Grand Prix Motorcycle Engine Development, 1949 – 2008

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The Federation Internationale de Motocyclisme (FIM) inaugurated a Riders' World Championship in 1949. There was also a Manufacturers' Championship which usually, but not always, went to the marque which mounted the champion rider. These covered several engine swept volume classes, the premier being 500cc as it had been in prior years after 1911 (when it was adopted for the Senior British Tourist Trophy (TT)), except that only Naturally Aspirated (NA) engines were now allowed. Before WW2 pressure charging was permitted.

Ref. 1 gives details of the 500cc machines ridden by the Champions in each of the 53 years until the premier class size was nearly doubled to 990cc *for 4-strokes only* in 2002 and relabelled " MotoGP ". This change to 4-strokes after 27 years of 2-strokes was to demonstrate a " greener " aspect by reducing emissions and improving fuel efficiency. A further 7 years is covered by the ref. source to carry its data to the end of 2008, MotoGP size having been reduced to 800cc in 2007 (it was increased again in 2012 to 1,000cc).This source of data for the "Bike of the Year" has been used to produce the analyses of the engines over the 60 years which are described in this review. Some MotoGP figures have been estimated by the ref. author and attention will be drawn to that in its place but the *trend* from an experienced observer is probably reasonably reliable. Most readers will understand that power data for racing engines is not given on oath! Another factor to be considered is that some powers were quoted at the crank and others at the rear chain wheel after gear and chain losses, without the difference being made clear in the sources.

The smaller classes were as hotly contested as the 500cc/MotoGP class, sometimes more so, and reference is made to these where necessary to describe technical advances.

Included in this period were the achievements of 2-stroke designers in driving the 4-stroke out of the competition in all classes, starting with the smaller engines, and then reaching their "Promised Land" of Brake Mean Effective Pressure (BMEP) equal to the best contemporary 4-strokes in other racing arenas, so that Power/Swept Volume was twice as great. Only the x2 size rule change for premier class 4-strokes in 2002 allowed them back into motorcycle racing.

The really outstanding feature of these 60 years of racing motorcycles has been the more-than-fourfold increase in power – from 50HP to more than 200HP – transmitted to the road by a single tyre with no addition of aero downforce, unlike Grand Prix cars. Tyre development to more than double the coefficient of friction, with doubled sections and slick treads plus electronic wheel-spin control, has permitted that result.

The 60 years of this review can be understood best by dividing them into 4 eras:-

1st, 13 years 1949-1961: 4-strokes supreme;
2nd, 13 years 1962-1974: 2-strokes overtaking 4-strokes, class-by-class;
3rd, 27 years 1975-2001: 2-strokes supreme;
4th, 7 years 2002-2008: MotoGP 4-strokes.

Power and performance factors over 1949 – 2008

Fig. 1 plots the **Maximum HP versus year** for the Grand Prix "Bike-of-the-Year" (BoY) from ref.1. The key identifies whether the engine was 4- or 2-stroke. Until the end of 2001 the Swept Volume was 500cc; for 2002 – 2006 it was 990cc; from then it was 800cc. [see P.22].

Fig.2 shows how **RPM** have increased in the 60 years. [see P.22].

Fig. 3 gives **Brake Mean Effective Pressure (BMEP).** [see P.23].

Fig.4 gives **Mean Piston Speed (MPS).** [see P.23].

Fig.5 illustrates **Power (P)/Swept Volume (V)** ratio. [see P.24].

The details for each year are published as Appendix 4 of http://www.grandprixengines.co.uk

Illustrations

An Appendix of illustrations has been added (10 Feb. 2014), pages A1 to A11.
Marginal notes in this text give the locations of relevant pictures in the Appendix.

The basis of piston engine power

A few notes on how piston engine power is produced will help to explain how the "Bike-of-the-Year" (BoY) engines were developed.

In a piston engine where the Swept Volume (V) is regulated, as it always has been in motorcycle racing, the designer has to address the optimum ratio of Power (P)/ V which is given by the formula:-

$$\left(\frac{P}{V}\right)\left(\frac{\text{BHP}}{\text{Litre}}\right) = C \times \frac{[\text{BMEP (Bar)} \times \text{Mean Piston Speed (MPS) (m/s)}]}{\text{Stroke (mm)}}$$

[1 Bar = 14.5psi; 1 m/s = 197ft/min.]

For a 4-stroke the value of C = 33.5; for a 2-stroke C = 67.

When pressure-charging is allowed, depending on any rule limits and the fuel permitted, BMEP can be variable according to the inlet charge density and the net power required to produce it.

For NA engines when the fuel has been specified , *at a given level of technology regarding efficiencies*, the BMEP is fixed. For 4-strokes there was some gain in efficiencies over the period of the review. BMEP increased from 11 Bar to 12½ by 1974 after the Keith Duckworth innovations and again to around 13 in 2005 during the MotoGP period. For 2-strokes the caveat about efficiencies is very important. A crankshaft-mounted disc valve to extend the crankcase filling period was introduced by Walter Kaaden of MZ in East Germany in 1953. In 1959 Kaaden discovered the value of a 3rd transfer port fed through a piston "window". When copied by Suzuki for their 1962 125 single the power gain from their 1961 twin was 60% (ref. 2). This was followed by intensive development of highly "tuned" exhaust systems to improve Volumetric Efficiency. Water-cooling was introduced over 1964 – 1965 to increase reliability and to reduce the power drop-off as parts heated up, e.g. in the 125cc Yamaha an aircooled loss of 12% after 4 minutes running was cut to half by watercooling (ref. 3). This all meant that BMEP increased at a very rapid rate, rising from about 5 Bar in 1961 to 9 by 1976 and 14 in 1997.

