Porsche RSR (Reen Sport Racing) racing car belonging to a Portuguese driver, was carried out by means of the LES software. The main objective was to define guidelines to increase the vehicle performance, and consequently the numerical study evaluated the engine modifications to be done, according to the existing regulations of the Portuguese Classical Cars Championship.

2. SOFTWARE CONSTRUCTION OF THE ORIGINAL ENGINE

2.1 Introduction

The car whose engine was analyzed was the 1974 Porsche 911 RSR from the then FIA GT, group 3 or 4 racing categories (Web.archive.org, 2020). This 911 RSR has an atmospheric air intake system and a mechanical port fuel injection system, as depicted in Tab. 1. Through the LES software all the engine characteristics were used to build its software version. The first approach was to evaluate the guidelines for the original atmospheric engine preparation. The software construction of the engine took into consideration all the original dimensions of the different engine components. As much of such information was not easily found in the scarce technical literature available for this engine, several measurements were done in the engine, while staying in the workshop for the inter season annual engine revision. The validation of the correctness of such measurements was by means of the comparison of the results from the software

engine performance with real data available. Acting on the valve dynamics, type of fuel and doing changes in some engine components, lead to results that were compared with those available, Tab. 1. Subsequently, and according to the regulations of the competition authority, the use of a turbo compressor was analyzed to improve the engine performance. The torque and power gains with the use of this last option were evaluated and subsequent guidelines were proposed for the vehicle owner to improve the engine and vehicle performance.

2.2 The boxer engine configuration

This type of engine layout, 180 ° opposed cylinders, reminds a boxer fighter while punching his opponent (Santo, 2015), being this the reason for its practical designation. The cylinders operate in a parallel disposition relatively to the soil. Each pair of cylinders moves along a symmetrical opposing back and forth movement, during the same time interval, promoting an equilibrium of the forces acting upon them, thus reducing undesirable vibrations and eliminating the need for connecting rods counterweights. Such engine operation is rather smooth, but this configuration is being less and less used because of practical limitations concerning its accessibility for handling and maintenance tasks.

Figure 1. Porsche 911 RSR with the engine under study

Table 1. Technical specifications of the Porsche RSR (Racing Cars Technology, 2019).

1974 Porsche 911 RSR 3.0 L	
Engine type	6 cylinder boxer (180º), 4 stroke, Otto, compression ratio 10.5:1
Capacity	2996 cm^3, Bore × Stroke : 95 × 70.44 mm
Power and torque	232 kW at 8000 rpm and 313 N m at 6500 rpm
Valves	2 valves per cylinder, admission diameter: 49 mm; exhaust diameter: 41.5 mm
Connecting rods	Titanium, Length: 127.8 mm
Ignition order	1-6-2-4-3-5
Intake	Atmospheric intake. Mechanical port fuel injection

This cylinder layout leads to irregular piston wear, imposing a tighter and more expensive lubrication and maintenance procedure, imposing to a two-part engine block design and arrangement. On the top of that, its construction is also more expensive (Policarpo, 2018).
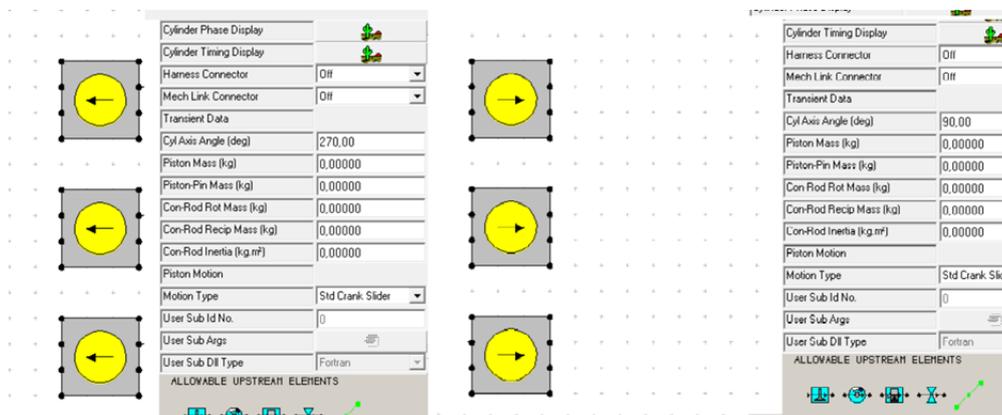

Figure 2. Placement of the opposing cylinders, with the indication of the cylinders angles

The construction of the engine software model is relatively straightforward. Figure 2 shows the placement of the six opposing cylinders and the indication of the angles between each set of opposing cylinders. By clicking on each cylinder, each one of them is specified in terms of bore, stroke, com-rod length and compression ratio. The right hand side set of cylinders is 90 ° oriented whereas the left hand side set of cylinders is 270 ° oriented. The reference is the central mass center reference axis of the engine.

