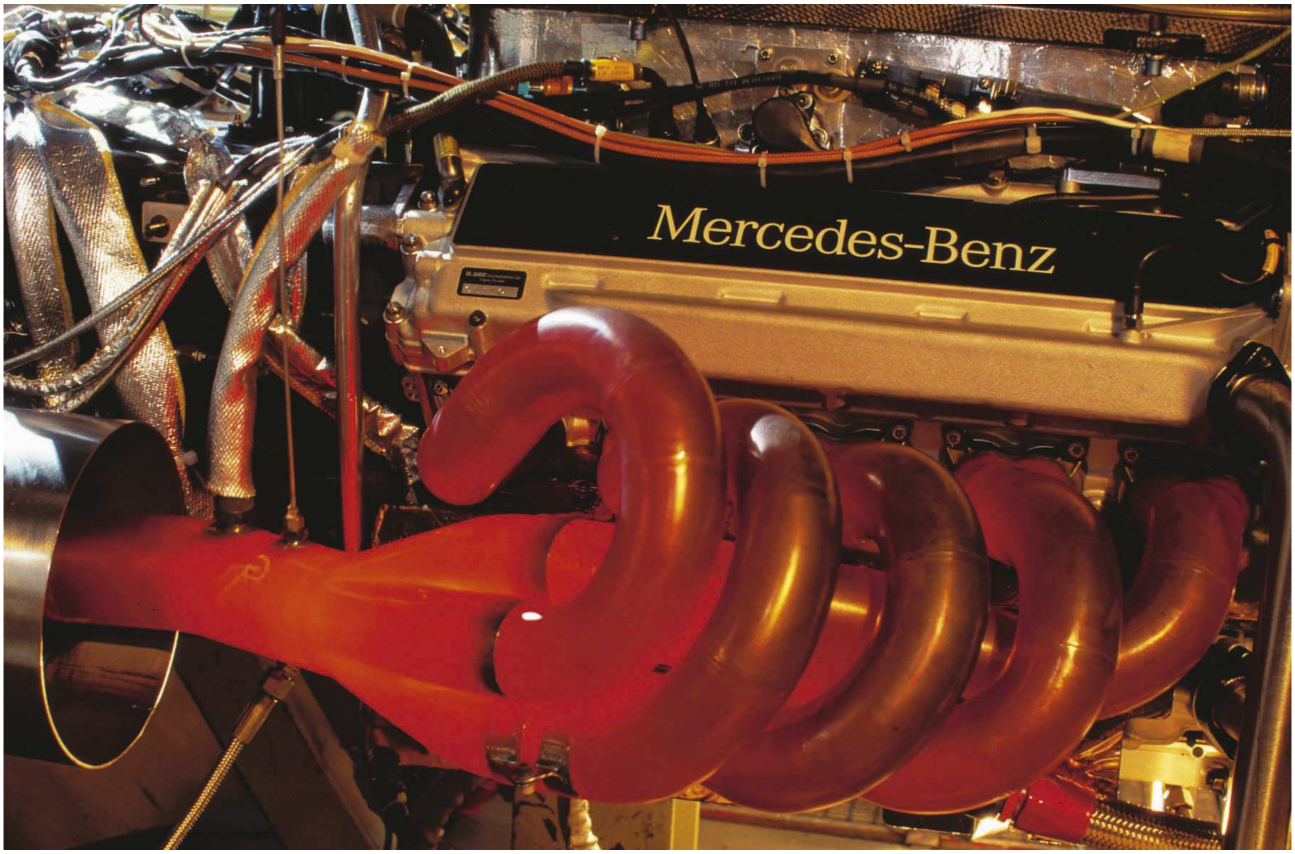

Mercedes-ILMOR: 10 Years of Power Development of the FO110 V10-3.0L Formula 1 Engine

The worldwide success of Formula One is strongly influenced by the application of high-level technology and has been made possible by the great commitment and dedication of the engine manufacturers.

Besides the skills of the drivers and the optimisation of the vehicle through the use of sophisticated aerodynamics, the persistent reduction in lap times can be attributed to the enormous development concerning the tyres and the ever more powerful engines. Since the beginning of 1995, the power performance of the Mercedes F1 engine has increased by over 30% and currently lies at 310PS per litre of total displacement.

The racing season of 2005 will be the last one for now to permit the use of 3.0L V10 engines. The past ten years of development of the V10 engine have been rewarded with two Drivers' Championship titles, a Constructor Championship title and 34 GP victories for the Mercedes McLaren Team altogether.

1 INTRODUCTION

The history of Mercedes-Benz is traditionally strongly linked to the history of motorsport in Europe in general. After becoming legendary due to countless victories during the 50s, the Silver Arrows resumed their participation in Formula One racing after a 50-year-long absence and are now embodied by the Mercedes McLaren Team.

The engines used are produced by Mercedes-ILMOR in Brixworth/England, a subsidiary company of DaimlerChrysler. Like the engines of the other competitors, they are naturally aspirated 3.0L V10 engines.

The technical rules and regulations, which today's engines are subject to, were put forward in 1994 and with the exception of minor limitations, concerning the permitted materials, very little has changed over the past ten years. This consistency has enabled engineers to produce an unprecedented power performance of 310PS per litre of total displacement.

The process of finding the best performance and durability of the engine, followed by its integration into the driver & car package, requires making efficient use of all available resources; due to the great pressure created by competition it is unlike any other engine production process. The rapid development and the ever-changing boundary constraints in all fields of technology call for an above-average adaptability and dedication. It is these criteria, which create the fascination of motorsport from the point of view of the engineer. The power development discussed in this article may only be a small part of the overall picture, but probably one of the most exciting ones.