A1-1
A1-2
A2-3

The MPS is determined mainly by the **√**[Stress/Density] of the materials available at a date for the reciprocating parts, especially the piston, although redesign of that part for 4-strokes to reduce its mass substantially for a given bore and so raise MPS has occurred over the time period. This happened as valve arrangements moved from wide angle 2-valves per cylinder with "humped" crowns to narrow angle 4-valves with flat tops. For those interested in the theory of mechanical limits in piston engine design there are analyses in the website "grandprixengines.co.uk". A significant difference in piston material as developed for 2-strokes, with their higher heat loading per HP and need to reduce expansion so as to keep close clearances to control port events, was a silicon content around 20% of the Al-alloy (ref. 20). For 4-strokes piston alloys contained only a small amount of silicon (e.g. the widely-used RR58 had only 0.2% Si).

This leaves Stroke as the major variable in increasing P/V *at a given date*. This needs to be considered separately for 4-strokes and 2-strokes.

4-strokes

Stroke has been reduced over the years in 4-strokes by increasing the Bore (B)/ Stroke (S) ratio at a given number of cylinders, or by increasing the number of cylinders at a given B/S ratio, or by a combination of the two methods. Increasing the B/S ratio requires design and material improvements in the valve gear so as to raise the Mean Valve Speed limit, which have been forthcoming as will be described in considering the BoY history.

As an example of 4-stroke practice conforming to theory, it is interesting to consider the development by Joe Craig of the highly-successful Norton single cylinder 500cc engine from its first redesign in 1930. Originally S was 100mm (B/S = 79mm/100 = 0.79). This was reduced gradually until it reached 78.5mm in 1954, at the end of full works participation in International racing (90/78.5 = 1.146), a "reciprocal S" increase of 27%. After further experiments by Doug Hele, in 1958 a stroke of 73.5mm was tried (93/73.5 = 1.265), 1/S change from original increased to 36%, and this machine was ridden to win the Swedish TT of that year. The original single overhead camshaft valve gear was changed in 1938 to double and with the short stroke in 1959 mechanical closing of the valves ("desmodromic" gear) was tried. On the other tack, secretly Norton in the early 50s had BRM design them a 4-cylinder transverse watercooled engine with a stroke of 54mm (54/54 =1). A 125cc portion was tested extensively but Norton finances did not permit full development.

After a long run of Norton successes in the 30s (which would be added to especially in the TT 1947 -1954), their major rivals preferred to take the multi-cylinder route to shorter strokes, both before WW2 when BMW and Gilera also adopted mechanical supercharging and post-War when NA was prescribed. The Championship results from 1949 show that this approach was much more successful although also much more costly since cost is certainly highly related to number of cylinders. The ultimate design in the 500cc class for shorter stroke (until Honda designed an "oval" cylinder engine in 1979, to be described later) was the 90^0V8-cylinder water-cooled Moto Guzzi of 1956 at 41mm (B/S = 44/41 = 1.073). This did not win Championship honours while being developed to an output of 160HP/L (ref. 4) and its cost was undoubtedly a major factor in Moto Guzzi's withdrawal from racing at the end of 1957, together with Gilera whose 4-cylinder engine (by then 52/58.8 = 0.884) was near the end of its development. Before they took this decision, MV Agusta had prepared a reply as a 6-cylinder transverse engine of 46mm stroke (48/46 = 1.043)(ref. 12) but, while the firm continued to race, they set aside this expensive solution as no longer required and retained their 4-cylinder (by then 52/58 = 0.897) machine. As an example of later short stroke in the 125 class, the Honda 5-cylinder of 1966 was 25.1mm (B/S = 35.5/25.1 = 1.41) and gave 263HP/L. The power of 33HP was about the same as the Norton of 1930 with 4 times the capacity.

When Honda in 1967 was believed to be planning engines with more cylinders in all classes, the FIM intervened. Rules were made, to be effective in 1970, that cylinder numbers would be limited to one for the 50cc class, two for 125s and 250s and four for 350s and 500s. This rule remained until the MotoGP introduction in 2002, when a rising rate of number of cylinders (up to 6) versus minimum motorcycle weight was set.

In 1970 the number of gears was also limited to 6 to enforce a wider power range.

In the MotoGP era of 4-strokes the effect of increasing B/S ratio came into play again in " Bikes-of-the-Year " as better valve gear was available:- firstly, titanium-alloy for all 4 valves per cylinder permitted B/S = 1.6 for Honda in 2002; next, for Ducati in 2007 with desmodromic gear ref. 1 believes that B/S = nearly 2.2; then, in 2008 for Yamaha with a Pneumatic Valve Return System (PVRS) ref.1 also estimates the same B/S as Ducati. These last two engines, both 4-cylinders, are thought to have had a Stroke around 38mm (works figures are not available), near to the lowest figure for the premier class of 36mm in the 1979 Honda "oval" piston NR500.

Going beyond the review period, when the MotoGP rules were changed in 2012 to 1,000cc and 4-cylinders a restriction was placed on Bore at 81mm maximum so that the corresponding S had to be 48.5mm and B/S = 1.67.

<u>2-strokes</u>

In 2-strokes it turns out that variation of B/S ratio far from 1 is not a fruitful development. This is thought to be associated with the required cross-flow in the cylinder. The successful 1912 -1913 2-cylinder Scotts had B/S = 1.11. When Yamaha and Suzuki were contesting the smaller classes with 2-strokes over 1961 – 1968 their winning machines had B/S ratios in the range 1 to 1.12. Yamaha had a useful comparison in 1973 between a 250 twin at B/S = 1 and a 350 derived from the smaller engine by increasing the bore to 64mm from 54 mm so that B/S rose to 1.185 – this had a 7½ % lower BMEP. They retained 1 to 1.1 for their early 500s, as did every other of the dominant 500cc 2-strokes in the 27 years from 1976 to 2001, except a Honda 3-cylinder engine in 1983 at 1.16. It is probably significant that the last eight 2-stroke Champions up to 2001 were all at B/S =1.