2.3 Fuel feeding system

The LES software automatically places the fuel feeding system in the engine layout and it is only necessary to indicate the type of fuel and the type of fuel injection system (Lotus, 2001), in the present situation, Porsche 911 RSR, a port injection one, Fig. 3. The initial fuel tested was a standard gasoline (RON 95) with a Lower Heating Value (*LHV*) of 43000 kJ/kg.
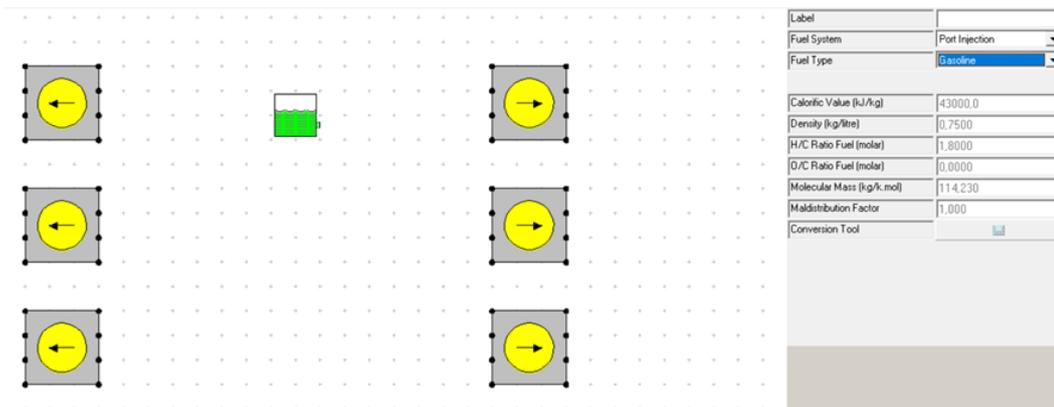
Figure 3. Fuel feeding system

2.4 - Air intake system

For the engine under study, the measurements carried out at the workshop, of the initial and final diameters, and length of the air inlet pipe, lead to the following values, 42, 68 and 185 mm respectively, which were used for the construction of the software model, Fig. 4. For this engine, the intake pipes are external to the engine head and in the software instructions were given to connect them directly to the valve seats. Its material is plastic, another information to be given to the software. The air refrigeration condition of the engine was also included. As already referred into Tab. 1 the engine has two valves per cylinder, one for admission and the other for exhaustion, with 49 a 41.5 mm diameter respectively. For the valve lifting a value of 12.192 mm was adopted for the intake valves and a value of 10.922 mm was adopted for the exhaust valves (Racing Cars Technology, 2019). This information was introduced in the valve seat windows of the LES. In a first approach, the valves opening and closing angles were the default ones (Pereira, 2012).
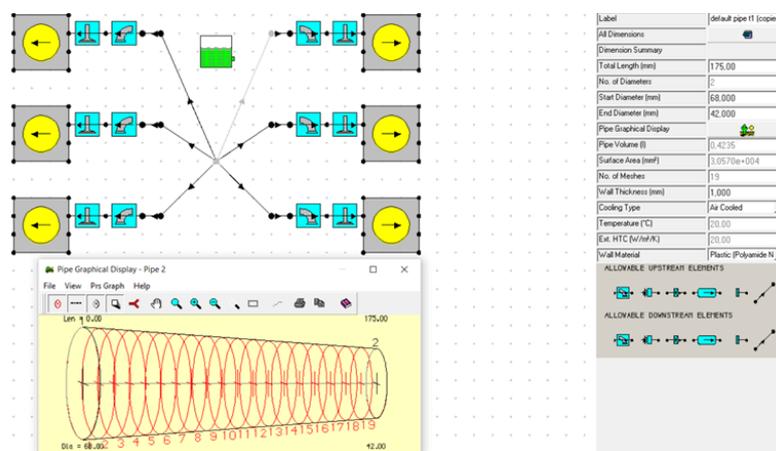
Figure 4. Construction of the intake pipes in the LES. They were external to the engine head

