GRAND PRIX ENGINE DEVELOPMENT, 1906 – 2000

Review of Salient Design Features

A broad review of salient "Grand Prix Car of the Year" (CoY) power-train features over 1906 – 2000 has been made under the following headings:-

1. Configurations;
2. Cylinder and Head Junction;
3. Valve Arrangements;
4. Inlet Systems;
5. Pressure-Charging;
6. Air Filters;
7. Exhaust Systems;
8. Ignition Systems;
9. Lubrication Systems;
10. Stressing Conditions;
11. Materials;
12. Weight and Centre of Gravity;
13. Engine and Chassis Integration;
14. Clutches;
15. Gearboxes;
16. Design and Development Quality.

1. Configurations

All CoY engines (and all classic Grand Prix winners bar one) have been 4-stroke spark-ignition liquid-cooled piston engines with conventional “Bottom-ends”, i.e., crank, connecting-rod, gudgeon-pin (“piston-pin”) and piston; and with conventional “Top-ends”, i.e., cam-opened, spring-closed poppet-valves (with one type exception).

The *exceptions* were:- an air-cooled Porsche F8 1.5L which won the 1962 French GP, its sole classic GP success; and mechanically-closed valves in the Mercedes-Benz M196 IL8 2.5L in 1954 – 1955 (Egs. 32 & 33).

Valve springs were steel coils or steel hairpins up to 1989 and since then have become pneumatic. The latter system was a design innovation by Renault in 1986 but it did not feature in a CoY until 1990, after which it became universal in that selection of examples (see Note 15 for more details).

No 2-Stroke engine, no Diesel and no Wankel engine have started in a Grand Prix and the foremost type is now banned because its emissions are unacceptable (Note 24).

The In-Line (IL) engine configuration was successful until after 1935, an exception being the Delage 60V12 2L in 1925 (Eg. 11). This period was followed by a mixture of Single-bank and Double-bank designs until 1960 when the latter became supreme with one exception which was the BMW IL4 1.5L TurboCharged (TC) of 1983 (Eg. 64).

Non-CoY GP engines were tried with more than 2 banks:- a 4-bank 2-crank engine appeared from BRM in 1966 (Flat-H16 3L) which won a single classic GP (in a Lotus chassis) but was very expensive, not very powerful and very unreliable – a 64-valve(!) redesign of 1969 never raced; and a 3-bank 1-crank engine from Life in 1990 (60 +60 W12 3.5L) which was under-funded and never qualified for a race. Neither configuration was *inherently* bad, the 4-bank 2-crank Flat-H24 Napier *Sabre* aero engine making a useful contribution to the later years of WW2, while its forerunner, the 3-bank 1-crank 60+60W12 Napier *Lion* aero engine post-WW1 was not only commercially-successful but also powered the Schneider Trophy winners in 1922 and 1927.

Some other configurations are described in Note 24B.

All 2-bank CoY engines, Vee or Flat, *except* one have used side-by-side con-rod big-ends on a common crank-pin. The exception was the 1958 Ferrari 65V6 2.4L (Eg. 36) where the unusual bank angle and a desire for even firing intervals gave rise to a (heavy) 6-pin crank. An offset between cylinder banks was therefore universal in 2-bank units.

Power, has always been delivered at one end of the crank in CoY engines, *except* for the M196 IL8 which had an output shaft geared to the crank centre. This did not save it from torsional vibrations which required a damper at each end of the crank.

Cranks for CoY up to 1936 had supporting journals *either* each side of 2 throws *except* the 1921 Duesenberg (Eg. 7) which had 4-throws between journals *or* the stiffer but greater frictional loss layout of a journal either side of each throw. The 1912 Peugeot (Eg. 4) was the 1st with that arrangement. Afterwards, as RPM rose, the latter system became general *excepting* that the 1971 – 1980 Ferrari F12 (Egs. 54, 56, 57 & 59) reverted to 2-throw support (see Note 18).

Cylinder numbers (CN) from 4 to 16 have been successful in CoY, the latter once only in 1936 in the mid-engined Auto Union (Eg. 22) and the former not since 1983 – the TC BMW. The 8-cylinder engine has been the most successful (46% of the 85 examples), split about evenly between early IL (21%) beginning with the 1921 Duesenberg* and later 90V (25%), of which the 1956 Ferrari-Lancia (Eg. 34) was 1st in the CoY series. However, the V10, introduced simultaneously in 1989 by Renault and Honda, virtually supplanted all other configurations in the 3rd NA Era. It is a (fairly) happy compromise between higher peak power from a V12 and a less-powerful V8 having a lighter weight of engine + fuel. Each of the V12 and V8 configurations powered a single CoY in this 3rd NA Era, respectively in 1991 (Eg. 74 Honda) and 1994 (Eg. 77 Cosworth).

*See P.3 top.

*It is interesting that there were 3 makes of IL8 engines in the 1907 French GP but none went further than 70% distance (835) and the configuration did not reappear in GPs until 1921.

The FIA rules for2001 made use of a V10 *compulsory* until the end of the 3L size in 2005, superseding a rule since1966 which had allowed free choice of cylinder number up to 12. Prior to 1966 there was no restriction on CN. The new rule began a process, which has continued since then, for the FIA to define ever more closely the specification of the engine until, for 2014, even the minimum diameter of the valve stems is laid down. At one time it even appeared that a standardised engine to be chosen by competitive tender would be enforced, as it is in junior formulae, but this did not quite happen.