2 THE REGULATIONS

The technical rules of F1 Racing are stipulated by the Fédération Internationale de L'Automobile (FIA), see article 5 [1]. The key points can be summarised as follows:

- 4 stroke piston engines
- Naturally aspirated 3.0L V10 engines with no more than 5 valves per cylinder
- Variable exhaust volumes are not permitted
- Air may not be cooled during induction
- Composite materials may not be used for the pistons, the cylinder head or the engine block
- Camshafts and crankshaft must be made of steel or cast iron
- External starting aids are allowed

A further rule forbids the use of any metallic materials which have a specific elastic modulus of elasticity greater than 40 GPa / (g/cm^3) for any parts of the car.

3 THE FO110Q - ENGINE

Complying with the regulations, the engine is a 10-cylinder construction with a V-angle of 90º - see **Figure 1**. The aluminium cylinder head, manufactured in a sand cast process, carries two hollow-drilled steel camshafts on each side, which are driven by a gear drive and dampers at the front. The four valves for each cylinder are partly pre-forged or manufactured through friction welding from titanium. The engine block is a closed-deck construction and also produced from aluminium by sand casting.

Figure 1: The Mercedes FO110 Q F1-Engine, 2004

The casing of the water pumps on each side is integrated into the casting. The pistons are equipped with an oil ring and a compression ring and are constantly cooled by oil from below. The nitrite steel crankshaft runs in six bearings and is produced in its entirety at Mercedes-ILMOR. The lower main bearing caps are screwed to the crankcase vertically as well as horizontally. The sump plate is a load-bearing part of the chassis hence it must be constructed in an appropriately stout way.

All auxiliaries are located on either side beneath the exhaust manifold - see **Figure 2**. Coming from the water pump we find the centrifuge, the pump for the pneumatics and all five suction pump systems (which are driven by an intermediate transmission) located on the right-hand side.

On the opposite side we see the hydraulic pump, the fuel pump and the drive for the generator (also via an intermediate transmission). Two oil pumps are used and situated centrally at the end of the crankshaft.

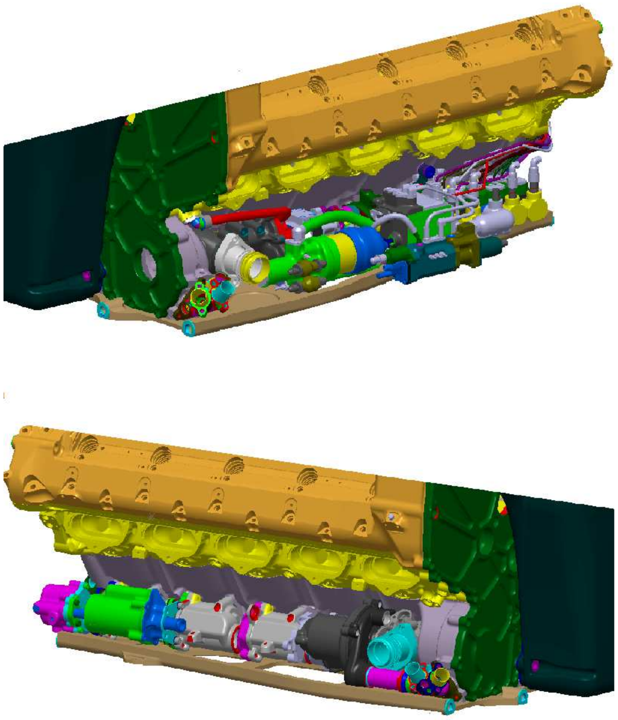

Figure 2: Arrangement of the auxiliary drives

The overall mass of the engine including the clutch is around 95kg. For the control of the engine management the TAG 2000 Electronic System came into action.

4 POWER

The induced amount of air and fuel in a naturally aspirated Otto-cycle engine is moderated by natural limits. Despite maximisation of intake volume and making the combustion process as efficient as possible, a further significant increase in performance could not be achieved in that area. Instead, attention over the last 20 years turned towards achieving an increment in engine speed, though this meant the control of valve motion by steel springs posed a serious obstacle. By making full use of the technology available at the time, the maximum engine speeds were limited to 14000 - 16000 rpm/min.
Only after having solved the practical difficulties of the pneumatic springs, did the engine speeds experience another rise. In 2005, Formula 1 engines have a maximum power output at rated speeds of over 18000 rpm/min and are capable of dealing with an over-speed of 19000 rpm/min.
To guarantee the increase in power performance that would be expected from the rise in engine speeds, the specific torque must be adapted accordingly. This demands constant adjustments to the inlet and exhaust manifolds in order to attain optimal gas exchange and devise ideal conditions for combustion. At this point we return to the classical power development of internal combustion engines, which is characterised by the following three concepts:

- Optimisation of the gas exchange for maximum volumetric efficiency
- Optimised combustion process
- Minimising frictional losses

According to the F1 regalement not more than 7 gears are used. Therefore at nearly all race circuits the engine is used in a speed range between 5.000 and 19.000 rpm. Especially the low and mid-range engine speeds require a good response and predictable torque outputs for optimum acceleration. Even though electronic aids can be used for additional support the issue of

- Drivability

is accredited with even greater importance when it comes to making use of the statistically developed power output in the dynamic operations.

