A new product aimed to optimize air intake systems for low end torque enhancement

Leadership in Filtration

MANN+HUMMEL

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Abstract

Low end torque enhancement for turbocharged engines is now more important than ever due to upcoming new regulations after Euro 6 with real drive emission application. With further trends to reduce the weight of the next generation of cars, there is the need to adapt and reduce continuously the size of engine and its components to find a good trade-off between engine size, vehicle performance, fuel consumption and costs. This paper describes how air intake systems can be optimized taking into account the special challenges of small turbo charged Diesel engines of passenger cars. The novelty of the paper is to address the benefit value thanks to the optimization of interaction between all stand-alone components such as turbo chargers, charge air coolers, ducts and air intake manifolds. It is described and demonstrated using both simulation and testing, how switchable volume and length can help the performance improvement while reducing the engine displacement. As resonance charging is the physics used here to help low end torque improvement up to more than 10 percent for 4-cylinder engines, and even more for 3-cylinder engines, a special new design of a switchable air intake system is shown, giving good performance in terms of pressure waves propagation and pressure loss. Tests on prototypes made on engine dynos show the benefits of such a concept compared to state of the art. The complete air intake system composed of plastic parts routing the air from the charge air cooler to different charge air duct geometry will enable a new possibility for increasing volumetric efficiency thanks to resonance charging - also for small turbocharged engines, at a reasonable cost. This can also apply for new turbo charged gasoline engines, as real drive emissions could impact scavenging and air/fuel ratio control in a wider engine operating range. In this case again, resonance charging thanks to air intake system geometry could be a way to compensate lack of performance, especially at very low engine speed.

Introduction

Following the changes in emissions regulations, with introduction of real driving emissions (RDE) tests for passenger cars, the trend for Diesel cars should shift to reduce dramatically the NO_x emissions thanks to usage of EGR even at full load during transient operations. It could be used in combination with SCR for further exhaust NO_x emissions reduction, and this combination can help to reduce urea consumption over time. At high load operating points, and especially at low engine speed when turbocharger action is limited, it will become necessary to introduce more gas inside the cylinders to achieve an acceptable trade-off between NO_x emissions, and performance. Firstly this paper will demonstrate using engine tests how resonance charging using an active device and special geometry in air intake is a possible way to increase volumetric efficiency at a reasonable cost for both 4-cylinder and 3-cylinder Diesel engines. In transient conditions for the vehicle, we can even consider enhancing the acceleration thanks to instantaneous increase of low end torque; this will be shown thanks to system simulation made with engine data. A detailed description will be then made on a so called “Active Charge Air Duct” using a “Rotary Shifter” to transition between a torque mode and a power mode.

This device can also be used with a special control strategy at part load to optimize BSFC, by reducing pumping losses. The Rotary Shifter can bring also good efficiency to bypass the intercooler and regulate the inlet temperature, and decrease risk of low pressure EGR condensation in very cold conditions. Based on experience with Diesel engines, some preliminary work has been also initiated with modern turbo charged gasoline engines to prove the benefits of resonance charging. In this case the challenges are more to reduce fuel enrichment at full load, and reduce need of scavenging due to new RDE emissions. Again here, and particularly for new modern small highly downsized gasoline turbocharged engines, resonance charging can be used to compensate lack of performance.

1. Resonance charging using switchable ducts

1.1 Product description

During the last decades many solutions have been found to enhance the air mass trap in the cylinder. Obviously one of the most efficient methods is the turbo-charger as it is using part of waste energy from the exhaust to compress the air at the inlet and thus increases the air mass trap in the cylinder [1-2]. The main draw-back of such technology is the lack of performance at low engine speed when the exhaust enthalpy is not sufficient. The engineers also developed some solutions for naturally aspirated engines to improve the power by increasing the air mass trap in cylinders by tuning the air intake manifold in order to control the pressure waves, leading to an added air mass in cylinder at the intake valve closing [3-6-10].

The proposed products developed by MANN+HUMMEL aim to combine these solutions to get a good performance at low engine speed as well as efficient behavior at higher speed. Therefore the air intake manifold is not the only possibility for tuning the intake system for resonance charging. Because of the long pipe are needed to reach the right tuning at low engine speed the complete air intake has to be considered from the turbo outlet to the intake valve.