While the number of cylinders was free the gain in P/V from smaller strokes from larger number of cylinders was not neglected. The 1968 Yamaha 125 was 4-cylinders with S = 32.4mm, producing 353HP/Litre; Suzuki even built in 1967 an experimental 3-cylinder 50cc with S = 26.5mm which gave the still record value of 404HP/Litre. After the FIM stopped this cylinder multiplication in 1970 all the Championship 2-strokes in the premier class were 4-cylinders, with the exception of the 1983 Honda.

<u>Other considerations</u>

Apart from power the RPM range over which useful torque is available is important– which in the case of highly "tuned" 2-strokes was very little indeed, although this did not actually hamper their initial success against 4-strokes. Weight and bulk of the engine have also to be considered, of course, particularly for a motorcycle where engine weight is a large proportion of the machine total weight and where it has to be swung rapidly about the cycle axis. Two-stroke engines gained on these factors, particularly in not having the top hamper of valve gear, but offset in installation weight by water radiators – 4-strokes did not need watercooling in the years to 1975. Drag and banking angle also affect the choice of configuration. Tyre coefficient of friction was less than 1 in 1949 so that the maximum banking angle was under 45^0. By the end of the period under review this coefficient was about 2, "worth" 63^0 which was used to allow a machine banking angle of about 55^0 with the centre of gravity shifted further into the corner by the rider hanging well off the machine on the inside, which was possible on *modern* circuits with only low kerbs defining the track.

Lastly, but by no means least, cost may be decisive and in that factor 2-strokes had a big advantage in greatly reduced number of parts.

Having discussed these basic points, this review describes briefly the pre-1949 motorcycle racing scene.

<u>Motorcycle racing in the pre-1949 Championship era</u>

From 1907 until 1938 the major International racing motorcycle event was the British Tourist Trophy (TT) held in the Isle of Man. The Senior TT 500cc winner of that race, held since 1911 on the 37¾ miles circuit over the 1,400 feet high Snaefell sector and since 1926 over 7 laps totalling 264 miles, was undoubtedly the "Bike-of-the-Year". Various Continental Grands Prix were important but they were held on less demanding courses over shorter distances. In 1938 the first season-long 7 race European Championship was inaugurated, a forerunner of the 1949 calendar, and this was the equal of the TT in prestige.

After consecutive wins by 2-cylinder 2-stroke Scotts in 1912 -1913, but with 2 exceptions, the TT up to 1939 was won by British NA 1-cylinder aircooled 4-strokes – the "classic" configuration. The 1923 exception was a 2-cylinder "fore & aft" Douglas. From 1931 to 1938 excluding 1935, the Senior TT winner was mounted on a Norton. The 1935 exception was a 120^{0}V2-cylinder Moto Guzzi (68/68 = 1) which beat a "classic" Norton by 4 seconds. Its swinging-arm rear suspension, compared to the rigid-rear-framed British machine, was probably a major contributor to that victory over the far from smooth TT circuit.

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A2-5

By 1937 BMW had developed their "trade mark" horizontally-opposed 2-cylinder aircooled engine (66/72 = 0.917) with a Zoller eccentric-vane supercharger to be a winner, although not then in the IoM. They mounted the European Champion in 1938. Their 1st TT win plus 2nd place came in 1939 – the only time that horizontal-opposed cylinders and shaft drive have figured in solo BoY. All other Championship motorcycles have had chain final drive.

Meanwhile Gilera had taken over the CNA transverse 4-cylinder water-cooled Roots-supercharged motorcycle (52/58 = 0.897) and, after development and many tussles with BMW in 1938 and 1939, became the European Champion's mount in the latter year.

A3-8

Power outputs rose steadily in the years to 1939. The Scotts probably had less than 20HP. The 1922 TT-winning Sunbeam claimed 29HP, the 1930 Rudge-Whitworth 34HP (ref.5), the 1935 Moto Guzzi over 44HP (ref. 6). The double overhead camshaft (82/94.3 = 0.87) Norton won in 1938 with 49HP (ref.7). This was the 1st NA engine to claim all-but-100HP/Litre. The 1939 BMW certainly had 55HP or more with a much flatter torque curve than the megaphone-exhausted Norton (ref. 8). The motorcycle was also 9% lighter (ref.9) by not having the heavy flywheels needed for a 1-cylinder engine but would have had more drag with its horizontally-opposed layout. Post-War, unsupercharged , it did not figure in solo championships but had a phenomenal run in sidecars where the frontal area did not matter and banking was not required.

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A3-7

The 1939 Gilera produced about 75HP (ref. 9).

Regarding fuels, which had a major effect on power, pre-WW1 petrol was rated retrospectively at about 50 Octane Number (ON). Alcohol fuel had appeared in 1921 and was permitted until 1925 after which a mixture of 50% petrol + 50% benzole was regulation, with an ON of 90, which permitted the 1938 Norton to use a compression ratio of 11.

<u>Post-WW2, pre-1949</u>

Post-WW2 German makers were excluded from International racing for several years. The FIM banned pressure-charging in late 1946 but before that applied the Gilera did appear in pre-War form to win the Swiss GP. Piero Remor, who had had a large hand in the pre-War engine, then recast it completely as NA and aircooled which appeared in 1948. Nortons returned practically unaltered except for compression ratio dropped to about 7 to run on government-regulated “Pool” petrol of 72 ON and they won the TT again in 1947 and 1948 with around 43HP for a limited period. They were joined in these years by another new engine, the AJS E90 “Porcupine”, of which more and the new Gilera, below.