5 THE ENGINE DEMANDS

During the qualifying session (counting one fast lap) the line-up on the starting grid is determined for the race on Sunday. The vehicle setup is the same as that used during the race itself since no further changes, including refuelling, are allowed to be made.
The running order of the cars during qualifying session, which can actually be of great strategical importance, is determined in the so-called pre-qualifying session, where adjustments to the vehicle are permitted in order to achieve the fastest possible time. Therefore, it comes as no surprise that the fastest lap times are set during pre-qualifying and these times will be used as the basis for the following analyses. The characteristics of a circuit, and one of the measures for the demands the engine is faced with, can be seen from the average speed of the car. The corresponding mean engine speed and average power output exhibit similar trends - see **Figure 3**. As expected, the lowest power output occurs at the street circuit of Monaco and the narrow Hungaro-Ring in Budapest/Hungary. The extremely fast races in Italy (Monza) and Belgium (Spa) represent the biggest challenge for the engines.
Such interpretations act as a reasonable guideline, but reveal no exact details. In this context the circuit of Indianapolis shall be mentioned as an example, where the banked curve leading up to the start-finish line allows driving at 100% throttle position for over 23 seconds.

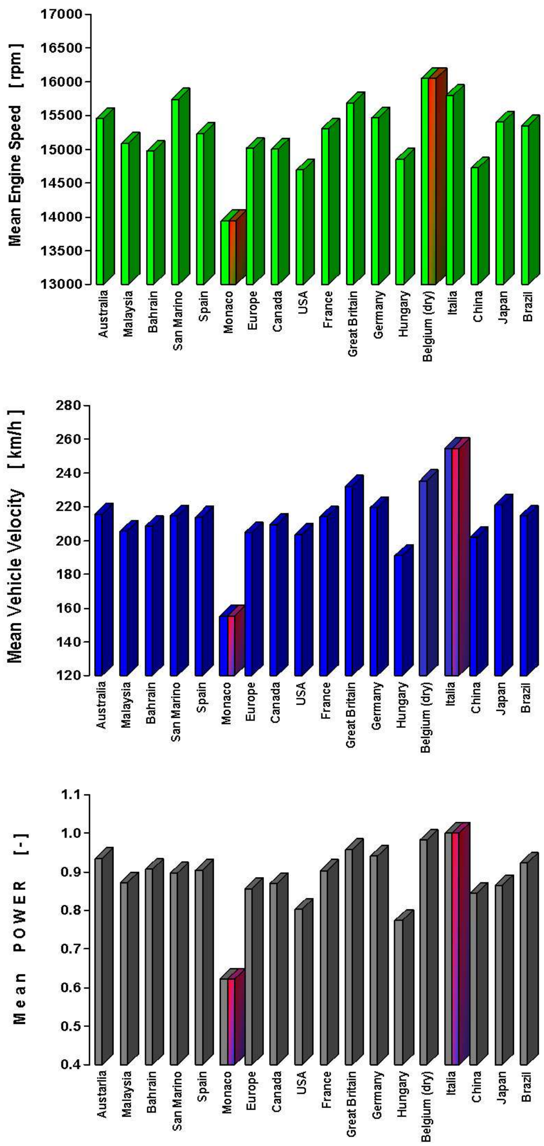

Figure 3: Lap Analysis from Qualifying 2004

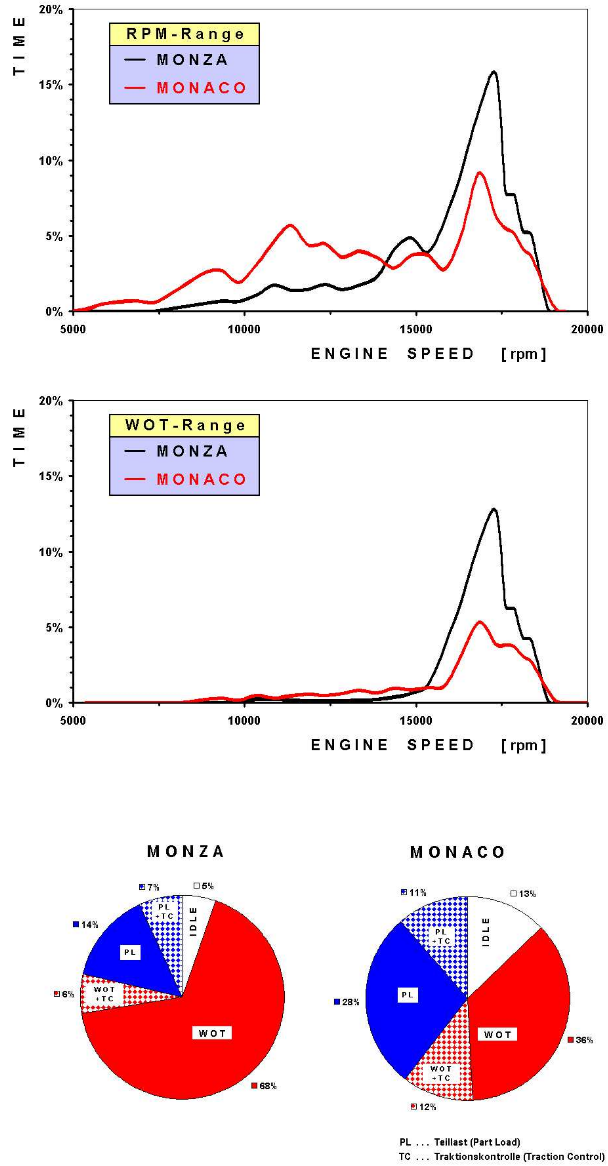

Figure 4: Engine Speed and WOT analysis

By analysing the percentage of time spent driving the engine at wide open throttle (WOT) for the fastest and the slowest race of the season, we can deduce that even though the percentage of time at WOT may be lower for slow circuits, the engines still predominantly perform in the highest speed range between maximum torque and peak power output – see **Figure 4**.