Although the engine has individual admission trumpets for each cylinder and accordingly has no common admission intake pipe, due to software limitations, such common intake pipe had to be placed in the engine configuration, To circumvent this limitation, and trying to give an almost infinite volumetric capacity, its volume was considered equal to

the engine capacity, 3.0 L. After the introduction of the fictitious inlet pipe, there was the introduction of the air inlet orifice and of the acceleration butterfly, as well as the characterization of the exhaust pipes, Fig. 5.
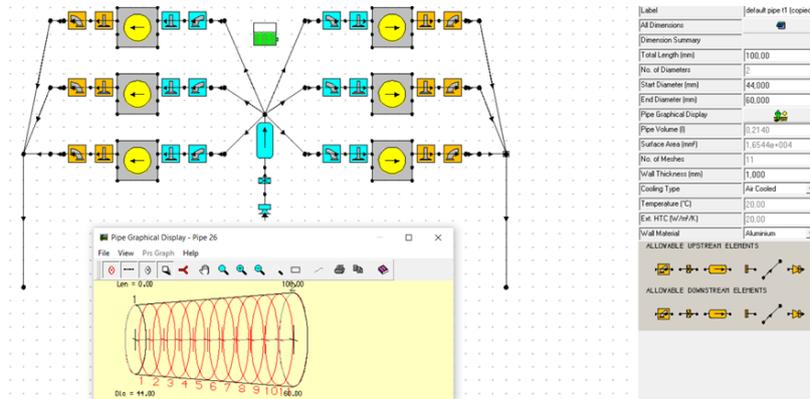

Figure 5. Introduction of the fictitious inlet pipe, engine air inlet orifice and acceleration butterfly and characterization of the exhaust pipes

To end the information about the exhaust components an exhaust control orifice had also to be included in the engine layout, Fig. 6. This last figure shows the final LES layout of the Porsche RSR atmospheric engine, to be simulated.
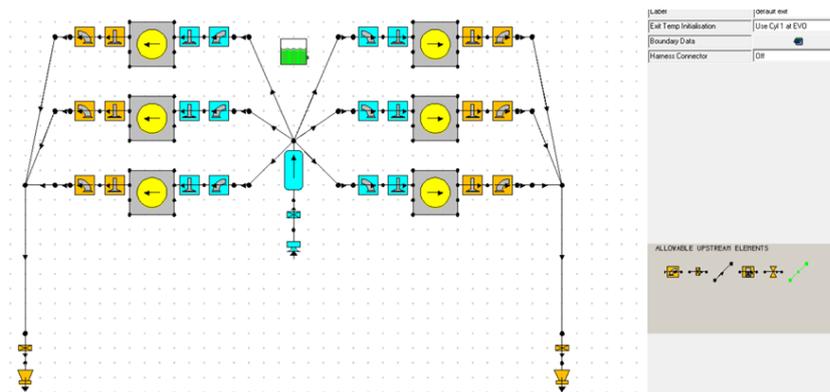

Figure 6. Final LES Porsche RSR engine before the first simulation step

3- INITIAL ENGINE TESTING CONDITIONS AND RESULTS

After the software construction of the engine, the following operating conditions were chosen. Ten runs, one at every 1000 rpm, for ambient temperature and pressure of 36 ºC and 1.006 bar, with an absolute humidity of 0.0088 kg/kg, conditions that are typical of a summer race day in the Vila Real city race track, in the Northern region of Portugal.
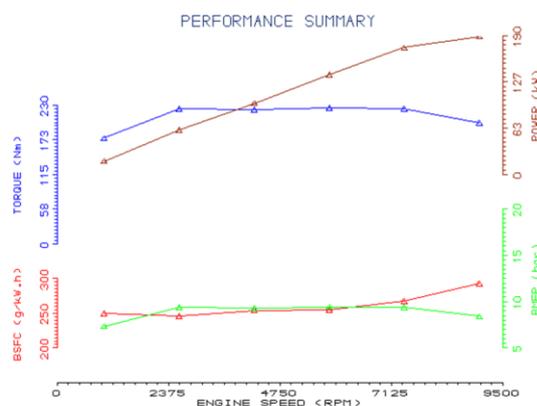