Common features of engines in 1949 and onward

Before turning to year-by-year comments on the engines of the motorcycles ridden by the World Champion in each year 1949 -2008, the “Bike-of-the-Year (BoY), it will be helpful to summarise here some common features across the 60 years and 4 eras.

- All engines were Naturally Aspirated (NA) and spark ignition;
- Four-strokes won to 1974 inclusive, two-strokes from 1975 to 2001 inclusive, then, after their given x2 size advantage, 4-strokes won in 2002 and onward;
- To 1974 inclusive all engines were aircooled, afterwards all were watercooled. When comparing machine weights it should be remembered to add the weight of water to the usual quoted “dry” figure;
- All 4-stroke engines had valves operated by double overhead camshafts. Up to 1965 they had 2 valves per cylinder (v/c) at wide included angle (VIA: 100^0 to 60^0) then 4 v/c at wide VIA for 1966-1972, then narrow VIA (35^0 down to ,probably, around 20^0 in the MotoGP period). Titanium-alloy for all valves was available for 2002. Until 2006 inclusive valves were returned by steel springs, being coils in torsion except in the 1949 AJS and 1951 Norton using hairpins in bending. The Ducati which won in 2007 used mechanical valve closing (“desmodromic” system). In 2008 a Pneumatic Valve Return System (PVRS) was introduced to BoY by Yamaha. On valve timing, while published data are scarce, it can be stated confidently that the figures would be similar to those of the 1938 Norton:- inlet opens 60^0 before top Dead Centre (DC), closes 80^0 after bottom DC; exhaust opens 85^0 before bottom DC, closes 55^0 after top DC, so that the inlet open period = 320^0, exhaust open period = 320^0 and inlet/exhaust overlap = 115^0.
- All engines used carburetters up to 2001 inclusive, thereafter they had port fuel injection systems. All cylinders were fed individually via “tuned” inlet tracts (except for the 1950 Gilera which were paired from one carburetter).
- All cylinders had individual “tuned” exhausts. Except for Gileras over 1950 -1955 which had plain exhaust pipes, all engines had area-variation systems fitted up to 2001. These were divergent extractors (“ megaphones “) for 4-strokes, very elaborate divergent/convergent pipes in the case of 2-strokes which firstly extracted the exhaust and then sent a pressure pulse back to prevent loss of fresh charge. MotoGP engines from 2002 used plain pipes. Silencers were required by regulation after July 1976, but quoted powers probably exclude their losses.
- Petrol fuel was 72 Octane number (ON) until 1950 when 80 ON was available, followed by 100 ON by 1956. “Low-lead” petrol was mandated in 1993 and then “No-lead” in 1998.

1st era: 13 years 1949-1961: 4-strokes supreme

!949 – 1955: British and Italian competition

Winning mounts: 1949 AJS; 1950 Gilera; (winning marque: 1950 Norton); 1951 Norton; 1952- 1955 Gilera

The winning 1949 Champion, Les Graham, was mounted on the AJS E90 2-cylinder (B/S = 68/68.25 = 0.996) although this machine suffered from being intended for supercharging before the late 1946 ban on this system. That had led to its engine being laid down at 15^0 to the horizontal so that airflow would reach the hotter-than-NA cylinder head directly and when adapted to NA the carburettors were at the end of pipes turning through 80^{0}. It was not until 1952 that Moto Guzzi showed that a horizontal cylinder could be fed very efficiently with a straight highly-downdraught inlet tract, and AJS either did not think of this or the cost of a new head was too much in 1947. The exhausts also were somewhat cramped. However, the machine with 44HP (corrected from 50 in ref. 1) was good enough in its 3rd season of racing to beat the 1-cylinder Norton and 4-cylinder Gilera. It was the only post-War twin to mount a World Champion. A4-9

Gilera, in *their* 3rd season since their new engine's debut in 1948, was the 1950 winner with Umberto Masetti because of the failure of tyres twice on a new-Rex McCandless-designed "Featherbed" chassis Norton when Geoff Duke was leading. However, Norton won the Manufacturers' title. All engines were more powerful in 1950 because 80 Octane Number (ON) fuel was available to supersede the previous 72ON "Pool" petrol, although by lack of aromatic content this did not permit compression ratios to be as high as pre-War 50/50 petrol/benzole mixture. The transverse 4-cylinder engine of the Gilera (52/58 = 0.897, the same as the pre-War supercharged engine; the forward inclination was reduced from 45^{0} to 30^{0}) was no heavier than the 55 kg Norton unit (ref. 10) because it did not need the heavy flywheels of the single, so that both motorcycles weighed about 136 kg (ref. 1).

The following year Norton and Duke obtained, what would turn out to be, the "last hurrah" for a 1-cylinder engine in Championship racing, although this configuration (for 1951 at 84/90 = 0.933) with still more development would continue to win the very-arduous Isle of Man TTs until 1954. In 1951 they were on a different make of tyre! At 45HP (also corrected from ref. 1) they had 17% less power A4-10
than the rival Gilera, which had gained 2HP with 4 carburetters instead of 2 (ref.9), but this was A4-11
more than made up by the chassis and Duke's ability. In 1952 this was not enough as the Italian A5-12
engine produced another 6% more power and so Masetti regained the title.