Grand Prix Cars of the Year (CoY), 1906-2000

Summary table of Configurations (85 CoY)

	IN LINE			2-BANK				
No. of Cylinders	4	6	8	V6			V8	
Vee Angle^0				65	80	120	75	90
No. of CoY units	12	3	18	1	6	3	1	20
				10			21	
% of Total	14.1	3.5	21.2	11.8			24.7	

	2-BANK (Continued)							
No. of Cylinders	V10					V12	F12	V16
Vee Angle^0	67	71	72	80	90	60	180	45
No. of CoY units	5	1	4	1	1	5	3	1
	12							
% of Total	14.1					5.9	3.5	1.2

2.Cylinder and Head junction

Up to 1955 inclusive CoY engines used 3 types of cylinder and Head junction, with 24 units being either cast or forged integrally, a further 5 with cylinder liners screwed into the head (Alfa Romeo 1948 – 1951 (Egs. 26 ,28 & 29) and Ferrari (Egs. 30 & 31)). Only 4 had bolted-on detachable heads (1921 Duesenberg, 1933 Maserati (Eg. 19), 1936 Auto Union (Eg. 22) and 1949 Ferrari (Eg. 27)). The majority of fixed head designs (24 + 5 effectively fixed) in this period avoided gasket sealing problems but at the cost of manufacturing difficulty and extra maintenance effort. Valve included angles above 60^0 (and Bugatti vertical valves overlapping the bore) in fixed heads had to have removable guides to permit valve insertion upwards from the cylinder with the guides then being fitted around the stems from the top.

Post-1955 all CoY engines have had detachable heads, even when Turbo charged up to 5 ATA inlet pressure. This must be a consequence of improved gas sealing at the junction, usually by various kinds of compressed rings with some spring rather than gaskets over the whole interface. Examples are:- multi-layer steel/Nimonic 75 in the Vanwall (Eg. 37) and Climax engines of the 1958 – 1965 period(Egs. 38, 39, 42, %44) (Cooper's rings (33, 34)) and bronze rings in the 1998 Ilmor (Eg. 82).

The latest types permit very-small lands between cylinders which reduces block and crank length and hence weight.

3.Valve arrangements

All CoY engines, with the *exceptions* of the 1906 side-valve Renault (Eg. 1) and the 1908 Mercedes (Eg.3) with side exhausts, have been Over-Head-Valved. Thus the major change required to minimise the combustion chamber [Surface area/Volume] ratio and so raise Combustion Efficiency (EC) occurred very early in the review period. It also improved the *potential* Volumetric Efficiency (EV) by eliminating the extra 180^0 turning involved in side-valve airflow, although this did not seem to make much difference while only one updraught carburetter fed multiple cylinders (see Note 25).

Since 1912, when the Henry-designed Peugeot introduced direct-camshaft-actuation of a double row of inclined, opposed, overhead valves (DOHC) the great majority of engines – 89% have had this layout in the review period. The angle included between valves (VIA) has varied between 102^0 and 20^0, the narrower angles being the most recent. The big reduction in VIA with DOHC for GP racing came in 1967 with Keith Duckworth's Cosworth DFV (1968 CoY, Eg. 47), when he adopted 32^0 – his F2 FVA had preceded it with VIA = 40^0 in 1966.

The one-time competitor to DOHC, the single overhead camshaft (SOHC – 11% of CoY from 1912 onwards), sometimes with lever actuation of inclined or vertical valves in double line, sometimes direct actuation of a single valve line and once (1936 Auto Union) with a hybrid direct inlet plus push-rod-and-rocker operation of the exhaust valves, has not been successful since 1966 – 1967 (in the Repco, Egs. 45 & 46). This was 15 years after the previous SOHC classic GP winner (but not CoY, the 1951 Ferrari type 375 4.5L NA; see under Eg. 27).

The last major GPs to be won by a push-rod-operated OHV (Riley-type) engine , but again not CoY, were in 1949 by the Lago-Talbot IL6 4.5L NA; this was competing with 1.5L PC engines and beat them by non-stop runs made possible by lower fuel consumption.

More details of valve-spring problems and their solutions are given in Note 15, culminating in the replacement of steel coils by pneumatic springs in 1990 onward.

Prior to WW1 GP CoY valve springs were exposed, probably to gain air-cooling, especially of the exhaust side, but perhaps it did not occur to anyone to enclose them. Ettore Bugatti was already building a few cars with enclosed springs by 1910 but it was possibly the Marc Birkigt – designed 1916 Hispano-Suiza aero engine mass-produced with this feature which really established it. Of course, enclosed springs had to have oil-cooling. Racing engine designers post-WW1 accepted enclosure generally and, of all subsequent engines, only the 1958 Vanwall reverted to open springs. This was a carry-over from its Norton racing motorcycle ancestor which had persisted with exposed hairpin springs into the '60s although most rival units had adopted enclosure many years before.

Note 25B describes the origin of the inverted-cup tappets which were, in most of the later review period, the most popular way of taking cam side-thrust in DOHC designs (52%) with finger-followers the next most frequent (26%). The latter were mostly in earlier engines until they were revived in the last 3 years as Mean Valve Speeds (MVS) rose.