Figure 7. First set of performance results with maximum power and torque values of 188.95 kW and 225.07 Nm

These ambient conditions were chosen for the starting run of the numerical testing because one of the authors had seen the car racing at that track under such conditions. The engine ignition sequence adopted was 1-6-2-4-3-5 (GtSparkPlugs, 2020), Tab. 1, as well as a fuel equivalence ratio of 1.05 and an exhaust pressure of 1.1 bar.

The first set of results, lead to the curves shown in Fig. 7 for torque, power, brake specific fuel consumption (BSFC) and brake mean effective pressure (BMEP), and gave a maximum power of 188.95 kW and maximum torque of 22.07 N m, Fig. 7. The power and torque output of this first run are well below the expected performance for the engine (Tab. 1). A sequence of numerical experiments were then carried out through changes on the opening and closing of the valves, as suggested by several authors (Smith, 1977), Heywood (1988) and (Arias-Paz, 2010), leading to an adequate valve overlap. The sequence of experiments is presented in Tab. 2, as well as the resulting maximum power and torque outputs, and the corresponding engine speeds. In experiment 6 the angle values were those recommended by Ariaz-Paz (2010), while in the experiments 7, 8 and 9, the angle values were based in Heywood (1988), respectively the minimum of such values, in test 7, average values in test 8 and the maximum values in test 9. The other tests were based on a search supported by the angle values proposed by Smith (1977). The best output was obtained for test 18. To speed up this search process, all these experiments were carried out at six different engine speeds. Figure 8 shows the output curves for the engine operating under test 18 conditions, but for ten engine speed values.

Table 2. Inlet and exhaust valve opening and closing angles for the atmospheric engine.

| Test	IVO (°)	IVC (°)	EVO (°)	EVC (°)	Maximum power	Maximum torque
1	10	66	38	38	188.95 kW at 9000 rpm	225.07 Nm at 5800 rpm
2	15	66	45	38	189.58 kW at 9000 rpm	229.43 Nm at 7400 rpm
3	10	75	38	40	184.37 kW at 9000 rpm	216.70 Nm at 7400 rpm
4	20	65	50	20	203.61 kW at 9000 rpm	238.88 Nm at 7400 rpm
5	20	75	50	20	199.21 kW at 9000 rpm	231.14 Nm at 7400 rpm
6	20	65	60	20	203.78 kW at 9000 rpm	243.49 Nm at 7400 rpm
7	10	40	50	8	201.65 kW at 9000 rpm	275.65 Nm at 2600 rpm
8	15	50	55	14	209.07 kW at 9000 rpm	263.14 Nm at 2600 rpm
9	20	60	60	20	207.74 kW at 9000 rpm	246.21 Nm at 7400 rpm
10	25	80	80	25	188.91 kW at 9000 rpm	226.23 Nm at 7400 rpm
11	40	100	100	40	189.97 kW at 9000 rpm	201.56 Nm at 9000 rpm
12	12	47	47	12	206.39 kW at 9000 rpm	268.77 Nm at 2600 rpm
13	15	57	57	15	207.54 kW at 9000 rpm	254.40 Nm at 2600 rpm
14	8	50	50	8	205.86 kW at 9000 rpm	266.89 Nm at 2600 rpm
15	10	55	55	10	208.09 kW at 9000 rpm	260.11 Nm at 2600 rpm
16	18	62	60	18	206.72 kW at 9000 rpm	244.05 Nm at 4200 rpm
17	14	49	49	14	207.41 kW at 9000 rpm	265.59 Nm at 2600 rpm
18	**21**	**62**	**62**	**21**	**209.89 kW at 9000 rpm**	**245.65 Nm at 7400 rpm**
19	13	51	51	13	208.14 kW at 9000 rpm	264.04 Nm at 2600 rpm
20	15	55	55	15	208.23 kW at 9000 rpm	257.38 Nm at 2600 rpm
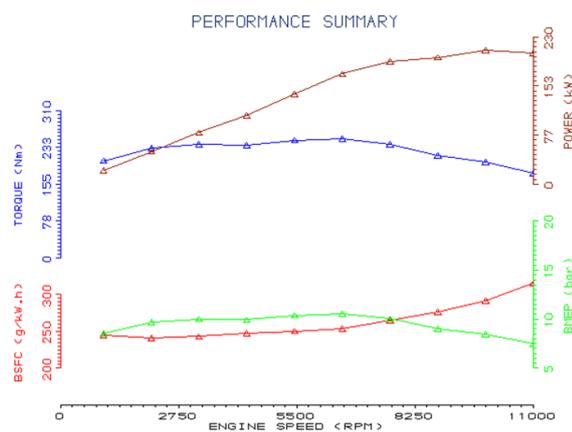
Figure 8. Engine performance for test 18