With Gilera continuing to develop, and a 4-cylinder Norton only just being thought about, Duke moved over to the Italian company in 1953 and proceeded to bring them three Championships consecutively, including finally winning the Senior TT in 1955, missing the prestigious "ton" lap by 0.7 second!.He had lost the probability of winning the two previous TTs because of the Gilera's characteristics – in 1953 by being caught out on wet tar when leading through the engine's rapid acceleration on a premature throttle opening, unlike the Norton; and in 1954 by the heavier fuel consumption which required a fuel stop at the end of the 3rd lap in a wet race, again in the lead, A5-13
while the Norton carried on to the end of the 4th lap when the race was stopped with the British machine leading. By 1955 the British full-scale works competition had left the scene, AJS and Norton now being under one Company (AMC) which had adopted a policy after 1954 of developing only their production racing motorcycles. Gilera were before then much more concerned by the up-coming rivalry of another Italian company, MV Agusta, as will be described next, and had enlarged their engine in 1954 nearer to the full 500cc at 52/58.8 = 0.884 and 65HP. Although very little has ever been revealed on the internals, ref. 9 states that Franco Passoni (who had replaced Remor in 1950 as chief designer) had also increased the angle between the valves from 90^{0} to 100^{0}, presumably to fit larger valves (2 v/c).

Partial streamlining had appeared on the Gilera in 1954, with a "dustbin" over the front wheel, which had necessitated scoops to feed cooling air to the engine.

Part of Gilera's success was due to the advice from Duke on how to improve the cycle parts from his experience with the "Featherbed" Norton.

<u>1956-1957: Internecine Italian warfare</u>
<u>Winning mounts: 1956 MV Agusta; 1957 Gilera</u>

A little MV history is relevant at this point, since the marque became so significant in the following two decades. Count Domenico Agusta had diversified the family aeronautical business pre-WW2 by making small motorcycles and these were raced post-War (the company became licensees for Bell helicopter production in 1952 and this became their main business). At the end of 1949 the Count persuaded Piero Remor to leave Gilera and design for MV a 500cc machine. Not surprisingly when this appeared in 1950 it looked very like the 4-cylinder Gilera, except for B/S = 54/54 = 1 and shaft drive which latter was replaced by the otherwise "standard" chain drive after 2 seasons. Those were not very successful seasons but for 1952 Les Graham joined them. In MV's 3rd senior season he came close to winning that years' TT and then defeated Gilera in the Italian and Spanish Grands Prix. A possible improvement in 1953 was prevented tragically by Graham's fatal accident in the TT. The next two years were undistinguished, again affected by the death in his first race for MV in 1955 of Ray Amm, who had won for Norton the 1953 and 1954 TTs. Count Agusta then obtained the services of John Surtees. Aided by a 6-month racing ban on Duke in 1956 (for supporting a 1955 private owners' strike for better starting money) Surtees finally brought to MV a TT win and a World Championship. The engine was by then 52/58 = 0.897.

Gilera struck back in 1957 with an engine now giving 70HP @ 10,400RPM with megaphone exhausts at last adopted in 1956, a 46% improvement over 1949 which was 48HP @ 8,500RPM(ref. 9). These outputs represent respectively:- a BMEP of 12.05Bar @ a MPS of 20.38 m/s compared to 10.26Bar @ 16.43 m/s, a gain of 17.4% in pressure at 24% in speed or 54% in stress. Some of the power gain was from 80 ON fuel in 1950 and 100 ON by 1956 permitting higher compression ratios. The Gilera ratio was about 11 in 1957. Although Libero Liberati won the Championship, Bob McIntyre took the 8-lap Centennial TT with a lap at 101.1 mph.

Withdrawal of major Italian teams

At the end of 1957 Gilera, Moto Guzzi and Mondial (who had been very significant in the smaller classes), suddenly withdrew from racing. This was mainly because of the costs involved but in Giuseppe Gilera's case also affected by the death in late 1956 of his son, who had been managing the team. MV did not join this pact because to Count Agusta his racing was more a personally-financed hobby than a means of advertising his road products (ref. 11).

The withdrawal meant that the V8-cylinder Moto Guzzi and the transverse 6-cylinder MV were never developed fully to settle which was the better solution.

1958 rule change on streamlining

A major technical change in 1958 and onward by FIM rule was that enclosure of the front wheel was banned for safety reasons in cross-wind conditions. This led designers to use a "dolphin" type of front-end cowling.

1958-1965: 8 years with MV mostly unchallenged

The years 1958 to 1965 saw MV Agusta mostly unchallenged in the premier 500cc class from which the BoY are listed. Gilera. d*id* return in 1963 under Duke's management but only scored 3rd place in the Championship. A single Gilera also raced occasionally in 1964. The MV Champions, in order, were:- Surtees (3 times); Gary Hocking (once); and Mike Hailwood (4 times). With the lack of competition MV did little 500cc engine development. A5-14

1966-1967: Italy versus Japan

Winning rider's mounts:1966-1967 MV: 1966 Manufacturers' Championship Honda

In the years during which the big MVs were taking all the Championships, a very different situation was developing in the smaller classes which foreshadowed a major fight in the premier class. Over 1958-1960 MV made a clean sweep of the 125 and 250 classes using 1-cylinder and 2-cylinder machines, respectively, both derived from the 500 engine specification and in the 350 class they also won with a reduced-size 4-cylinder engine. From 1961, however, all these motorcycles were supplanted by machines from the other side of the world – the Japanese Hondas. Seeing Honda's success two more Japanese firms followed them to Europe and, in their turn, from 1962, these makes began to challenge Honda in the smaller classes.

The particular purpose of now describing the small class scene Is to illustrate how Honda built up their expertise and organisation there until they were ready to enter the 500cc class in 1966 and confront MV for premier honours.