Most CoY overhead camshafts have been gear-driven, usually by spur-wheel trains but occasionally by shaft-and bevel-gears. In non-Coy engines Gioachino Colombo and Aurelio Lampredi had used chain drive in 1948 – 1951 SOHC V12 Ferraris. The first CoY to use chain drive was Vittorio Jano's 1953-designed Lancia D50 in 1956 after it was taken over by Ferrari. This drive type was retained in a number of semi-derivative Ferrari GP engines subsequently, also in Coventry Climax V8s and Repco V8s up to 1967. The last CoY application of chain camshaft drive was the 1994 Cosworth type EC (aka Ford Zetec –R, Eg. 77), 27 years after the previous CoY use of the system.

The number of inlet valves per cylinder oscillated between 1 and 2 until 1967 after which the Cosworth DFV V8 3L architecture of 2 inlet and 2 exhaust valves at VIA under 40^0 became *almost* universal. Ferrari V12 3.5L engines using 3 inlets/2 exhausts per cylinder, following a Yamaha racing motorcycle lead of 1985, *did* secure 9 classic GP wins over 1989 – 1990, with a near-miss of the Drivers' Championship in the second year (see under Eg.84).

4. Inlet Systems

All CoY GP engines *except* 2 up to 1961 inclusive had carburetters. The exceptions were :- the 1954 – 1955 Mercedes-Benz M196 which used Bosch direct-into - cylinder fuel injection; and Vanwall which used the same type of Bosch pump to provide *indirect* injection, i.e. into the inlet tracts. After 1961 all CoY engines had indirect injection *except* the 1964 Ferrari (Eg. 43) with the Bosch direct system.

All inlets have been side-ported *except* the M196 and the 1964 Ferrari, both with downdraught (or "axial") ports. Many other non-CoY engines in the late'60s also used downdraught ports but they were swept aside by the Cosworth DFV which had side ports with deliberate" Barrel Turbulence" (aka "Tumble Swirl") creation (see Note 26). The downdraught port almost certainly suffered because there could be *no tumble Swirl.*

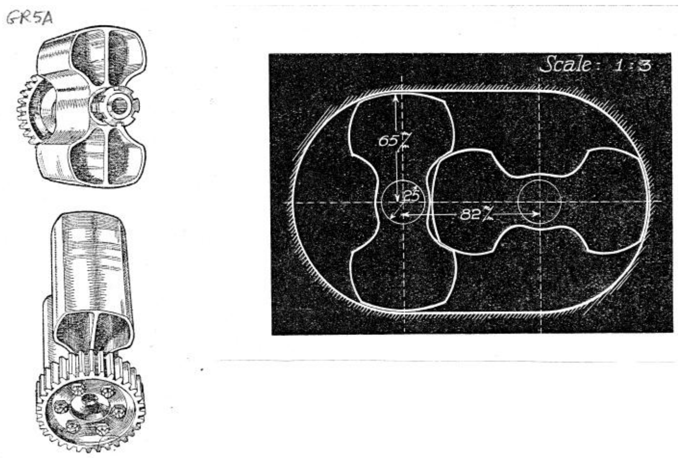
The possibility of tuning an inlet system for each individual cylinder to raise Volumetric Efficiency (EV) at a selected RPM, whether NA or PC, was unused in GP CoY circles until 1952 but became the norm thereafter (see Note 27). When PC was revived in 1977 by Renault using a TurboCharger (TC) (see Note 89) they retained the tuned inlets of a de-stroked NA F2 engine with these breathing from a pressurised plenum chamber. This inlet system was used by all subsequent TC contenders.

Variation of inlet tract length over the RPM range so as to broaden the useful power band became common in the '90s with the return to NA.

5. Pressure-Charging

All GP CoY engines from 1924 to 1951 were Pressure-Charged (PC) by additional machines called "Superchargers", mechanically-driven from the crank (MSC). They were all of the Roots-type (patented in 1866 (2)) with 2- or 3-lobe over-lapping-but-not-touching rotors to displace the inlet charge into the engine manifold without *internal* compression. The pressure rise therefore took place as each delivery was forced into the manifold against the limited acceptance of the flow by the piston displacement. A typical Roots "Blower" is illustrated on Fig. GR5A.

Fig. GR5A
Roots Supercharger
A section of the 1924 Sunbeam "Blower".
Conventional 2-lobed forged steel rotors in an Al-alloy case,
but with wider-than-usual outer perimeters to reduce over-tip leakage.
DASO 4 p. 168



The consequence of having no internal compression was that the pulsating flow made the Roots supercharger very inefficient. At IVP = 2 Atmospheres Absolute (ATA) about 55% of the power input was producing pressure rise and the rest was wasted in heating the charge to a higher temperature than would have been reached with ideal compression. The efficiency deteriorated beyond IVP = 2.5 such that there was no further power gain.

Above IVP = 2.4, therefore, 2 superchargers in series were used, the separate units each not exceeding a 2 : 1 pressure ratio.

The 1st PC Era can be sub-divided into:-

- 1924 – 1938: 15 years: 1 stage MSC (IVP from 1.5 to 2.4 ATA);
- 1939 – 1951: 5 racing years: 2 stage MSC (IVP from 2.3 to 3.9 ATA).