The next step was to look for the influence of a better fuel as normal in racecar events. Several simulations were then executed in the 43000 to 46000 kJ/kg range (World Nuclear Association, 2018), and logically the best result, based on the test 18 configuration (Table 2), was found for the upper limit of the above mentioned *LHV* range, 46000 kJ/kg, Fig. 9, namely, 228.57 kW at 9000 rpm and 280.29 Nm at 7400 rpm.
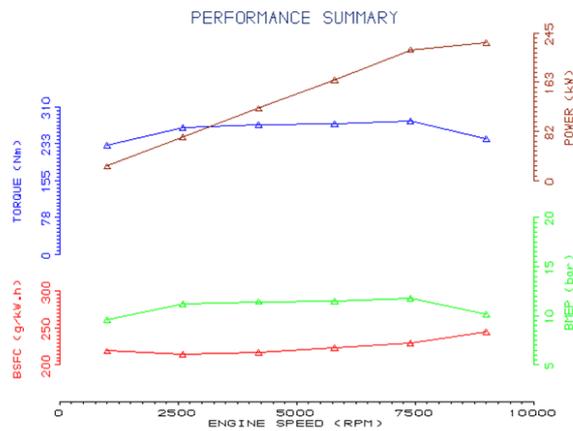
Figure 9. Engine output for a gasoline with 46,000 kJ/kg

To finish with the evaluation of the atmospheric engine configuration, changes were done in the admission and exhaust pipes (Fialho, 2017). Using an admission pipe diameter of 42 mm, maximum values of power and torque for different exhaust pipe sizes are in Tab. 3, while the final performance curves, for the best exhaust diameter and ambient winter temperature of 5.9 ºC, an admission air temperature of 8.6 ºC, ambient and admission pressure of 0.9815 bar, exhaust gas pressure of 1.1 bar and still with the fuel equivalence ratio of 1.05. The considered ambient relative humidity was of 30.5 %, leading to an absolute humidity of 0.00215 kg/kg. These conditions are typical of a winter day in the Northern region of Portugal. The best performance was found for 38 mm diameter exhaust pipes. The final performance of the atmospheric engine is shown in Fig. 10. At 8000 rpm, the LES calculations gave a maximum power of 242.73 kW and at 6500 rpm, the maximum torque was 306.17 Nm. These values are 4.63 % above in terms of power and 2.18 % in terms of torque, considering the reference data of Tab. 1.

Table 3. Engine performance for different exhaust pipe diameters.

| Exhaust pipe diameter	Maximum power	Maximum torque
44 mm	228.57 kW at 9000 rpm	280.29 Nm at 7400 rpm
43 mm	234.62 kW at 9000 rpm	279.28 Nm at 5800 rpm
42 mm	237.70 kW at 9000 rpm	283.19 Nm at 5800 rpm
41 mm	238.57 kW at 9000 rpm	289.64 Nm at 5800 rpm
40 mm	239.65 kW at 9000 rpm	298.73 Nm at 4200 rpm
39 mm	246.67 kW at 9000 rpm	297.61 Nm at 4200 rpm
38 mm	**248.00 kW at 9000 rpm**	**296.36 Nm at 7400 rpm**
37 mm	245.38 kW at 9000 rpm	298.13 Nm at 4200 rpm
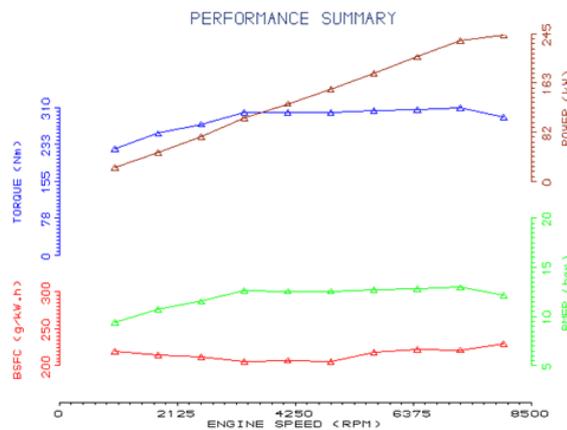
Figure 10. Final performance curves of the atmospheric engine