Besides optimising the full load curve, the development engineer is also interested in the region where the engine runs at part load conditions, which plays a vital role in controlling torque on accelerating out of corners. This shall be illustrated by looking at the circuit of Magny Cours (France), which contains a typical mixture of high and low speed corners.

The first curve after the start finish line is driven under WOT, whilst curve no. 2 is a fast right hand corner, taken in 4th gear and barely causes a reduction in engine speed, yet the next corner (a hairpin turn) is taken in 1st and the engine runs through a rpm-range of 11500 rpm/min – see **Figure 5 (top)**. All remaining corners are taken in 2nd gear.

Once past the apex of a corner, the driver pushes down on the accelerator fully, but the maximum possible torque is not yet applied because electronics are in charge of controlling the optimal transmitted torque by adjusting the throttle position, the number of firing cylinders and the ignition timing.

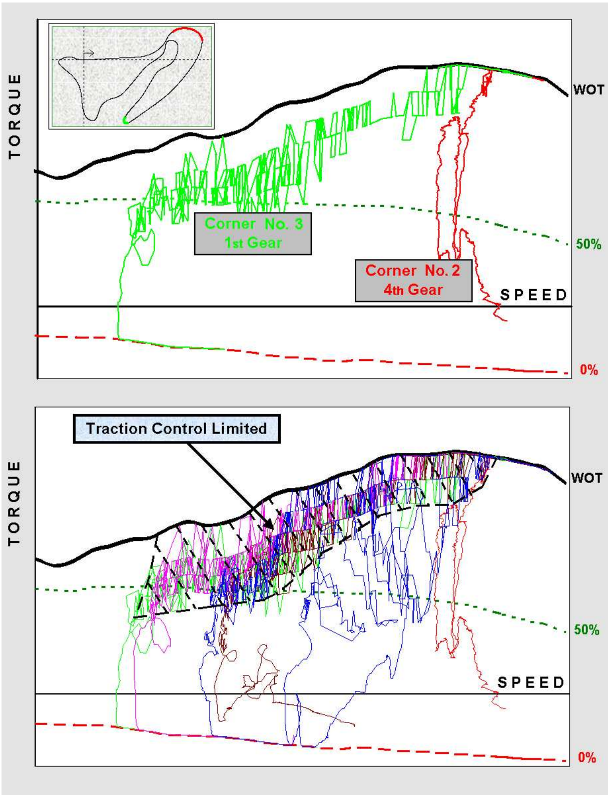

Figure 5: Part Load output during cornering

When summarising all part load accelerations, as in **Figure 5 (bottom)**, we realise that wide areas are entirely controlled by electronics. The area concerned has shrunk considerably due to specific calibrations of the engine, which has led to a reduced alternating load and lower fuel consumption. In the race itself the length of time for which traction control is active can increase by up to 50% as the grip of the tyres diminishes.

6 ENGINE DEVELOPMENT

The season of 2003 saw the debut of the FO110Q engine that had evolved from the engine used during the previous year. The constructional improvements mainly focused on the cylinder block and the cylinder lining, in addition to trying to lower the centre of gravity. The continuous rise in maximum engine speed obviously had to be accompanied by the optimisation of the piston design, the conrods and their bearings. Another focal point was the adaptation of the air stream above the trumpet, which became necessary due to the altered geometry of the vehicle.

6.1 The Gas Exchange Process

The main measurements concerning inlet and exhaust geometries, the valve timings and all variables relevant to thermodynamic and gasdynamic processes can be calculated in advance with assistance of 1D-process simulation tools. Modules specific to the engine such as cylinder, throttle and plenum are connected via pipes – see **Figure 6** – constitute the fundamentals of these computations. They are used to set up and solve the transient equations for the one-dimensional flow in pipes with varying cross sectional areas and taking the local wall friction and heat transfers into account [2, 3]. At the transition points themselves, the process of flow in or out is solved iteratively until equilibrium is reached for the time span in question. Additionally, one or more transport equations can be incorporated to provide information about the gas composition as a function of time and distance. The calculations for a particular load point are complete when the variables averaged over a set period of time remain unchanged.