Despite its inefficiency the popularity of Roots MSC was due probably to:-

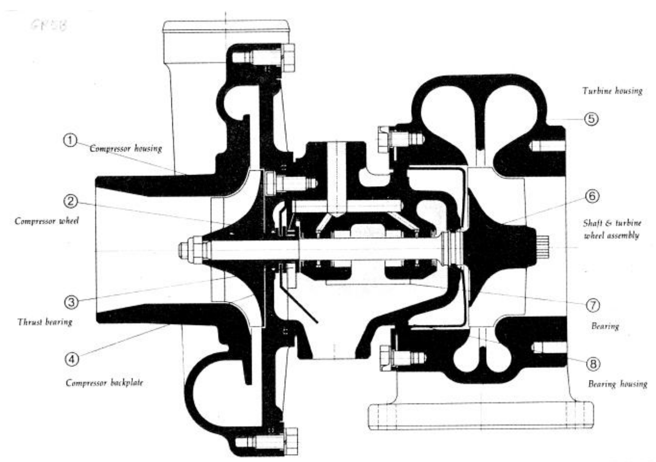
- Its ease of manufacture;
- Flat delivery pressure v. RPM when feeding a piston engine;
- Reliability with high tolerance of road grit;
- Simple lubrication requirement which did not contaminate the inlet charge.

As M. Panhard is said to have remarked about the sliding-wheel gearbox: "*C'est brutale – mais ca* marche *!*" ("it's crude – but it works!").

Practically from 1st use of supercharging – post 1924, which was its 1st CoY use – the heat of compression was deducted as far as possible by the evaporation of alcohol-base fuel in the inlet charge, of increasing alcohol content and mixture richness as IVP rose to produce more power. This fuel was sucked in from a carburetter upstream of the blower except for Mercedes-Benz who preferred downstream pressurised carburation until mid-1937.

In the 2nd PC Era (1982 – 1988) all CoY used TurboChargers (TC) to produce the pressure rise. All these TC had a single centrifugal compressor driven directly by a single radial –inflow turbine. A typical TurboCharger is shown on Fig. GR5B. Turbocharging background is given in Note 89.

Fig. GR5B
Section of a typical TurboCharger.
Single-stage radial inflow exhaust-driven turbine
driving directly a single-stage centrifugal compressor.
(This TC is probably a Garrett unit developed for the BMW M12/13 of 1985
since the exhaust inlet volute is bifurcated to suit flow from
the 2-into-1 tuned manifolds of a 4-cylinder engine.
DASO 569



Being a steady-flow machine a given flow could be provided with much less weight of compressor than a Roots blower. The single-stage pressure rise could be up to double the Roots practical limit with a similar efficiency. However, as the rise was proportional to $(\text{speed})^2$ the TurboCharger had to be "over-sized" with an exhaust-overboard waste-gate opening at a preset boost pressure to lop off the top of the curve and produce a usefully-flat pressure v. engine RPM characteristic for road-racing.

The power input to the TurboCharger was *not* "free" since the engine exhaust back-pressure had to rise *but* this was more than offset by the inlet charge pressure into the cylinders (until the pressure ratio approached 4). This "pneumatic-power-coupling" was additional to the basic power gain from the higher charge density.

All CoY TC were made by specialist firms already producing them commercially, in particular for HGV, egs. Kuhnle-Kopp-Kausch (KKK); Ishikawajima-Harima Heavy Indutries (IHI).

Compulsory use of petrol fuel by that date required an intercooler (all air-to-air type in CoY) before the charge entered the cylinders, so as to permit a reasonably high compression ratio (7 to 8) without knocking.

6. Air Filters

Up to 1989 racing engines had, at most, only coarse wire mesh grilles over their air inlets to keep out stones or accidentally-dropped nuts and such like. The growing use of gravel traps to slow off-course cars led to much finer dust particles being ingested, either through such an occurrence directly or indirectly from the on-track debris from someone else's incident. This gradually damaged the valve seats and caused a loss of power during a race.

While paper or cotton-gauze filters could have been fitted to prevent dust ingestion these had a limited capability to absorb dust before clogging caused an unacceptable pressure drop and power loss so they were not used.

In 1989 a superior air filter became available using polyurethane foam impregnated with a dust-retaining fluid which greatly increased dust-absorbing capacity before the pressure drop became unacceptable (282). It then became standard practice for all the new 3.5L NA GP engines to fit such filters at the exit from the equally-standard cool-air-plus ram-intakes.

Exhaust Systems

GP engines have taken advantage from the beginning of being unsilenced by using free-flowing exhausts but not until 1952 in CoY was there enough knowledge of – or interest in – the application of tuned systems to harness deliberately otherwise-wasted energy to extract the gases and induce extra charge. This process then became standard (see also Note 83

The shapes of the pipework to provide equal lengths from each cylinder within the limited space from a mid-mounted engine are wonderful to behold! See Figs. GR7A & GR7B.

Fig. GR7A

1963 Coventry Climax Mk. 3/Lotus type 25 exhaust system

In this installation the optimum tuning of the system with a V8 crank having a "1932 Ford 90^0

2-plane crank involved connecting pipes from opposite banks of the engine.

Note low-taper final megaphones.

This illustration also shows the post-1958 "Standard GP suspension"

of "Double transverse links at each corner" (see also Note 66).

Colin Chapman, Lotus design genius, is examining a plug.