4 – THE TURBO CHARGED ENGINE

The next step was to analyze the increase of engine performance through the application of a turbocharger. This is allowed by the Classic Car Championship regulations. The reference for this new addition was the 1976 Porsche 934 turbo, based on the 3.0 L boxer engine, like the previously studied atmospheric RSR. This Porsche 934 turbo engine had a KKK turbocharger, model K36, and could produce a power in the 362 kW to 441 kW range, according to its operating pressure. Table 4 presents the specification for this turbocharged engine and Fig. 11 presents its LES layout.

Table 4. Engine specification for the 1976 Porsche 934 turbo (Ultimatecarpage.com, 2020).

| 1976 Porsche 934 Turbo 3.0 L	
Engine type	6 opposing boxer (180º), 4 stroke, Otto, compression ratio 6.5:1
Capacity	2996 cm^3, Bore × Stroke: 95 × 70.44 mm
Power and Torque	362 kW at 7000 rpm and 588 Nm at 5400 rpm
Valves	2 valves per cylinder, admission diameter: unknown; exhaust diameter: unknown
Connecting rods	Titanium, Length: 127.8 mm
Ignition order	1-6-2-4-3-5
Intake	Turbocharger. Mechanical port fuel injection
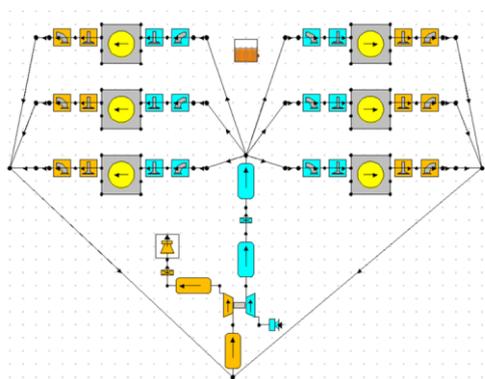
Figure 11. Layout of the turbocharged engine

Next, it was necessary to get the adequate compressor map for the engine to be upgraded. The turbocharger performance maps are obtained through field tests carried out by the manufacturers (Bell, 1997). Although two maps should be taken into account, one for the turbine and the other for the compressor, it is the last one the most important, and because of that the turbine map is seldom made available by the manufacturer. Figure 12 presents a generic compressor map as well as the KKK K36 turbocharger, compressor map (André, 2016; Ebay, 2020).
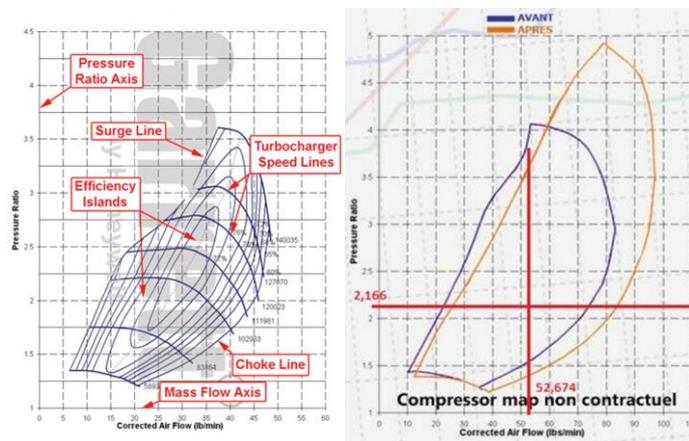

Figure 12. Generic compressor map (left) (André, 2017), and the KKK K36 turbocharger compressor map (right) (Ebay, 2020)