In order to be able to well characterize the intake system, it is mounted on a dedicated test bench – the so-called dynamic flow bench. The first measurement allows obtaining the impedance of the complete system, which will give the resonant frequencies. Then it is possible to tune the system by adding duct length or by changing the duct diameter [7].

Therefore, different geometries have been considered. The simplest one named ACAD (Active Charge Air Duct) [8-9] consists of two ducts with different length and diameter. The first is a long duct with a small diameter which allows getting resonance around 1500 RPM and thus helps to compensate the lack of enthalpy at low engine speed. At higher engine speed the duct is designed with a larger cross section and a shorter length in order to get both a lower pressure drop and a higher frequency resonance. To switch from one configuration to the other a dedicated product, the so called “Rotary Shifter”, has been designed and will be presented in a later section. Furthermore, in order to ensure robust control of the

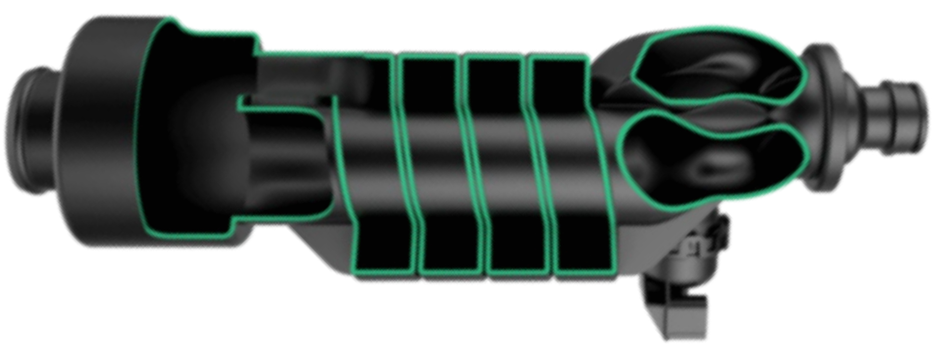


Figure 1: ACAD (Active Charge Air Duct) concept description

position of the reflection in the air intake line and ensure a good flow stream, a volume is placed just downstream the charge air cooler as described on the picture Figure 1.

Another solution consists of using additional volumes and ducts. The so-called DRS (Double Resonance System) has been tested on 3-cylinder Diesel engines.

In order to understand the interaction of resonance charging with the complete engine and turbocharger, a primary evaluation of the potential has been completed using a GT Power simulation model. Thanks to that study further benefits of resonance charging on a turbo charged engine have been noticed compare to naturally aspirated engine. Indeed there is a loop effect when the right wave action gives an increase in air mass trap in the cylinder - here the enthalpy at the exhaust increases. This will lead to more available energy at the turbine being converted, whether on reduction of the backpressure - or more advantageously in an enhancement of the boost pressure giving again an added mass air trap in the cylinder. The result is effectively a virtuous cycle. With this measured loop effect it can be possible to double the improvement purely due to the pressure wave action.

1.2. Engine tests description

The ACAD geometry has first been sized thanks to GT Power simulations, and 2 loops of prototypes have been used. The fine tuning has been carried out with impedance measurements on the dynamic flow bench[5]. The engine used for the test is a 1.5 liter 4-cylinder, turbocharged Diesel engine.

The engine has been installed in Centrale Nantes's engine dyno and equipped with different sensors in intake and exhaust lines, including high performance pressure transducers (cylinder, inlet and exhaust manifolds) for high sampling rate data acquisition. For each test, the air-fuel ratio has been kept constant and the efficiency of the system has been evaluated by comparing the output brake torque for three main configurations:

- ACAD system with a long duct (torque mode)
- ACAD system with a short duct (power mode)
- Water Charge Air Cooler (WCAC) directly connected close to the inlet manifold entrance as “a stand-alone WCAC” solution.

Tests have been realized in steady state at full and part load, in order to evaluate the impact of the three different architectures on engine performance.

Then, load transient tests have been performed to evaluate the impact of resonance charging on torque response with step demand.