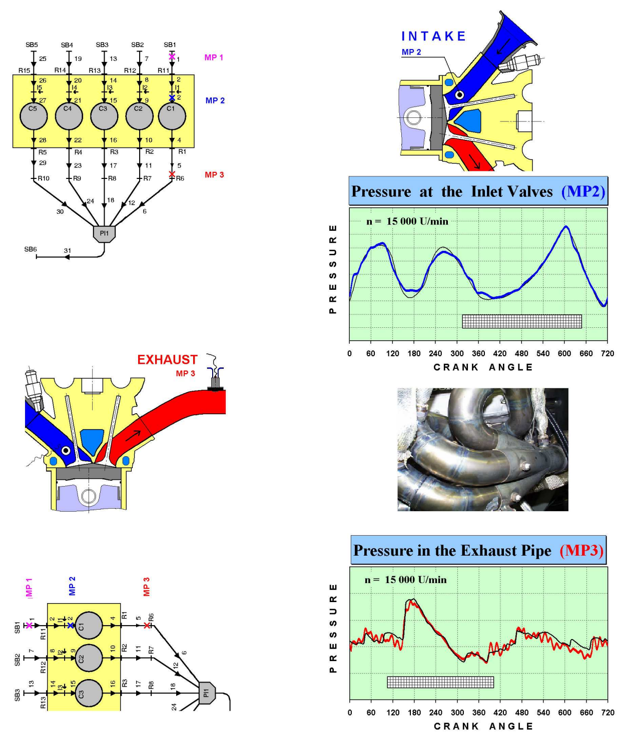

Figure 6: Inlet and Exhaust Pressure Measurements

The results obtained can be sorted into two main categories: The integral results such as power, fuel consumption and indicated mean effective pressure; and those variables that change over the period of one cycle, like the local pressures or mass flow. In order to verify these values, there are the data from the test bed protocols and the indication data collected for checking the transient pressure traces. The latter are often difficult to obtain in Formula 1 engines due to the lack of space, hence the need for further adjustments to fix the sensors in the required positions. Apart from the need for space, the severe vibrations also pose a problem, as they produce excessive noise signals particularly during the application of piezoresistive low-pressure sensors. Without taking preventive measures these vibrations can easily lead to the breakage of these sensor types.

Because of the strong dynamics within the inlet manifolds it is a great advantage to carry out the pressure readings as close to the valves as possible, but for structural and design reasons this can only be done on the four outermost cylinders. Another reason for taking accurate readings of the inlet pressure is the necessary adjustment of the geometric length to the actual active length. The reflections of the pressure waves do not take place at the geometric trumpet inlet but slightly beyond. The required correction length depends on the engine speed and has an order of magnitude of up to 15% of the overall inlet length.
The readings of the single-Lambda measurements and the indicated mean effective pressures in all cylinders were used to measure the varying degrees to which the cylinders were filled. These variations could only be brought about by the pressure boundary conditions within the inlet ports; all other dimensions/conditions are symmetrical (2 x 5 cylinders). 1D and 3D simulation systems were coupled to investigate this phenomenon.

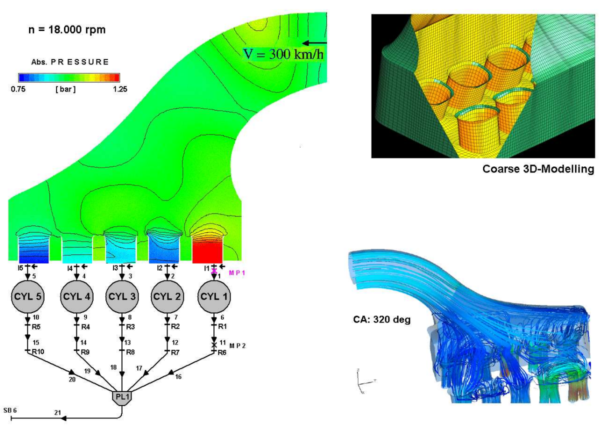

Figure 7: Coupled 1D-3D Flow simulation

The entire inlet starting at the opening above the driver's helmet and going to the region near the valves, is covered by a fine grid for the three-dimensional flow calculation (see **Figure 7**). The rest of the engine is simulated with the conventional 1D tool. The pressure boundary conditions at the transitions are controlled by the 1D code. Once the flow in 3D domain has been solved, the altered conditions of the coupled region become the new starting terms for the succeeding time period of the 1D programme. Again, the simulations can only be regarded as complete once the readings at the chosen monitor points remain constant for a fixed length of time.
These time-consuming computations can be shortened by various means, for example, the application of a coarser grid at the start of the operation or the inclusion of solutions obtained in previous studies. This technology and the use of parallel-linked computers with faster processors are capable of reproducing and illustrating the measured effects. The succeeding step – solving problems concerning equal distribution amongst cylinders and achieving their maximum volumetric efficiencies – is a lengthy process and inevitably only leads to a compromise.
For measurements of all in-cylinder pressure values we rely exclusively on the use of the smallest none cooled piezoelectric sensors (Quartzes). These are screwed into the combustion chambers via extensions through the water channels, and have proven to be reliable in terms of the quality of their signals and lifetime.
However, sensors and dampers, which are water-cooled, need to be used on the exhaust-facing side as a result of the high temperatures and vibrations. This assemblage itself, combined with the mounting device for screwing it onto the thin-walled exhaust pipes, is relatively heavy. Special support for the exhaust system is required when aiming to install several measuring units.
Despite the fact that the measured data were strongly affected by noise interferences the pressure traces for the gas exchange analyses were very helpful.

6.2 Combustion

Applying the second law of thermodynamics to the measured pressure trace allows the calculation of the heat released [4, 5]. The more precise the available values for air and fuel in the cylinder are known (and how much residual gases are remaining), the more accurate these calculations will be.
Compared to conventional engines, the F1 engine undergoes strong cyclical variations. The standard IMEP deviation at rated speed lies at about 1.4%.
The extremely forceful closing of the inlet valves and the small thickness of the walls can be seen in the corresponding interferences in the cylinder pressure signal. The short compression phase, from closing the valves until start of combustion, limits a deduction of the trapped mass in the cylinder and the actual compression ratio. For statistical evaluations 100 consecutive cycles are recorded at least, see **Figure 8**. Afterwards the data are averaged and either analysed in terms of the characteristic combustion variables (VIEBE) or is used directly in the 1D engine simulation as target. Furthermore, this information regarding cylinder pressure and heat output is necessary for FEM calculations and various heat balance analyses.