The compressor should be used in its most efficient operating region, the efficiency islands, as shown in Fig. 12. Beyond the high efficiency regions, two range limit lines must be taken into account, the surge line and the choke line. If the compressor works at the left of the surge line, it might be compressing an amount of air above that the engine can

handle, whereas working at the right of the choke line, the gas reaches speeds close to the sound speed, thus blocking its flow, and the air compression ceases. Thus, the compressor must operate in the region inside these two lines, the region of efficiency islands (André, 2016). It was not possible to find out a better compressor map for the KKK K36 turbocharger than that depicted in Fig. 12. It can be seen by the two red crossing straight lines, representing the optimum pressure ratio (2.166) and air mass flow rate (52.674 lb/min) for the 1976 Porsche 934 turbo engine, calculated in the present study, that this was indeed a good choice. This available map was transferred, point to point into the LES compressor map, using the compressor map data menu of LES engine intake characteristics window, Fig. 13. The adopted values for the compressor intake and turbine exhaust diameters were respectively 75.1 mm e 107.95 mm (Turbo rebuild, 2020), and now the software engine is ready for a new set of simulation runs in order to compare the results to be obtained, with the specifications of the 1976 Porsche 934 turbo, Tab. 4.
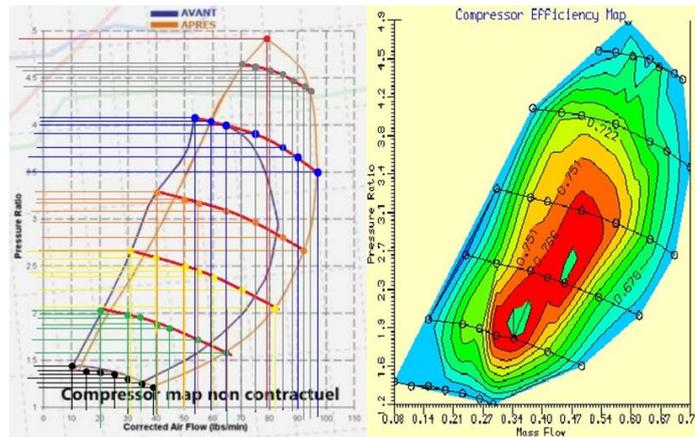

Figure 13. Original KKK K36 compressor map (left), and the LES replica (right)

Increasing the initial intake diameter to 68.5 mm and reducing it towards 54 mm just before the turbine entrance and putting an exhaust pipe diameter of 36.5 mm, in order to increase the output power at medium a high engine speeds, the maximum power output became stabilized at 376 kW in the 7500 to 9000 rpm range. For a competition engine, the maximum power output takes place close to the maximum recommended rotation regime, but being this power output almost linear in the above-mentioned rotation range, it leads to a relatively smooth engine operation, Fig. 14. These last results when compared with the original values for the 1976 turbocharged engine, Tab. 4, show an increase of 3.87 % on the engine power but also a decrease of 4.76 % on engine torque.
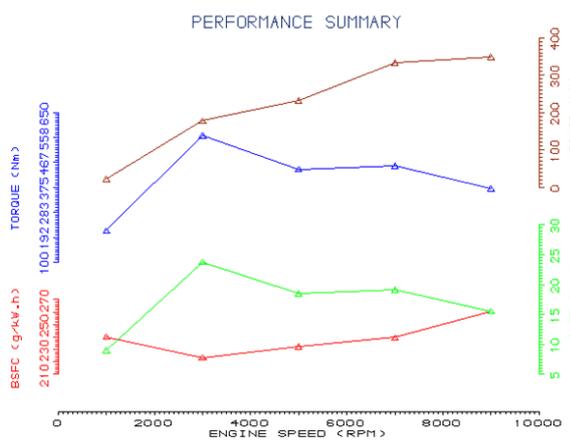

Figure 14. Turbocharged engine performance curves after compressor map and intake and exhaust pipe adjustments

5 – CHANGES IN THE TURBO CHARGED ENGINE HEAD

Further work was done to refine the engine performance, and the subsequent changes, done in software terms, were based on acceptable engine modifications according to the championship regulations. The proposed changes were the introduction of two more valves per cylinder and the work in the intake and exhaust pipes, namely porting, polishing

and dimpling. For the four valve per cylinder the respective diameters were 35.15 mm for the inlet valves and 30.40 mm for exhaust the valves (Heywood, 1988), while the diameter for the exhaust pipes was changed to 39 mm. Then different valve opening and closing angles were tested, again based on the Smith (1977), Heywood (1988) and Arias-Paz (2010) suggestions. Table 5 presents the results of such search.