1.3. Steady state engine tests

As showed in Figure 2, engine tests have been performed in full load configuration. The output torque difference between the long duct and the short duct configuration is higher than 10 percent at low engine speed due to the benefits of the resonant charging effect. As depicted in Figure 3a, the pressure wave amplitudes are quite different for each configuration and depend on the engine rotational speed. At 1800 RPM, the pressure wave amplitudes are very important for the long duct configuration in comparison to the short duct configuration. For this reason, it is possible to improve the air mass flow. Furthermore, the tests were realized with the same air-fuel ratio. As a consequence, it is possible to increase the engine torque. It can be observed that the pressure wave amplitude is smaller for the stand-alone WCAC close to the air intake manifold. This is why the engine output torque is also smaller than the two other configurations.

As depicted in Figure 3b, a wave supercharging effect can be obtained with the short duct as well for a higher engine speed for instance at 2600 RPM. In combination with a reduction of pressure drop due to a larger cross section, the engine torque raises around 10 percent. The standalone WCAC with a short distance to the air intake manifold configuration provides lower pressure, but the benefit compare to the long duct is not that much compared to the opportunity of tuning provided by the short duct.

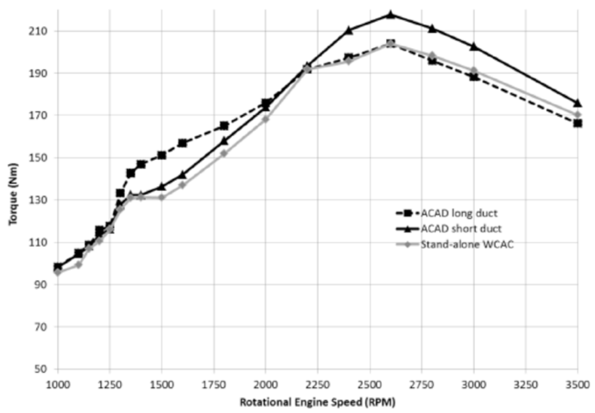


Figure 2: Engine torque evolution

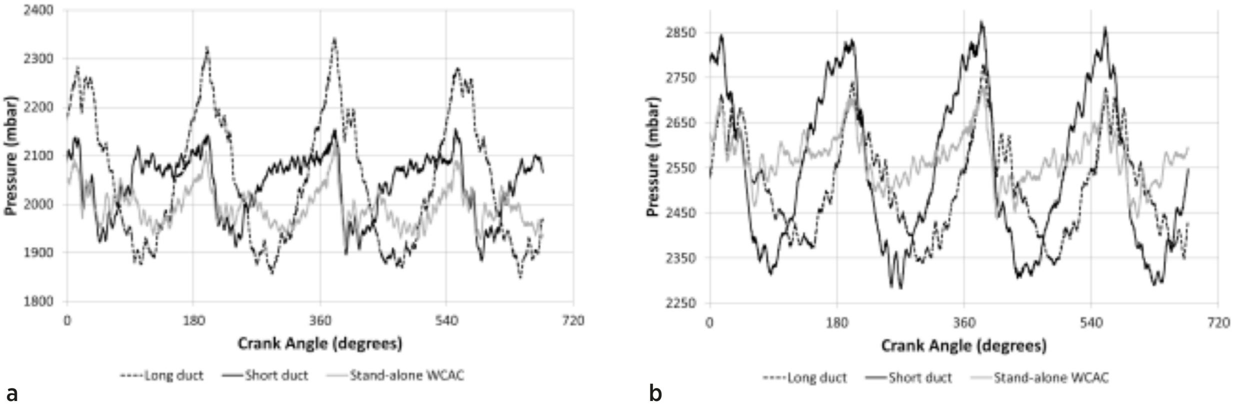
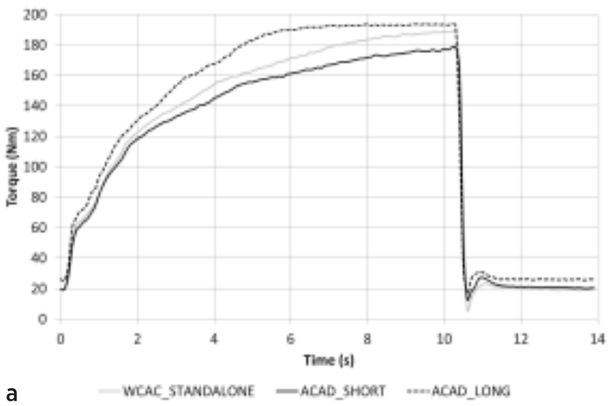