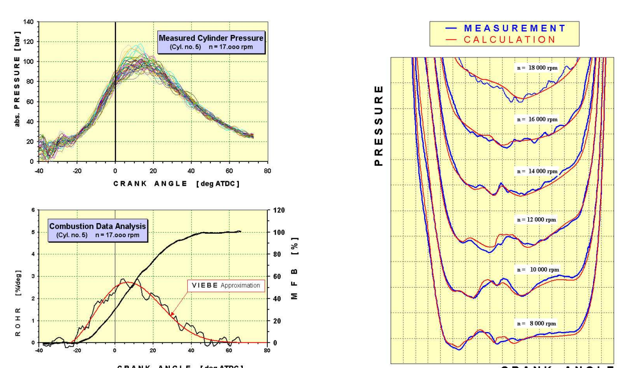

Figure 8: Cyl. Pressure and Combustion Data Analysis

The freedom concerning the combustion chamber design is rather restricted in Formula One engines. The valves are arranged in such a way, as to create an almost spherical combustion surface.
The high compression ratio (ε > 14.5 : 1), the size of the valves and the valve pockets on the piston crowns create a very rigged combustion chamber. Influencing and controlling the combustion process is primarily carried out through the interaction of the position and geometrical arrangement of the inlet ports [6, 7].

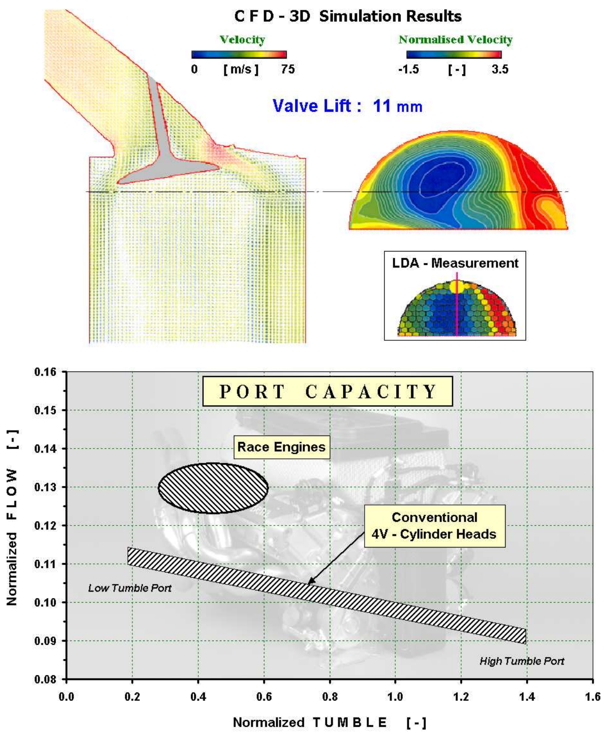

Figure 9: Tumble Flow – Calc. and Measured Data

High-performance race engines with an external mixture preparation do not require a well controlled air motion in the cylinder, such that the design of the inlet and outlet passages can concentrate on minimising throttle losses. As investigations have revealed, even under such extreme conditions there is still a small tumble motion which splits into several smaller eddies at the start of combustion. Due to their high turbulence energy they have a positive effect on the rate of combustion as CFD calculation showed.
Today countless 3D computer simulations are used to continually expand upon these discoveries and elaborate procedures such as LDA-measurements and supersonic flow benches are employed to complement the results, summarised in **Figure 9**. Experience has shown that even after many years of development it is still possible to finds further potential and thus power in optimising the port and combustion chamber geometry.

Another field within combustion development is the optimisation of the fuel injection system. To create an injection jet of extremely fine droplets a high-pressure pump, working at around 10MPa, comes into action. The electromagnetic controlled injection nozzles are located above the trumpets. The fuel itself is delivered via one shared pipe per cylinder bank. Aerodynamic losses or flow restriction due to this arrangement could not be detected.

6.3 Friction

The sum of the internal losses can be divided into two groups: The resistances within the block and the cylinder head - mainly due to friction within the bearings - the gear train and along the sealing between the pistons and liners and the necessary power for driving all the auxiliary drives. As a consequence of the extremely high number of revolutions, there are considerable pumping losses in the crankcase. With the help of strong sucking pumps the oil is drained out of the chambers as quickly as possible, where these losses can be greatly reduced by making the appropriate design solutions.
One other focus point is the determination and development of the lubricant itself. Computer-aided analysis turned out to be a good approach to determine the state of lubrication of the bearings. The demands on the oil found in this investigation were appointed by several parameters that would allow the manufacturers to produce customised tailored lubricants.
The determining of the friction losses can be carried out from the differences between the indicated mean effective cylinder pressure and the brake mean effective pressure as recorded via torque measurements at the clutch in great detail. Such sophisticated processes are subject to the signal quality and can be substituted by motored tests. Both systems require corrections in terms of losses introduced from applied intermediate transmission drives.

6.4 Steady State Power Measurements

After a precisely defined warm-up phase every engine that will be employed in a vehicle undergoes a power check on a steady state test bed twice. The air sucked in has to be conditioned concerning pressure, temperature and humidity. The brakes used are either those developed by ILMOR itself (water brakes) or AC electric motors with a reduction drive set before them. During the automated measurements the engines are driven towards the WOT points and held at these for approximately 15 seconds to enable stabilisation and recording of data. Afterwards, it is allowed to idle before reaching the next load point. The engine undergoes a further visual and pressure check, after having completed the power test phase, before it receives the 'all-clear' to be built into the vehicle.