Table 5. Inlet and exhaust valve opening and closing angles for the turbocharged engine.

Test	IVO (°)	IVC (°)	EVO (°)	EVC (°)	Maximum power	Maximum torque
1	21	62	62	21	393.86 kW at 9000 rpm	891.69 Nm at 3000 rpm
2	20	65	60	20	393.75 kW at 9000 rpm	892.49 Nm at 3000 rpm
3	10	40	50	8	388.06 kW at 5000 rpm	1007.27 Nm at 3000 rpm
4	**15**	**50**	**55**	**14**	**408.53 kW at 7000 rpm**	**978.71 Nm 3000 rpm**
5	20	60	60	20	394.47 kW at 9000 rpm	909.16 Nm 3000 rpm
6	10	66	38	38	396.54 kW at 9000 rpm	765.09 Nm 3000 rpm

Test 1 has the valve opening and closing angles that lead to the best atmospheric engine performance, test 18 from Tab. 2. Test 2 uses values recommended by Arias-Paz (2010), while tests 3 to 5 are respectively, the minimum, the average and the maximum values suggested by Heywood (1988). Test 6 was made with angle values suggested by Smith (1977). The best situation, as stressed in bold, refers to test 4 and this combination of valve opening and closing angles was the adopted onwards. It gave the best power output and the second best torque output, 408.53 kW at 9000 rpm and 978.71 Nm at 3000 rpm. These runs were all for a compression ratio of 6.5:1.

Finally, a set of small interventions on the quality of the pipe surfaces in contact with the gas flow. The already referred porting, polishing and dimpling (Fialho, 2017), that were accounted for in the friction coefficient windows of the LES. The use of a competition gasoline with a RON of 115, as supplied by BP (BP Australia, 2006), allowing a higher engine compression ratio (De Cesare et al., 2017; Ultimatecarpage, 2020), thus making the assumption that a value of engine compression ratio of 9.95, typical of Otto supercharged engines with port injection, would be acceptable (De Cesare et al., 2017). The final performance curves for the turbocharged Porsche engine are in Fig. 15. The two auxiliary black lines in Fig. 15 show that a power output above 400 kW can be obtained for a rather wide engine velocity range. The maximum power is now 468.05 kW at 9000 rpm, while the maximum torque 1027 Nm, is available at 3000 rpm.
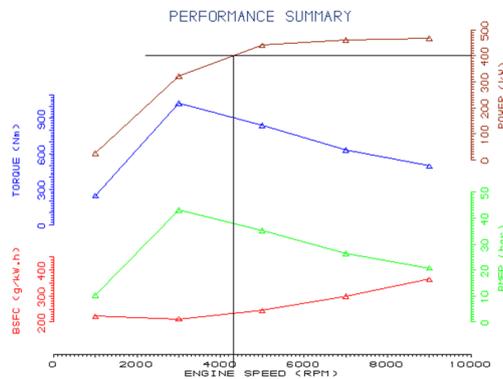

Figure 15. Final performance curves for the Porsche 3.0 L turbocharged engine, with four valves per cylinder

6 CONCLUSION

A 1D software simulation using the Lotus Engine Simulation was used to evaluated the performance and to carry out further engine upgrades of a 1974 Porsche RSR racing car, with a 3.0 L boxer engine. The initial studied configuration was for the atmospheric engine, and the final obtained power peaked at 242.73 kW at 8000 rpm, while the maximum torque was of 307.7 Nm at 6500 rpm. Then, the introduction of a KKK K36 turbocharger was analyzed and after several engine modifications tested in the software, the final maximum performance values were 468.05 kW power at 9000 rpm and 1027 Nm torque at 3000 rpm. The use of this type of numerical tools allows the safe previous study of the possible attainable performance for a competition car engine, before any serious physical modification can be implemented, thus guaranteeing a reliable approach of racing car engine tuning.

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4 RESPONSIBILITY NOTICE

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