Figure 3: Instantaneous pressure signals at 1800 RPM (a) and 2600 RPM (b)

1.4 Non-steady state engine tests

The ACAD gives the possibility to increase the engine volumetric efficiency thanks to the resonant charging effect. It is quite different from the transient case using only a turbocharger, with the well-known lag effect.
Transient tests were realized at constant rotational engine speed. The initial torque is chosen in order to obtain a Brake Mean Effective Pressure (BMEP) close to idle conditions. An acceleration step demand is applied. It is then possible to measure the torque evolution for each configuration (long duct, short duct and stand-alone WCAC close to the inlet manifold). Two experimental results are presented in this paper (as depicted in Figure 4): 1750 RPM and 2500 RPM.
For this kind of experiment, it appears that the long duct configuration gives the possibility to reduce the time necessary to increase the torque for low engine rotational speed. The same kind of conclusion is observed for the short duct for higher rotational engine speed. These results are in agreement with the steady state results.



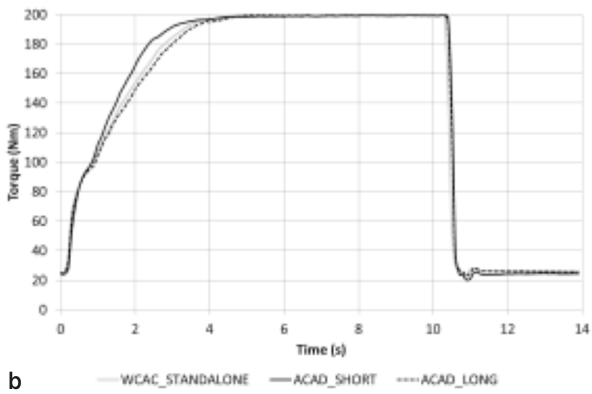


Figure 4: Torque evolution during load transient tests at 1750 RPM (a) and 2500 RPM (b)

2. Resonance charging effect using switchable volumes

2.1 Simulation

The resonance charging effect can be obtained by using different volumes placed in the air intake. One of these volumes can be advantageously the charge air cooler, with different valves used to connect or disconnect another volume to the main pipe. The following figure shows the different steps that have been considered to optimize the volumetric efficiency.

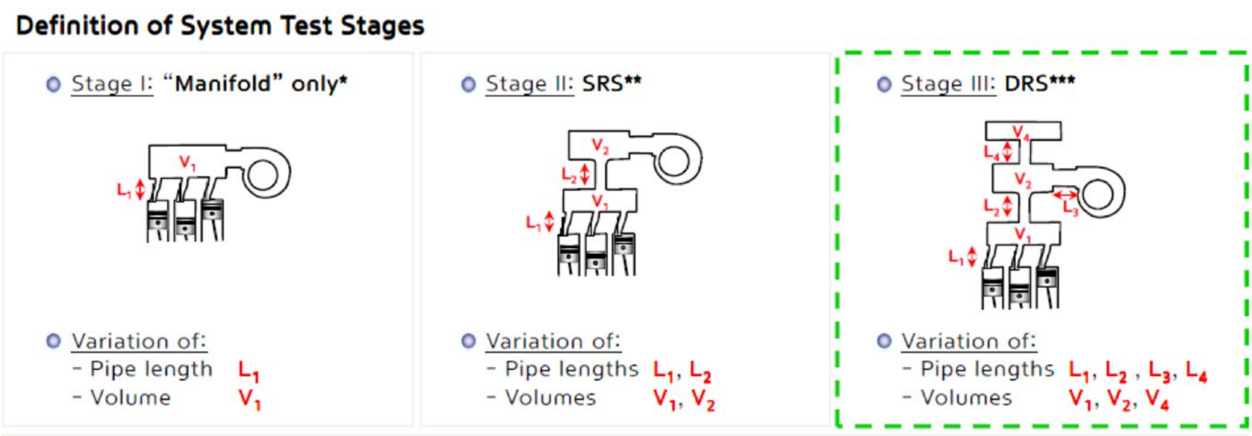
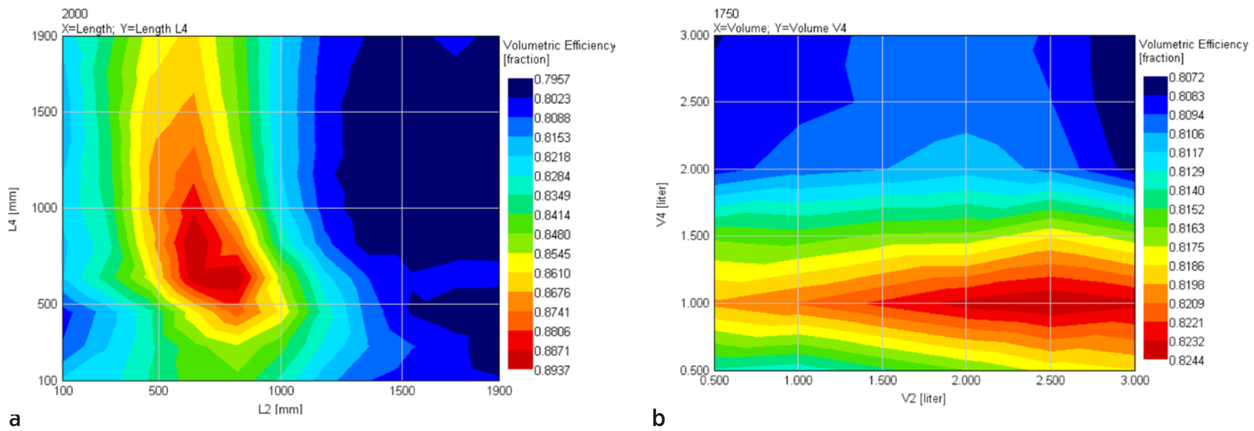