6.5 Transient Power Measurements

A rather considerable proportion of the engines produced are used for further power development and endurance runs. To simulate the demands of the racetrack as closely as possible, the engine – including the gearbox of the vehicle – is tested on a high-dynamic transient test bed. For this purpose, the ends of both side shafts are connected to two independently operating motors, which recreate the exact conditions between tyres and track, see **Figure 10**.

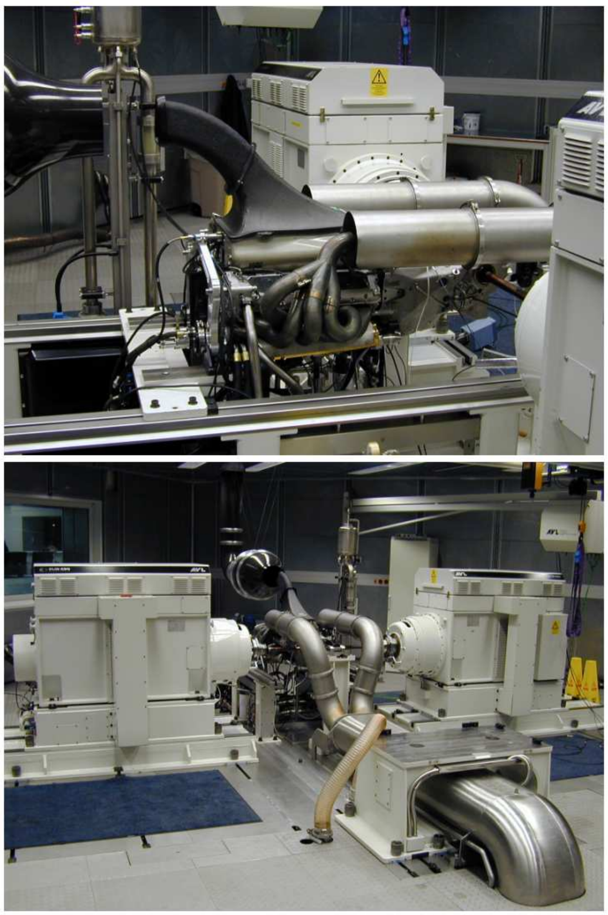

Figure 10: Transient Dyno with Car Gearbox

During simplified endurance tests a one-step reduction drive is sufficient, which simulates the gearshifts appropriately. For this testing procedure the circuit is simulated using a load-time collective controller. The setup with the car gearbox involves a parallel processing unit with an integrated racetrack simulation in real time for controlling engine speed, gear number and torque output. The advantage of this operation is that all possible scenarios and strategies, which used to have to be worked out in a time-consuming manner at the racetrack, can now be reconstructed on the test beds. Additionally, the assessment of the lap times is more objective that way, as the factor "driver" can be negated.

However, only the practical test itself can show whether the setup found suits the driver, but even here work is currently done to create numerical driver models for shortening the testing periods.

There are many possible approaches to assessing drivability of an engine [8]. One important criterion for the driver is the continuous and predictable torque output within the entire mapping area. Therefore a specific map of pedal-throttle correlation is established and placed at the driver's disposal.

For controlling the engine response in the car either torque sensors are positioned along the drive train or the engine torque output is retraced from the acceleration signal and the known vehicle data, see example in **Figure 11**.

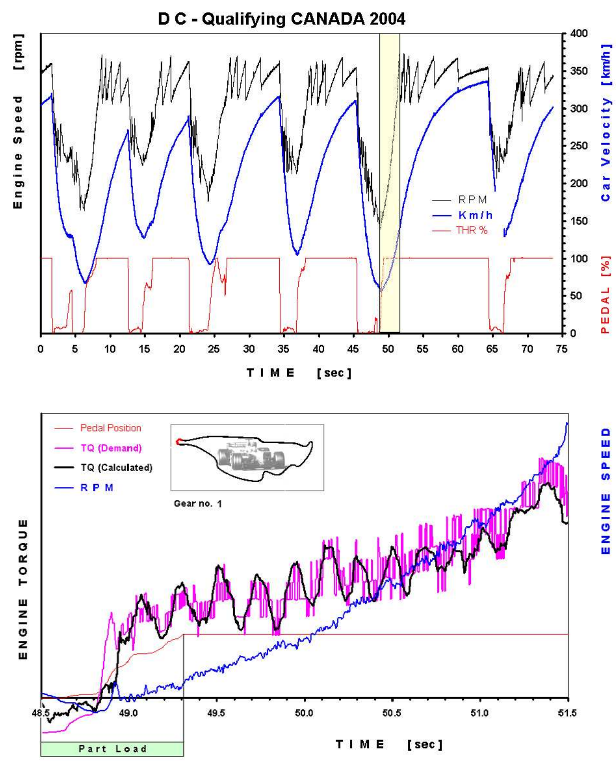

Figure 11: Transient Torque Output

For specialised work during engine calibration or when examination into the improvement of drivability is carried out, the engine undergoes dynamic pressure indication. Only that way can the precise internal power output be judged in relation to the rear wheel torque output. As experience with test beds and drivability investigations at the trackside have shown, this method is a good means of differentiating between problems arising from the engine and possible influences by the drive train.