DASO 958 p.222

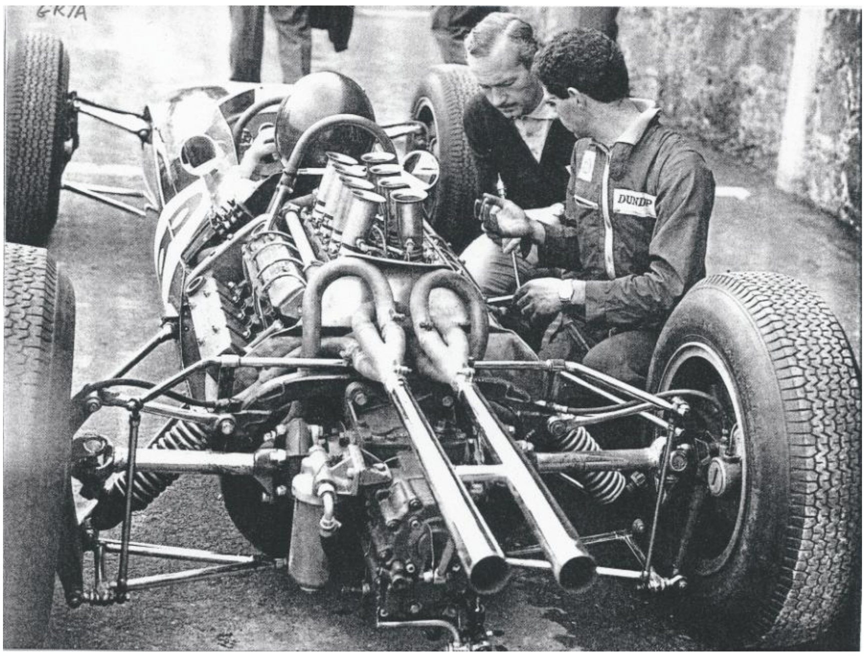


Fig. GR7B

1998 Ferrari 047 exhaust system

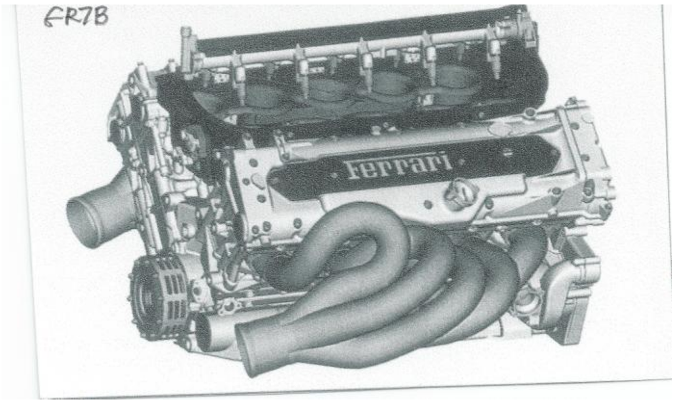
This illustrates the typical pipe bending job needed for a mid-mounted V10 engine.

At the 5th race of 1998 the low-level exits were raised to give a high-level exit into a metal-lined trough in the top CFC bodywork (see also Eg. 85).

Note the fuel injection nozzles mounted well above the inlet trumpets.

The 3-plate carbon-carbon small-diameter clutch is also well shown.

DASO 578 p.40



9. Lubrication System

Lubrication systems have had to cope with crank speeds rising from 1,200 to 18,000 RPM in the review period, with all that means in potential overheating, frothing and splash-drag problems. Simultaneously they have had to cope with increases in axial and lateral car accelerations as road grip increased because of better road surfaces, "stickier" tyres and aero downforce (see Note 30). The maxima for 'g' were perhaps ½ initially, 1 by the mid-'50s, 2 by the late –'70s and 4 in the early-'80s (730, falling back to around 3 in 1998 under formula rules introduced for that purpose but up to 4 again by 2000 (987, 988)*.The problem that this sets a fluid system is illustrated by the fact that a free surface under 4g axiallyor laterally would have an angle to the horizontal of $TAN^{-1}(4) = 76^0$!

Pressure lubrication, pioneered for touring engines by Frederick Lanchester in 1905, was available at the start of the review period with oil still carried in the sump but, in practice the 1906 Renault and 1908 Mercedes (and probably the 1907 FIAT also) used simple gravity + splash systems (621).

Peugeot introduced the so-called "dry sump", i.e. a separate oil reservoir, in 1913 (Eg. 5), which both cooled the oil and prevented surging in the crankcase.

Separate oil-coolers appeared on Auto Unions in 1936.

As RPM rose, really extensive scavenging was introduced in the Cosworth DFV in 1967 (1968 CoY).

In 1980 the conventional air-air oil cooler was being replaced by water-oil heat exchangers in the main cooling system, using an enlarged main radiator which still gave less drag and was lighter than the dual system.

By 1992 Honda were evacuating the crankcase to 0.3 ATA to gain a net 2.8% of power (69).

Apart from its basic function of preventing metal-to metal contact, oil has been used to cool valve springs and also the underside of piston crowns. Serendipitously this latter cooling was originally by spray from the bearings but, from about the mid-'70s, was by specific jets in the crankcase.

The lubricant itself has been improved steadily, the big changes being from castor-base (i.e. vegetable) to mineral post-WW2 (but see Note 31) and then to synthetic from 1981.

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*Of course, the fuel system had to cope with the same accelerations.

10. Stressing Conditions

Grand Prix engines in 2000 had to race for only 20 to 40% of the distances required in 1906 – 1914 and for only 13 to 18% of the time required in 1931. By 2000 engines were being designed for only 400 km racing life and for Qualification with a different specification they were required to last for only 4 laps flat-out (with time to cool in between). This contrasts with earlier Grand Prix cars which, until "monoposto" bodies were adopted in 1932, were driven to and from the races. They might have needed a top overhaul before the return journey, eg. the 1923 Sunbeams which were 1st, 2nd and 4th in the French GP finished with badly burnt exhaust valves (294, 756) (see Note 32).