Figure 5: Double resonance system set up

Actually there are two main architectures for the current air intake: either the charge air cooler is integrated into the air intake manifold (Stage 1) or the cooler is a stand alone with direct or indirect cooling system (Stage 2). For the first version as described in Figure 5 there are few opportunities to tune the system for resonance charging as there is only a short duct between the valve and the volume of the charge air cooler. The second version provides further opportunities to experiment with the geometry as already explained with the ACAD. The version 3 is a step ahead as there is an added volume especially to obtain a new resonance that will allow new engine speeds to which the system can be tuned.

Indeed with both volume and duct length there is plenty of opportunities to optimize the volumetric efficiency. Therefore, there are four lengths and four volumes we can experiment with in order to achieve the expected performances in a given space available around an engine.

In order to evaluate the impact of each configuration, a GT Power model has been set up and all parameters have been evaluated. For instance at 2000 RPM the following simulation results (Figure 6) showed a kind of optimum when the length between the volume V2 and V4 is about 750 mm, and at the same time the length between the volume V2 and the air intake manifold plenum is also 750 mm while keeping all other parameters constant.



a b

Figure 6: Volumetric efficiency variation with ducts length (a) and with volume (b)

In the same way it is possible to change the volume V2 and V4 to evaluate the consequence on the volumetric efficiency. For instance Figure 6 shows the impact at 1750 RPM.

After having defined the right layout for all volumes and the different duct lengths, some engine tests have been carried out with prototypes. The considered engine is a 3-cylinder Diesel engine. Mainly the transient behavior has been evaluated starting from low load and with an abrupt request in torque until full load in 0 s. Test results for 1500 RPM are shown following in Figure 7.

Volume V2 can be further reduced to improve packaging volume situation without losing too much performance.

The improvement is pretty impressive as it is possible to reach a defined high torque much faster, and at the same time to increase the maximum torque by 30 percent.