Soicheiro Honda, having enlarged his post-WW2 piston-ring company to make small 4-stroke motorcycles, made a reconnaissance to the Isle of Man as early as 1954 to evaluate the racing which was still easily the most prestigious round of the World Championships. The upshot did not arrive until 1959 when a team of five 125cc machines was entered in that TT class. These Hondas were unusual in two ways (and completely upset the then-prevailing Western idea of the Japanese as mere copyists):-

1. they had 2-cylinder engines where no other Championship winner in the 125cc class up to 1959, including Mondial (4 Championships), MV (4) and NSU (2), had thought it worthwhile to use more than one (Gilera had raced a twin in 1956 but it only secured a single win);
2. the engines, despite their small bore of 44mm, had 4 valves per cylinder (4 v/c) at 84^0 between rows (VIA)(ref. 13), which had not been seen in motorcycle racing since the mid-30s. A 4 v/c engine has substantial theoretical advantages over 2 v/c with the same valve area:-

- The valve gear can be run at √2 higher speed for the same spring stress because of the lower individual valve mass;

- With the same seat widths the smaller exhaust valves run cooler than the larger.

At B/S = 44/41 = 1.073 and RPM limited by Mean Piston Speed appropriate to the materials of the time the valve speed advantage was not actually necessary but, at any rate, the engines were not going to suffer valve/piston clashes or valve overheating. The wide VIA, to get cooling air to the top of the head, coupled with the high compression to take advantage of 100 ON fuel, needed a high hump on the piston which hindered flame front development and which gave an "orange peel" combustion chamber with high surface area/volume ratio, both features which reduced Combustion Efficiency. Honda did do research to optimise this factor (ref. 14).

Miniaturisation of cylinder size, at B/S averaging about 1.1, in pursuit of higher HP/Litre (as explained previously) and 4 v/c at wide VIA became the "trademark" of Honda in the smallest classes for the next 9 years (excepting only their last 25cc cylinders at B/S = 1.414 and VIA = 56^0) but they restricted themselves to only 4 cylinders when attacking the 350 class by enlarging their 250cc and then moving on again to build their first 500cc.

The 1959 TT team took the 125 team prize there with lowly finishes. A return in 1960 with the addition of a doubled-up 4-cylinder 250 also did not achieve great success (4th place in the Riders' Championship). It took the, almost statutory, 3 years before Honda reached Championship status. In 1961 both 125 and 250 titles were won, partly because the firm were able to employ many top-level riders who had seen how the Japanese machines were being developed and were keen to join them.

In 1962 Honda attacked the 350 class and won that Championship as well. All these engines were 4-strokes, the type which Honda made for sale.

2nd era: 13 years 1962-1974: 2-strokes overtake 4-strokes, class-by-class

As mentioned, however, from 1962 Suzuki and Yamaha, who had followed Honda's entry into European races, began to threaten them with 2-strokes.A first sign of things to come was that a new 50cc class Championship was taken by a 1-cylinder Suzuki, the 1-cylinder Honda entry beaten into 3rd place by a 2-stroke Kreidler. The class winner was ridden by Ernst Degner, who had physically transferred Walter Kaaden's MZ 2-stroke technology from East Germany to Japan in 1961 (as described earlier), which had begun the gradual process which would in 12 years topple all 4-strokes from all classes. As the first 2-stroke to win a post-WW2 Championship (the DKW 2-strokes of 1952-1956 and the MZs of 1953-1971 never achieved that, although the 250cc MZ ridden by Horst Fuegner had taken the 1st Naturally-Aspirated 2-stroke GP win since the 1912-1913 Scotts in Sweden in 1958) it is worth considering the performance.

1962 50cc Championship

Make	1st Suzuki	3rd Honda
	2-stroke	4-stroke
B/S mm/mm	40/39.5	40.4/39
	= 1.013	= 1.036
V cc	49.64	49.99
Power HP	10	10
@ RPM	12,000	14,400
(Refs.)	(2)	(2, 13)
BMEP Bar	7.5	12.4
@ MPS m/s	15.8	18.7

Over the next 40 or so years, as both types of operating cycle were developed from a lower-than-normal MPS , where the 4-stroke was only able to produce around a further 10% more BMEP, the 2-stroke nearly doubled that parameter to equal the 4-stroke and so capitalise on the doubled power strokes.

[There was some size effect apparent on the 50cc Suzuki, which did not run up to the same MPS level as was usual at that date with larger cylinders i. e. about 20 m/s. This effect persisted with the even smaller cylinders created when both makes went to twins for the 50 class:- the 1966 Honda twin ran at 16.7 m/s (ref. 13) and the 1967 Suzuki at 17.3 m/s (ref. 2)].

First 2-stroke Championships followed in the 125 class in 1963 (Suzuki 2-cylinder) and the 250 class in 1964 (Yamaha 2-cylinder). Honda counter-attacked over 1964-1965 with a 2-cylinder 50, transverse 4- and 5-cylinder 125s and a transverse 6-cylinder 250.The year 1966 was the peak of Honda's racing motorcycle success in the 5 classes – all the Manufacturers' Championships and ¾ of the Riders' Championships, *bar* the 50cc and the "Blue Riband" 500cc, were taken.

Honda's new transverse 4-cylinder RC180 500cc engine was a logical expansion of the series of 4-cylinder units which they had built since 1960, as shown by the following table:-

Class	250	350			500
Date	1960-1964	1962	1962	1964-1966	1966
B/S mm/mm	44/41	47/41	49/45	50/44.5	57/48
	= 1.073	= 1.146	= 1.089	= 1.124	= 1.188
Vcc	249.4	284.5	339.4	349.5	489.9
Championships	1961,'62,'63	1962		1964,'65'66	1966*
			1963		

*Manufacturers only

This gradual enlargement to double the capacity was a good way to maximise Power/Weight ratio because it tended to squeeze out with experience any initial overlarge safety factors but it required careful consideration of all details to avoid overstressing parts. In the case of the 500cc gearbox and frame racing results seem to show that this reconsideration was insufficient.