However, because of the advances in road grip mentioned earlier, the Load Factor (LF = Average Power/Peak power) was substantially higher. Ricardo showed in 1922 that the 3L engine he designed for Vauxhall was operating at LF = 40% over the fairly twisty, hilly and loose-surfaced Isle of Man TT circuit (242). This would probably be typical of other venues up to the middle '20s, after which hard-surfacing began on the ordinary roads from which most circuits were formed. By 1988, ref. (20) shows that the LF of the 1.5L TC Honda at Imola (Eg. 71) was about 64%. A similar average figure was deduced for the 1993 3.5L Renault (Eg. 76) from ref. (574). On a circuit with long straights such as Monza the LF might reach 76% (574).

[Post the review period: revised Stressing Conditions.
The FIA addressed this subject with a series of required life changes post-2000, as follows:-

- 2003. Race engine to be used for both Qualification and the race; life required 500 km;
- 2004. Race engine to be used for whole race weekend; life required 800 km;
- 2005. Race engine to be used for two race weekends; life required 1,600 km;
- 2007. Red Line RPM to be a maximum of 19,000 (the 2006 Cosworth CA/6 2.4L 90V8 engine was reaching 20,000 RPM. With the Bore limited to a maximum of 98 mm by the formula this put Stroke at 39.77 mm (1107)* so that MPS = 26.5 m/s. The limit of 19,000 represented 25.2 m/s. With Stress proportional to $(MPS)^2$ this was a reduction of 10% of stress). Engines were to remain at pre-season standard;
- 2009. Maximum of 8 engines per driver for the season; life required 2,000 km for 17 races;

    Red Line RPM to be a maximum of 18,000. With the same engines as in 2006 by rule, this was MPS = 23.9 m/s and a further reduction of 10% in stress relative to 2007 as a contribution towards the life increase required;
- To apply in 2014 with 90V6 1.6L TC engines, maximum Bore 80 mm which puts Stroke at 53 mm.

  Maximum of 5 engines per driver for the season; life required 4,000 km (assuming 20 races);

  Red Line RPM to be 15,000 so that MPS = 26.5 m/s;
- To apply in 2015. Maximum of 4 engines per driver for the season; life required 5,000 km.]

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*DASO 1107: *Race Engine Technology* No. 073; Sept./Oct. 2013.

11. Materials

Exhaust valves were particularly critical items in the early days and the development of materials for these parts (and their internal cooling) is described in detail in Note 17. It is sufficient to note here that Austenitic steel and Mercury/Sodium cooling were available from the mid-'20s to solve the exhaust problem.

Cast-iron or steel pistons were used until 1914 in Grand Prix CoY engines and Al-alloys subsequently in the rest of the review period, with two *exceptions*. The exceptions were the 1998 and 1999 Ilmor engines which introduced pistons in a 62% Beryllium+ 38% Aluminium alloy (Egs. 82 & 83). Both the Al- and Be- alloys had been developed originally for military purposes. After 2000 the Be-alloy was banned by the FIA on cost grounds.

The subject of piston materials is discussed at length in Note 14 (remarking that the supposition therein that the Be-alloy was "Lockalloy" was confirmed after that Note was written).

Until 1932 static structure for cylinder blocks and heads was either cast-iron or steel fabrication (the welded-up steel structure – more expensive but lighter than cast-iron – was pioneered for CoY by Mercedes in 1914 (Eg. 6 and see Note 28). Cast Al-alloy was used for crankcases from the beginning of this review, having been used 1st for that purpose by the 1897 Panhard-Levassor.

In 1932 cast Al-alloy was extended to block and integral head by Alfa Romeo for their type B (or "P3") (Eg. 18), fitted with dry steel liners. Compared with cast-iron this solution was lighter and gave better head cooling but was again more expensive. The specific alloy used is not known but it may be relevant that Rolls-Royce had developed in 1929 their low-expansion RR50 material to solve static structural problems in their R-type Schneider Trophy-winning racing engine. This became widely used, supplied by High Duty Alloys. The %age composition was:-

Cu 1.1; Si 2.4; Fe 1; Ni 0.9; Mg 0.13; Al 94.47.

All Al-alloy basic structure with ferrous cylinder liners became fairly general post-1932, *except* that:-

- Mercedes-Benz retained successfully their fabricated-steel upperworks until 1955 (but their equally-successful Sports-Racing engine of that year had an Al-alloy block-cum-integral-head and bores Chromium-plated by Mahle (468);
- An Mg-alloy crankcase was tried by Mercedes-Benz in 1955 but was found to creep (i.e. stretch when exposed to a steady load *below* its elastic limit) and lose dimensional accuracy (468). Cosworth tried the same material for their combined crankcase and block in 1971 but poor casting quality and dimensional control with the greater expansion coefficient were problems which again forced abandonment;
- Some late-period engines (Eg. 1979 Cosworth DFV) used Al-alloy cylinder liners to save weight and reduce piston temperature by better heat transfer. These had Mahle Nickel-Silicon ("Nikasil") surface treatment to provide an adequate rubbing surface (see Note 29).
- The 1983 BMW TC engine (Eg. 64) used an iron cylinder block designed and manufactured originally for their production cars – actual ex-road-service high-mileage blocks were preferred since all residual casting stresses had been relieved (741);
- The Honda TC engines of 1986 – 1988 used a ductile iron cylinder block, casting technology having improved so that minimum thicknesses of 2 to 3.5 mm were possible (20). However, Al-alloy Nikasil-finished wet cylinder liners were still fitted (62);
- In 1998 Ilmor fitted liners of the same Be-Al-alloy as their pistons to reduce weight still further, the thinner liners permitting closer bore spacing