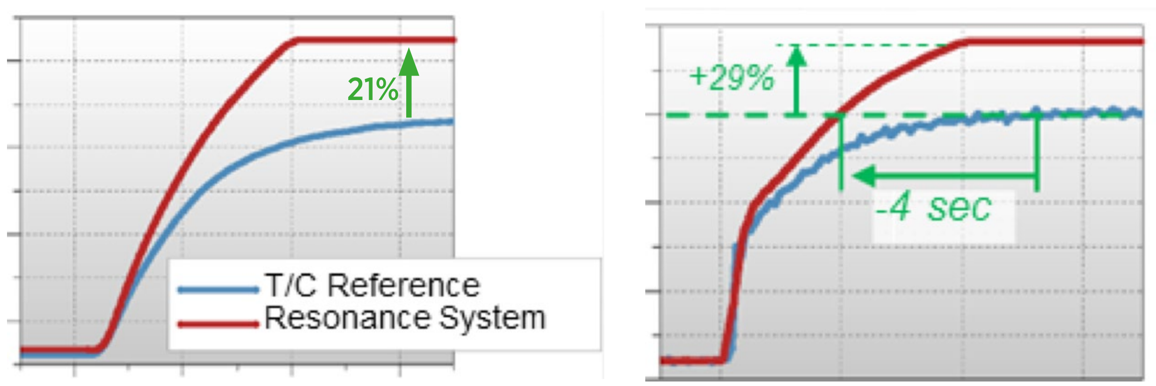


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Figure 7: Effect of DRS on transient behavior (a) boost pressure (b) output torque.

3. Presentation of new switchable intake system

3.1. Product description

In order to be able to shift from one configuration to the other a dedicated product has been developed. It has to be resistant against high pressure pulsation level, to be leak-tight, and offer a good permeability. The air path section is kept constant as it is known that expansion volume can affect wave propagation introducing reflection or dampening.
The product developed is composed of two thermoplastic injected shells, respectively a housing and a cover that are assembled using a conventional spin welding process (Figure 8). The housing provides two open ports, one for the power mode duct and the other used for the torque mode, whereas the outlet is located in the cover. Inside there is a rotary ball with an inner air path to shift from one configuration to the other.
Compared to the state of the art using flap and shaft crossing the air path, the Rotary Shifter concept has lower pressure loss and is less sensitive to the pressure pulsation. In the case of resonance charging, there is no need to work in an intermediate position, and a simple vacuum actuator can be used to drive the rotary ball.
Due to the need to produce the component in plastic, an innovative way to compensate tolerances has been developed and applied, enabling the product to ensure a high level of air tightness.

Figure 8: Rotary Shifter design.

3.2 Specifications set up

It has been shown that the BSFC can be improved at part load with the short duct [9]. Indeed the increase of the intake pressure helps to reduce the pumping losses as described in Figure 9.

This will define the strategy to shift from one duct to the other meaning that the long duct would be used only close to full load condition and for low engine speed. Then, considering the WLTC as a more realistic reference for real driving conditions it is possible to assess the number of activation cycles (Figure 10). Currently during the WLTC, the car runs around 23 km and the number of activa-tion cycles should be around 11. According to this kind of usage the part would be activated approximately every two kilometers.

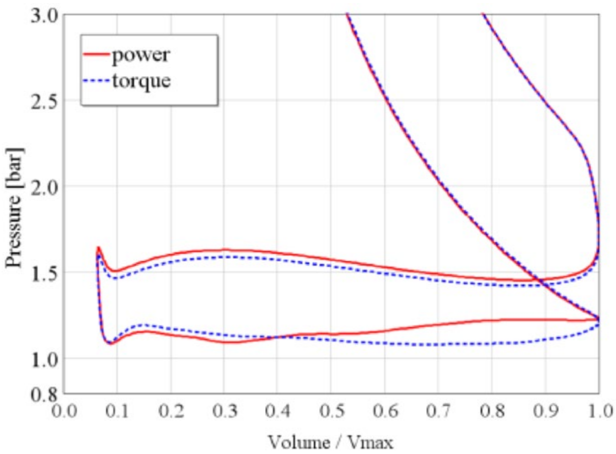

Figure 9: Low pressure PV diagram at 1600RPM and 30 Nm.

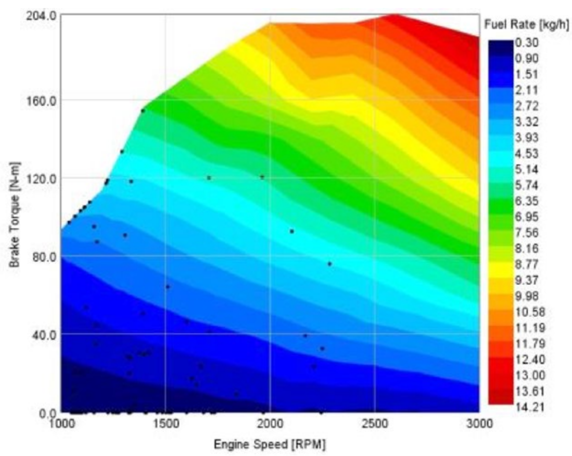

Figure 10: Fuel consumption map with main WLTC points.