The new engine produced 81HP @ 12,000RPM (ref. 15), a BMEP of 12.3 Bar @ 19.2 m/s. This was ample to beat the old 4-cylinder (70HP) 2 wide v/c MV Agusta in their 1st encounter on the simple Hockenheim circuit. However, MV very quickly enlarged a 350cc 3-cylinder engine which they had brought out in 1965 as a counter to the 350 Honda, from 56/47 = 1.191 with 4 wide (80^{o}) v/c like Honda, to give 420cc and about 67HP. With this in the next 6 months they secured 2 wins to Honda's 3. The engine was then enlarged further to 489cc (B/S = 62/54 = 1.148) to give 78HP @ 11.600RPM (BMEP = 12.3 Bar @ 20.9 m/s), which finished 2nd in the TT and won the final race at Monza when the Honda broke down under the MV's pressure. The final scoring gave Giacomo Agostini on the 3 versions of the MV the 1966 Riders' Championship although, as mentioned, the Honda secured the make title. The 3-cylinder MV had greater agility than the 4-cylinder Honda which suffered from bad handling on difficult circuits because of the use of the engine as a part of the frame and this had not been adequately rigid to keep the wheels in line under high power (ref. 16). Only Mike Hailwood's genius had been able to master the machine. The gearbox had also been unable to withstand the power in 2 early races. A6-16

For 1967, having refused to listen to Hailwood 's criticism about the frame, -he had managed, so why change? – Honda simply revised the engine to produce more power. The RC181 B/S was altered to (approximately) 59.6/44.7 = 1.323 and 95HP was produced @ 14,500RPM (ref.15)(BMEP = 11.7 Bar @ MPS = 21.6 m/s). The rival MV B/S was altered slightly but with the power unchanged (according to ref. 1). Racing was very close with 5 wins each (the TT was only won by Hailwood after Agostini's chain broke) but the Honda again had gearbox trouble twice, once a DNF and critically at Monza jamming in top gear when Hailwood was leading towards the Championship so that he dropped to 2nd. Overall, counting 2nd places, Agostini retained the Riders' Championship and MV Agusta regained the Manufacturers' crown. A6-17

<u>Piero Remor's contribution to Grand Prix engine design</u>

The defeat of the original MV 4 in early 1966 had brought to a close after two successful decades the career of the 1947 basic 500cc design of Piero Remor. Initially for Gilera, this introduced the Naturally Aspirated aircooled transverse 4-cylinder with double overhead camshafts and 2 wide angle valves per cylinder, with B/S around 1. Remor's concept, although changed in detail development by others in Gilera and MV Agusta, is worth commemorating here. There had also been successful 350cc versions. Remor had actually been associated with transverse 4s since 1925 when it was the layout of the Italian GRB (Gianini-Remor-Bonmartini)(ref. 9) which ultimately had been transformed into the watercooled supercharged Gilera which powered Dorino Serafini to the European Championship in 1939. A6-15

1967. The FIM limits on cylinders and gears for 1970 onward

In mid-1967 there was a report from Japan (ref. 17) that Honda intended to return to all classes in 1968 with more cylinders:- a 3-cylinder 50, a 6-cylinder 125, a V8-cylinder 250 and a 6-cylinder 500. Alarmed by this and with an intention to reduce costs the FIM announced that in 1970 the number of cylinders permitted per class would be limited and all would be allowed only 6 gears (the 1967 50cc Suzuki 2-stroke twin had got up to 14!). The figures were:- 50cc class, one cylinder; 125 and 250cc, two; 350 and 500cc, four.

Honda and Suzuki withdrawal from Grand Prix motorcycle racing

In February 1968 with no warning Honda withdrew from Grand Prix motorcycle racing. They continued with their Grand Prix car entries for a year but did not add to the 2 race wins which they had secured during the 5 year, 1964-1968, programme. This had overlapped the later years of the motorcycles and perhaps both had suffered as a result. The forthcoming rules for 1970, which would limit the lives of the complicated and expensive engines which they had been planning, must have influenced their decision. Suzuki certainly responded to the new limits by suspending Grand Prix participation for several years from 1967.

1968-1972: 5 more years of MV domination in the premier class
Champion: Giacomo Agostini

After Honda's unexpected withdrawal in early 1968 MV Agusta again were able to have a period of virtually unchallenged dominance in the premier class. This lasted for the 5 years 1968-1972, using the same 3-cylinder machine as in 1967 with the same rider, Agostini. In the 3-years 1968-1970 this engine had powered him to 30 race wins without any serious mechanical malfunction (ref. 11) which showed he had had no serious competition.

1972-1974. Yamaha 2-strokes threaten MV

In the 350 class MV certainly did *not* have things all their own way from 1971 as a 2-stroke Yamaha ridden by a new young star, Jarno Saarinen, attacked them and then, in a *reprise* of the 1966-1967 Honda v. MV period, went on to challenge them in the 500 class.

The gradual rise of the 2-stroke in Grand Prix motorcycle racing can be shown by the following table for the Manufacturers' title from 1962 to 1974.

Class	50	125	250	350	500
1st 2-stroke Championships					
	1962	1963	1964	1973*	1974**
Last 4-strokeChampionships					
	1966***	1966	1969	1972	1973

* Riders' Championship won on a 4-stroke.
** " " " " " "
and Manufacturers' points gained by both twins and fours.
*** Riders' Championship won on a 2-stroke.