6.6 Racetrack Simulation

The McLaren Mercedes Team has developed its own lap-simulation programme which is capable of retrieving all numerical vehicle data and provides a significant contribution to the chassis development and estimation of the relevant variables. Naturally, these tools are developed for trackside engineers and are specifically adjusted for the needs of car setup tunings. The engine development engineer, who is primarily interested in the results relating to the torque and power curves as well as their connection to the gearbox settings, can find the necessary information with the aid of simpler tools. Hence Mercedes-ILMOR developed a computer program, which, on the one hand, reconstructs the processes occurring during the acceleration phase very well, and on the other hand, is capable of analysing the telemetry data of the accelerations [9]. These calculations are generally much faster than a complete lap time simulation - yet provide results of similar quality.

Figure 12 (top) shows a comparison between calculated and recorded number of revolutions and the vehicle's speed at a section of the circuit in Montreal /Canada, starting in first gear after a hairpin corner. In the case of a good correlation, the model can be used for parameter studies.

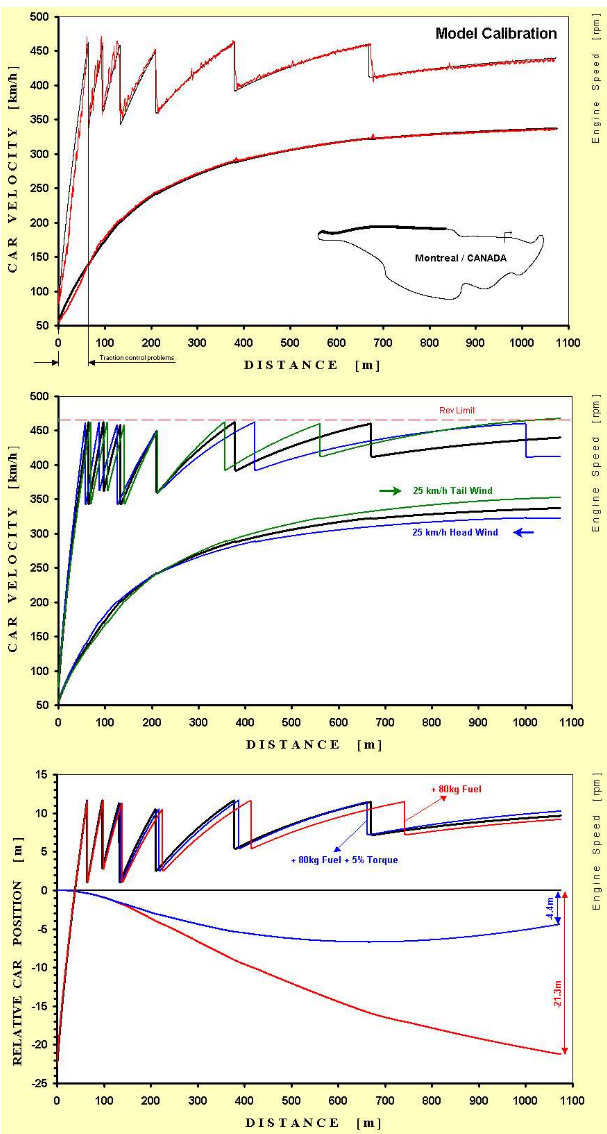

Figure 12: Acceleration Simulation

The diagram below that graph presents the results of a simulation of head- and tailwind of 25 km/h. In the starting phase the tailwind reduces the surface grip and thus the maximum acceleration, but leads to a noticeably higher final velocity and overspeed of the engine rpm. The gear ratio would have to be readjusted.

The bottom diagram in Fig. 12 shows the effect of 80kg additional mass when all other factors remain unchanged. This disadvantage in weight brings about a relative reduction in distance covered by about 21.6m, compared to a lighter basic vehicle over a track length of 1100m. Even, if the heavier vehicle were fitted with an engine whose torque were 5% higher it would still run behind the basic vehicle by approximately a car length at the end of the mentioned straight. The effect of these parameters on the braking and any effect during cornering cannot be calculated with this simplified method.

7 SUMMARY

As a consequence of the demands that the engineers were faced with, the development of the Mercedes-ILMOR F1 engines was primarily characterised by the need for power. This requires a continuous rise in engine speed and being able to control all the associated problems that can occur, particularly with the pistons, the conrods, as well as the severe oscillations and their resulting damages. The design of the engines aims to minimise the total weight and frictional losses, yet at the same time ensuring a low-lying centre of gravity. As the engine is a load-bearing component of the vehicle, its dimensioning and design must be accordingly robust. Fulfilling these demands calls for ever-new metallurgical methods, surface coating techniques and machining technology.

Power development on the whole relies on the same tools for calculation, simulation and measuring technology as conventional engine development. The challenge of data acquisition, constrained due to strong vibrations, lack of room and high temperatures, brings about new technologies, which eventually contribute towards serial productions.

Since the beginning of the 2004 season, only one engine per car and race weekend is allowed, which resulted in increased efforts in the work on durability and led to lower maximum engine speeds or even fewer testing laps during practice sessions. The regulations were tightened once again for 2005, which means engines must now last for two race weekends. And in 2006, engines will have to be a V8 design with the total displacement being limited to 2.4L in order to achieve a drastic reduction in engine power and overall expenditure. In other words, the era of development of the V10 engine appears to have come to a close, as further spectacular progress within this field of engineering is highly unlikely in the foreseeable future.

The freedom of constructing an 8-cylinder engine is greatly restricted by the rules for weight, dimensioning and materials permitted, and is only marginally different from some of the contemporary racing series. Personally, I very much doubt that these changes will retain the desired fascination of Formula One racing.

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Dr. techn. Hans Alten
Calculation, Simulation and Indication Techniques
Mercedes-ILMOR, Brixworth, England