4. Fun to drive simulation

The next step in this study is to define another possibility to use the short and long duct system. In this case, a vehicle simulation was made by full load acceleration from 90 km/h to 120 km/h in 5th gear. The aim is to reach the final vehicle speed as fast as possible. The experimental maps for the BFSC and FMEP feed a GT Suite model.

GT POWER simulations using DOE have been conducted with an ACAD (it is possible to switch between the long and the short duct) with a variation of the vehicle final drive ratio. The results are compared to those obtained with a conven-tional passive intake line, named reference. The results are presented in Figure 11. A modification of this last parameter gives the possibility to change the engine rotational speed and, as a consequence, the engine torque. For example, with a final drive ratio equal to 2.0, the engine torque is more important with the ACAD system (blue area). The vehicle reaches the final speed faster with the long duct. For a final drive ratio equal to 2.4, the average torque is the same with the two configurations and the same time is obtained in order to reach the final vehicle speed (yellow area). Finally, if the final drive ratio is equal to 3.4, it is necessary to select the short duct configuration and the results are better with the ACAD system (purple area).

In conclusion, it is very important to take into account the complete vehicle definition to get the maximum benefit of the ACAD. It actually gives the opportunity to combine fun to drive with a reduction of the fuel consumption and an improvement of the engine torque.

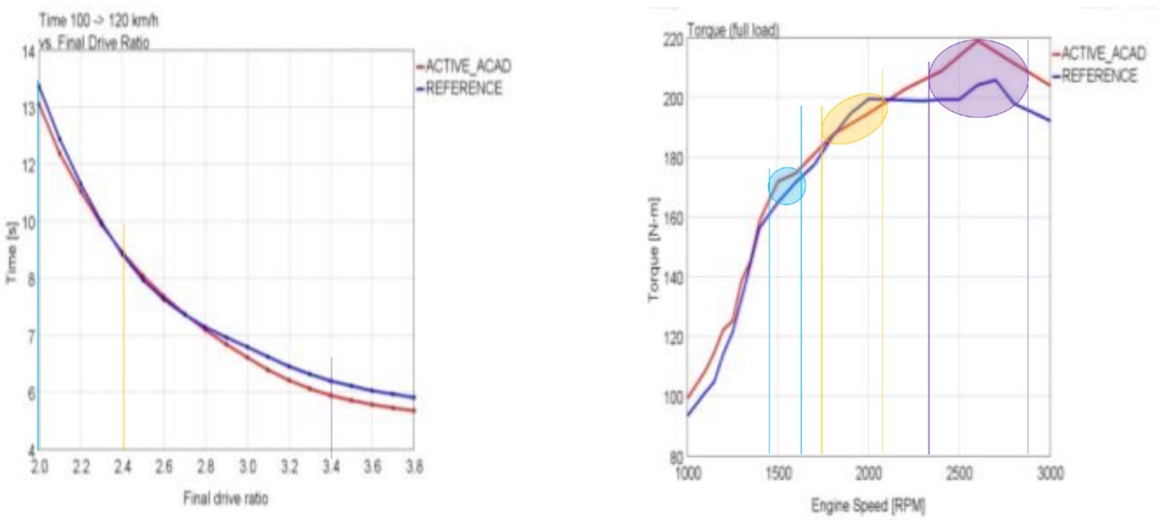

Figure 11: Fun to drive simulation results.

5. Application to Gasoline engine

For applying such resonance charging effects to modern gasoline engines, it is necessary to consider interaction with the complete system thus impact on knocking, exhaust temperature, turbocharger matching and valve control for cylinder scavenging.

Firstly, due to new regulations coming with at least the introduction of RDE, emissions control will have to be performed in higher range of engine speed, load and more in transient case. This will limit as a consequence usage of scavenging, and fuel enrichment.