12. Weight and Centre of Gravity

Engine weight has generally been secondary to competitive power because total car weight rises less rapidly than installed power, i.e. the (Power/Weight) ratio of the vehicle rises with Power (see Note 8). Obviously, weight is secondary to reliability. Over 1938 – 1939 and after 1960 and onwards there have been *minimum weight* rules for safety's sake, to prevent flimsy construction, and this might be thought to ease pressure to reduce engine weight. However, over the last few years to 2000 it was possible to build cars *under* the regulation minimum (which was 605 kg including the driver, coolant and oil but without fuel; this figure including a 5 kg allowance for a TV camera to improve the "circus" spectacle). The surplus weight to the minimum was then made up with ballast (once banned but now permitted since there are many other safety-of-construction requirements including crash tests). This ballast was placed as low as possible to bring down the Centre-of-Gravity and so improve cornering and braking performance. Engine makers have been subjected to extra pressure to reduce weight for this useful-ballast reason and they made substantial decreases from 1996 onward. The effect on engine Power/Weight ratio is shown on Fig. O3 of the Overview section.

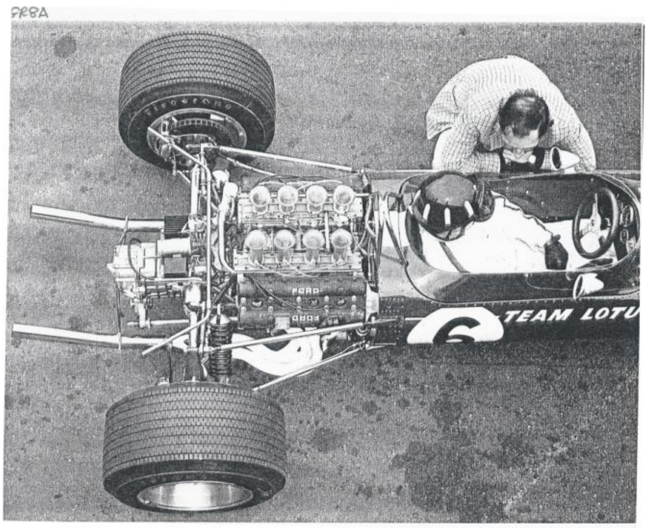
13. Engine and Chassis Integration

Up to WW2 engines, according to their designers' preference, were either mounted at 3 points on trunnions in order to prevent single-plane chassis flexure from twisting the crankcase (egs. Henri Peugeots; Delage; Mercedes-Benz); or, at 4 points so as to stiffen the frame in torsion (egs. especially Bugattis; later Alfa Romeos). After WW2 the stiffening option was general.

The 1st CoY space-frame, the Mercedes-Benz W196 of 1954, used the IL8 engine also as a stiffener. In 1956 the Ferrari-Lancia D50 CoY used the original Jano design of space frame in which the V8 engine had substituted for some tubes to save weight but with these tubes replaced, bolted-in – whether necessary or simply through Ferrari conservatism is not known.

The 1st CoY design in which the chassis weight was minimised by making the engine the *only* structural connection between front and rear of the car was the Cosworth V8 DFV in the Lotus 49 in 1968 (1st raced June 1967) (see GR8A and also "The Unique Cosworth Story").

Fig. GR8A
1967 Lotus 49/ Ford Cosworth DFV
Engine & chassis Integration
This illustrates how the engine formed the only structural connection
between front and back of the car.
The top mounting plate from each engine bank was designed to be flexible
so as to allow for thermal expansion.
Graham Hill in the cockpit.
DASO 958



The unsuccessful 1966 BRM Flat-H16 had pioneered this chassis integration. The BRM engine had been bought by Lotus in that year and fitted in their type 43 with the same principle and Jimmy Clark gave the unit its sole success.

Colin Chapman and Keith Duckworth then adopted the concept for the 1967 type 49/DFV, as described.

Eventually it became the standard method of construction. The Double-Bank Vee engine is ideal for the purpose since it permits widely-based load pick-up points while providing high beam and torsional stiffness for very little extra engine weight.

With the introduction of under-body venturis to increase road grip by ground-effect from 1977 onwards (Lotus type 78), all engine makers have been obliged *eventually* to choose Vee configurations. Temporary *exceptions* were Ferrari's F12 which was CoY in 1979 with the aid of Michelin radial-ply tyres – their F12 results collapsed completely in 1980; and the vertical IL4 TC BMW in a Brabham chassis which was Drivers' CoY in 1983 with the aid of Toluene-base fuel – the Constructors' Champion CoY in that year was the 120^0 V6 TC Ferrari.

It was also necessary to package accessories such as oil pressure and scavenge pumps alongside the crankcase, so that the exit diffuser shape was not spoiled.

14. Clutches

The essential connection between engine and gearbox until about 1967 consisted of a substantial flywheel and a large diameter clutch. In early cars the clutch was often cone-type as in the 1906 Renault, leather-lined, or multi-steel-plate.

Mercedes-Benz introduced a single-plate design in 1934. The 1939 Mercedes M163, with about 500 HP, had a single driven plate of 287 mm diameter (30). This *could* fail on starting, e.g. Dick Seaman's in the Eifelrenn of that year (775). The Mercedes M196 of 1954 – 1955, developed towards 300 HP, had a clutch of similar design with a single 232 mm plate (468, 30).

