The General Design of Racing Piston Engines

The basic formula for the power produced by a piston engine is:-

$$\mathbf{P \propto BMEP \times V \times N}$$

Where P = Power
BMEP = Brake Mean Effective Pressure
V = Swept Volume
N = Crank RPM

and the constant of the equation for an internal combustion engine depends on whether it is 4-stroke or 2-stroke (the latter constant is doubled) and on the system of units employed.

The highest power within the rules (including any fuel consumption limits), lasting just long enough to win, has been generally the first objective in racing engine design. Trade-offs involving Power versus Weight or "Driveability" (the % age spread of RPM between peak power and peak torque) have been of importance but secondary:- Weight because (at given technology) whole-car weight plus average load rises less rapidly than installed power (see Note 8); Driveability because ace drivers have always been well prepared to use their gearboxes and, since 1989, hands-on-wheel servo gearchanges on 6- or 7-speed gearboxes have been used (Note 9).
Cost perhaps mattered only in the lean GP periods 1928-1933. Noise (with the thrilling associated Doppler effect of passing-speed) is a by-product actually beneficial to the "circus" (although GP motor-cycles have been silenced by rule since 1976, probably because of the higher frequency of the by-then-dominant 2-strokes and its nuisance to circuit neighbours).

Certain limits apply to the elements of the basic power equation, apart from the chosen or regulated value of V:-

- **BMEP** is a function of:- **Fuel; Fuel/Air Ratio;**
  Manifold (Inlet Charge) Density Ratio (MDR);
  and **4 Efficiencies**
  Cycle (ASE); Volumetric (EV); Combustion (EC); Mechanical (EM).

Note 10 gives details of the basic expression for BMEP and shows that the value for all useable volatile liquid fuels is (near enough):-

BMEP = 38 x MDR x ASE x EV x EC x EM **Bar @ STP ambient conditions**

(STP = Standard Temperature and Pressure, is 15C and 1.013 Bar)(1Bar = 14.503 psi).
Note 10 also describes the influence of Fuel on Power and its development for racing.
Appendix 2 lists fuel mixtures which have been used over the review period.
The relation between racing fuels and the best commercial petrols (excluding features of the latter aimed at easier winter starting) can be summarised chronologically and broadly as follows:-

- Equal up to the end of 1924;
- Diverged completely between 1925 and 1957 inclusive; (racing used alcohol-base fuels);
- Equal to standard General Aviation petrol, 1958-60 inclusive;
- Equal to highest 1961 auto standard, 1961-mid 1983;
- Diverged again completely mid 1983 to mid 1992; (racing used toluene-base fuels up to 1988 inclusive);
- Again equal to highest 1961 auto standard, mid 1992 onward.

Manifold Density Ratio

The value of **MDR** for Pressure-Charged (PC) engines, given the Inlet Valve Pressure (IVP), depends on the efficiency of compression of the charging machine and any subsequent charge cooling by fuel evaporation or heat exchanger. The method of estimation of MDR is given in Note 10B.

RPM Limits

- **RPM** may be limited by **4 major factors**:

  (A):Naturally at a Peak Power determined by a complex inter-relation between "**Breathing, Burning and Turning**" (see Note 11);
  a study by the author relates this Peak Power speed to a geometrical Speed Correlation Factor (SCF) which is described in Note 12.

  (**B): Mechanically**:-

  I. At the "Bottom End" by factors of which the simplest is:-

  Mean Piston Speed (MPS) = 2 x Stroke (S) x N

  The maximum for this depends on the geometry and material properties of the piston. See Note 13 Part I and Note 14 for details.

  II. By **Piston-Ring Flutter**, which can cause ring failure and excessive blow-by leading to oil degradation and loss and bearing failure, related to:-

  Ring Axial Width (w) x Max. Piston Deceleration (MPD),

  the controlling value of this parameter depending on ring shape; position and material. See Note 13 Part II for details.

  III. At the "Top End" by the

  Mean Valve Speed (MVS) which, for the Inlet Valve (usually the heaviest)

  $$\propto \frac{\textbf{2 x Max. Valve Lift (IVL) x N}}{\textbf{Valve Open Duration (IOD)}}$$

  The maximum for this factor depends on the type of valve gear and its material properties.
  A surrogate for MVS where internal data are not available is

  Bore Speed (BN) = Bore (B) x RPM

  with a constant appropriate to the type of valve gear and its material. See Note 13 Part III and Note 15 for details.