The risk is to see degradation of performance due to impact on compression ratio to stay under the knocking limit, or to see lack of energy in turbine at low engine speed leading to poor boosting effect in transient. The need is thus even more important for strongly downsized engine such as 3-cylinder engines. Systems such as the double resonance system as described previously can be adapted to the gasoline engine's needs. Even if the potential can be limited by knocking and temperature increase due to heat transfer effect at inlet ports in the cylinder head, more enthalpy can be reused at the turbine, and it can be a virtuous additional gain for increasing in average the boost pressure purely due to advantage gained by resonance charging.

Conclusion

In the content of this article, it has been demonstrated that some improvements in terms of performance or fuel economy are possible for Diesel engines. The basic phenomena to be used is simply to obtain energy from the pressure waves due to opening and closing of inlet valves, followed by propagating and then amplifying pressure and density inside engine cylinders. The benefit seen on a dyno with a small 3-cylinder Diesel engine can even reach high levels of torque improvement nearing 30%. To achieve benefits across the whole engine map, it is necessary to activate either volumes, or duct lengths for charge air ducts; this is now possible with good performance (leakage and pressure loss) thanks to a new concept – the so called "Rotary Shifter". Made of standard thermoplastic material, and compact, it can be easily integrated into components such as intake manifolds, or charge air ducts.

Added value for the end customer can be basically either performance improvement as time to torque reduction for improving the fun to drive, torque and power improvement, or fuel consumption reduction in the range of a few percent – thanks to downspeeding and activation of the active air intake system also at part load.

Originating from Diesel applications, the scope is now extended into new activities dealing with resonance charging to be used for modern gasoline engine using turbochargers and direct injection. Due to new regulations (RDE and Euro 6.d), resonance charging combined with an optimal turbocharger matching can be a low cost solution to compensate lack of performance due to new strategies needed for emissions and knocking control.

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Bibliography

1 WINTERBONE D.E., PEARSON R.J. – Theory of Engine Manifold Design: Wave Action Methods for IC Engines – Professional Engineering Publishing, 2000.
2 BOREL M., – Les phénomènes d'ondes dans les moteurs (Wave phenomena in engines). Paris: Publications de l'IFP, Editions TECHNIP, 2000.
3 OHATA A. and ISHIDA Y. – Dynamic inlet pressure and volumetric efficiency of four cycle four cylinder engine, SAE paper 820407, 1982.
4 BROOME, D. – Induction ram – Part 3: wave phenomena and the design of ram intake systems, Automobile Engineer, pp. 262-267, 1969.
5 CHALET D., MAHE A., MIGAUD J., HETET J.-F. – A frequency modelling of the pressure waves in the inlet manifold of internal combustion – Applied Energy, Volume 88, n°9, pp. 2988-299, 2011.
6 KROMER G., POLTZ H.W., THUDE M, LEITNER P. The new Audi V6 engine. SAE paper 910678, 1991
7 MIGAUD J., RAIMBAULT V., MEZHER H., CHALET D., GRANDIN T. - A New Fast Method Combining Testing and Gas Exchange Simulations Applied to an Innovative Product Aimed to Increase Low-End Torque on Highly Downsized En-gines – ATZ –VPC.plus Simulation un Test für die Antriebsentwicklung, 16 MTZ-Fachtagung, Hanau, Germany, September 30 – October 1, 2014
8 MIGAUD J., RAIMBAULT V, CHALET D., MEZHER H. - Variable Charge Air Duct for Low-End Torque Enhancement and high Speed Performance _ MTZ Worldwide, Volume 76, n°1, pp. 20-25, DOI 10.1007/s38313-014-1006-y, 2015
9 MIGAUD J., BÜHL H, RAIMBAULT V., KORN A, CHALET D, MEZHER H, MON-TAIGNE Q, PRÉTOT P-E - A model based system approach to innovative smart in-take products: CO_2 savings and specific performance – 15th Stuttgart International Symposium, Automotive and Engine Technology, Forschungsinstitut für Kraftfahrwesen und Fahrzeugmotoren Stuttgart – FKFS, Volume 2, pp. 403-420, Stuttgart, Germany, March 17-18, 2015
10 HEYWOOD, J., Internal Combustion Engine Fundementals, MacGraw-Hill, 1988.