The 1967 Cosworth DFV for 400 HP had a new AP clutch with a Cosworth-designed 2-plate 7¼'' (184 mm) driven unit, weighing 4.15 kg (attached to a 2 kg flywheel). The friction material was bronze-based and sintered onto the steel driven plates (21).

This clutch type, with some strengthening and a small weight increase, remained the GP standard until 1987, even when coupled to TC engines of 1,200 HP.

In 1987 Tilton Engineering provided Lotus with a 5½'' (140 mm) 3-plate clutch with carbon-fibre-reinforced-carbon driving and driven plates, following the example of carbon-carbon racing brakes (developed from aero units) but using a novel lug drive. This design reduced weight and inertia compared to the still-current 7¼'' clutch yet with higher heat capacity. It won its first race. The flywheel effectively disappeared in 1987.

This began a new era of smaller clutches, so that by 1997 the diameter was down to 4½'' (114 mm) for 750 HP (and to 3 plates of 97.5 mm (3.84'') by 2001 for 800+ HP and weighing only 1.2 kg (917)).

These diameter reductions were all aimed at lowering the engine crankshaft and hence engine Centre of Gravity to reduce weight transfer under lateral and longitudinal 'g' and so benefit cornering and braking. The reduced inertia also assisted acceleration but made it very easy to stall the engine when starting or even if the RPM were allowed to drop too low in a slow corner – as Mansell (Canada in 1991, on the last slow corner when leading) and Prost (on several occasions in 1993) found to their cost with Renault V10 engines (in each case it was their first season with the engine type). Revised electronic controls later overcame that problem (except that *setting*-up the idle RPM actually did lead to one crash at a pit-lane entry curve – Coulthard, Renault V10, Australian GP, 1995).

15. Gearboxes

Some comment is required on gearboxes since, unfortunately, they are essential to an internal combustion piston engine which produces torque only at substantial crank speed.

All CoY gearboxes have been of a limited number of discrete forward ratios (a reverse is also mandatory for safety reasons). The friction or viscous losses in any infinitely-variable system has been thought generally to outweigh the advantage of filling in the gaps between gears. A determined effort to develop a worthwhile system by Williams was outlawed by the FIA in August 1993 before it could be raced (see Note 33).

In principle, short of infinite variation, the more gear ratios the better since the engine can then be designed to give more power if the %age RPM range between Max. Power and Max. Torque is reduced. However – there is nearly always an "however!" – bearing losses, gear up-change time and weight are offsets.

Up to 1935 the usual CoY box had 4 forward speeds, the *exceptions* being 3 in the 1st GP winner of 1906 (Renault) and in 1921 (Duesenberg, Eg. 7) and 1923 (Sunbeam, Eg. 9), with 5 in the 1925 and 1927 Delages (Egs. 11 & 13). Their 5th gear was an "overdrive" to limit the use of high RPM.

A period of 4 or 5 speeds followed until the 5-speed became virtually standard after 1953 until 1985. The 5-speed-and-reverse box of the !955 Maserati 250F weighed 48.5 kg* which was 27% of the engine weight (1052). There were 6-speed exceptions in 1964 (Ferrari, Eg. 43) and in 1983 (BMW TC, Eg.64). Then 6 speeds were used generally but rising to 7 at the end of the review period. In 1997 such a box's average weight was about 60 kg* (567), roughly half of the weight of the engine at that date. The Ferrari's 7-speed box in 2000 weighed 45 kg*, 42% of the engine weight (Eg. 85) (987). By then Internals were only used for one race (999).

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*All rear-mounted and understood to include the differential and final-drive output stub-shafts.

A major improvement in CoY was the use of a semi-automatic servo-powered (hydraulic or pneumatic) gear-change (SAGB), pioneered by John Barnard for Ferrari in 1989. Amazingly enough, it won its 1st race! This SAGB was controlled electronically from finger-tip levers ("paddles") under the steering-wheel, replacing the previous chassis-mounted manual change lever. With this new change system came a linking to electronic engine management making the necessary adjustments to RPM and clutch position. Gear-change time then came down from about a manual 250 milliseconds (741) to a servo-powered 50 m.sec (567) to add improved acceleration to the benefit of better steering control because the driver did not need to remove a hand from the wheel.

All competitors had to follow suit with SAGB. When Mc Laren were developing their own 6-speed SAGB they estimated that it would save 0.7% from lap time at Suzuka (742).

By 1999 the change time was down to 30 m.sec (584).

[Beyond the review period the number of gears became rule-limited to 7, which will rise to 8 in 2014. Gearbox internals are also now required to last longer.]

16.Design and Development Quality

A few words on the above topic are relevant. It can be assumed that CoY engines, either by good design or by subsequent *ruthless* development, coped well with several degrading factors which can reduce to ruin very quickly an engine whose *average* stresses are comfortably inside the *average* material properties at *average* temperatures which would *in theory* secure a sufficient fatigue life. These factors are:-

- Stress concentrations;
- Hot spots;
- Resonances;
- Differential thermal expansions.

As Power/Weight ratio rose through the years the chance of getting the design "right first time" receded and the need for development increased if success was to be obtained. The word *ruthless* is emphasised because a fear of breaking the job has spoilt many promising designs. If there is insufficient money to do development *ruthlessly* and reiterate the Modification – Test cycle as many times as necessary to qualify the engine it is better not to begin the project in the first place!

Simple mistakes could also lose races, of course, and a sample of these through the years is included in Note 110.