In the first 30 years of Grand Prix manufacture mechanical limits were also imposed by:- **Sparking Plugs; Exhaust Valves** and **Bearings**. The effects of these and their development are reviewed in Notes 16, 17 and 18 respectively. Some other limits are listed in Note 19, including the long-term problem of "instantaneous" failure when overhead valves and pistons collide.

Rated Power

If a mechanical limit is reached before the natural power-peak RPM, the result is a "Rated Power" at a lower level. This is believed to have occurred often in the early days since, although very few power curves are available for pre-1935 Grand Prix engines*, the available curves for most WW1 aero-engines show this effect (399)**and so do most of those for Sunbeam racing engines of all types of the 1914-1925 period (24), as also do some of the Mercedes-Benz 1935-1938 curves (468). No precise reasons have been published for such Ratings but it must be assumed that tests had shown that to exceed the specified RPM would result in a shorter life than desired, because of one or more of the causes given above. Appendix 1 therefore contains Rated Powers although generally it is not known which they are.

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* The 1914 Mercedes is an exception, having been tested over the power peak (468).
** Rolls-Royce were also exceptional in testing their "Eagle and "Falcon" engines over the peak (399).

The basic power equation can be re-arranged as:-

$$\frac{P}{V} \propto \frac{(BMEP) \times (MPS)}{S}$$

With MPS limited at a particular date by design convention and available materials and with BMEP at the best attainable level at that date (taking into account any rule limits on inlet charge pressure or on fuel quality), then, **if V is limited by regulation** (the most popular rule after 1913:-

$$P \propto \frac{1}{S}$$

Volume-Specific Power (Power/Swept Volume) has therefore been sought in such conditions by either **increasing the number of cylinders** (CN) to reduce S, or by **raising B/S ratio** or by a combination of the two methods, up to the point where these approaches have a more-than-offsetting effect on power by reducing BMEP and/or MPS (see Note 20 for details of such a situation in Coventry Climax engines). Where BN is also limited by the valve-gear design and/or materials available at the date, then there is an optimum B/S ratio which maximises N at any given CN and hence maximises power for the configuration (see Note 21).

With the units employed in this review (but V here in Litres), for 4-strokes,:-

$$\frac{P}{V} = 33.5 \times \frac{BMEP\ (Bar) \times MPS\ (m/s)}{Smm} \qquad \text{HP/Litre}$$

(1 m/s. = 196.85 ft/min)

Alternatively the expression can be written, using the basic BMEP equation, as:-

$$\frac{P}{V} = \frac{MDR \times N \times ASE \times EV \times EC \times EM}{23.55} \qquad \text{HP/Litre @ STP}$$

Internal Performance Analysis

It is suggested that, from start to finish of the period covered here, the following analyses applied to Grand Prix engines (the Ricardo 3 Litre Vauxhall TT unit has been included for comparison as a known fully-tested design (242) which confirms the power equation):-

TABLE 2

			NA, Petrol, at STP		
DATE	**1906**		**2000**		**1922**
MAKE	**Renault**		**Ferrari**	**2000/1906**	**Vauxhall**
TYPE	**AK (Eg 1)**		**049 (Eg 85)**		**Ricardo TT (SO8)**
MDR	**1**		**1**		**1**
V cc	**12,986**		**2,997**	**x 0.23**	**2,996**
NP RPM	**1,200**		**17,500**	**x 14.6**	**4,500**
R	**4**		**12**	**x 3**	**5.8**
ASE	**0.43**		**0.63**	**x 1.47**	**0.505**
		Suggested			
EV	***0.65***	***See Note 25***	***1.31***	***x 2.01***	**0.81**
EC	***0.6***	***."***	***0.7***	***x 1.17***	**0.69**
EM	***0.81***	***See Note 99***	***0.62***	***x 0.76***	**0.78**
PP HP	**90**		**795**	**x 8.83**	**126**

Further details are given in APPENDIX 1

The following sections will try to show the major steps by which these power-producing elements were improved from 1906 to 2000 or, in the case of EM, prevented from too great a deterioration due to the increase in RPM and associated piston speed, together with the ways in which MDR was raised above unity during two eras of racing.