The 350 Yamaha ridden by Saarinen which gave MV a hard time in 1972 was a pre-production TZ350 (2-cylinders watercooled plain-piston-ported, B/S = 64/54 = 1.185, producing 60HP @ 9,500RPM; BMEP = 8.1 Bar @ MPS = 17.1 m/s)(ref.18). This motorcycle (with a similar 250) was a steady development from a production aircooled model built originally in 1969 for private owners to meet the new FIM rules, after the firm had given up the full-scale works GP participation which had culminated in 1968 with Championship-winng watercooled disc-valved 4-cylinder engines in the 125 and 250 classes. With renewed works backing in 1972 the Yamaha forced MV to replace their 4-year-dominant 3-cylinder 350 with a new 4-cylinder in May 1972. This engine, B/S = 52/40.4 = 1.287, introduced 4 v/c at the narrow VIA of 35^0 (ref. 1), following the concept introduced by Keith Duckworth to Formula 2 car racing in 1966. This permitted a flat piston top of reduced mass. Revving at 15,000RPM (ref.11) the new engine reached an MPS of 20.2 m/s. It is doubtful if MV understood at that date the subtle inlet port shaping which produced in the Duckworth engines the in-cylinder "Barrel Turbulence" (aka "Tumble Swirl") to raise Combustion Efficiency since the inventor kept this secret for many years. At any rate, the new MV ridden by Agostini fought off the Yamaha ridden by Saarinen over the rest of 1972.

The following year Yamaha shook MV to its foundations with a new 500cc 4-cylinder engine based on doubling-up the latest TZ250A 51HP (ref. 18) version of their, now watercooled but plain-piston-ported, 250cc production racer. With B/S = 54/54 = 1 (ref.20) this OW20 type developed close to 100HP and Saarinen won the first premier race of 1973, defeating Agostini on the MV 3. This was the first defeat of an MV 500 by a 2-stroke. It was in spite of MV fielding for Phil Read, a newcomer to the team, a new 4-cylinder machine enlarged to 433cc (B/S = 56/44 = 1.273) from their 1972 350, which finished 2nd. Saarinen then won the 2nd race against the MV 3 and MV 4.

For the 3rd race the MV 4 was enlarged again, to 497cc (58/47 = 1.234) and Read was able to win but only after the Yamaha suffered a broken chain (ref. 19). Tragically, Saarinen was killed at the next race meeting in a 250cc race through no fault of his own. After that MV mainly fought an internecine battle between Read and Agostini which gave the former the title and resulted in the latter departing to ride Yamahas in 1974. A revised lighter 500 (B/S = 57/48.9 = 1.166) was introduced in the last third of the season. A6-18

In 1974 the MV v. Yamaha struggle was resumed with basically the same machines and Championship honours were even. Read won the Riders' again but Yamaha the Manufacturers'. This last 500cc aircooled 4-stroke "Bike-of-the-Year" had 102HP @ 14,800RPM (ref. 1) (BMEP = 12.4 Bar @ MPS = 24.1 m/s) and the engine weighed 55 kg (ref.11), i.e. the same as the 1951 1-cylinder Norton of 45% of the power. The Power/Weight ratio was therefore 1.85 HP/kg. This within a width of 41 cm. It is interesting to compare the 1974 MV performance factors with the Duckworth-designed 1974 Cosworth DFV V8 3 litre Grand Prix engine (B/S = 85.67/64.77 = 1.323) , also on 102 RON petrol and Naturally Aspirated, which produced a BMEP of 13.4 Bar @ 22.1 m/s (ref. Egs. 47-62 of www.grandprixengines.co.uk). The car engine dry Power/Weight ratio was 2.8 HP/kg but this did not include the water- or oil-cooling systems (the MV was wet-sump but had an oil-cooling radiator). It also had the advantage of x6 size (piston engine weight rises more slowly than swept volume). Neither weight includes the exhaust systems which were, of course, essential to produce the quoted power.

1975. Yamaha 2-stroke conquers the premier class

In 1974 MV Agusta had taken the 1st (Phil Read) and 2nd (Gianfranco Bonera) places in the premier class but perhaps this was because Agostini was still learning how to ride a narrow-power-band 2-stroke. The 250-2 Yamaha which had been doubled up to form their 500-4 had only a 500RPM (4.8%) range between peak power and peak torque (ref. 18) and only 6 gears were allowed by FIM rules. Refs 1 and 20 state that the Yamaha 4-cylinder 500 had reed valves at the inlet ports, although the 250 and 350 twins did not (ref. 18), and these should have increased the engine flexibility somewhat. Best results for a 2-stroke running on a petroil mixture also required attention to the fuel/air ratio by a manual control on the handlebar. Certainly one race was lost by Agostini through running out of petrol (ref. 19). In 1974 Agostini won only 2 races to Read's 4 and Boneras's 1. Yamaha's 2nd works 500-4 rider, Tepi Lansivuori, won 1 race. The Manufacturers' title went to Yamaha because of wins by nominally-over-bored TZ350 twins in 2 races (including the TT) which were boycotted by MV and the works Yamahas on safety grounds. A7-19

In 1975 Agostini reversed the situation with a lighter OW23 Yamaha, winning 4 races to Read's 2 and he became the first 2-stroke rider to take that Championship. With no major changes in the machines the credit must be given to Agostini. Yamaha retained the Manufacturers' title. The competing machines had very similar Power/Weight ratios: about 100HP/dry 133 kg plus something for the coolant for the OW23; about 102HP/135 kg for the MV.

A significant feature of 1975 was that Suzuki, who had returned in 1974 to field a works 2-stroke watercooled disc-valved square-4-cylinder 500cc, ridden by Barry Sheene, had won 2 races. This showed that the general state of development of the racing 2-stroke v. the 4-stroke had reached a level which at last had passed the latter in the premier class. Suzuki made a batch of such motorcycles for private owners in 1976. These RG500 machines were B/S = 56/50.5 = 1.108 and produced 100HP @ 11,200RPM (ref. 2)(BMEP = 8.03 Bar @ MPS = 18.85 m/s). The engine weight was 55 kg (ref.30) (which, interestingly, was the same as the 4-stroke 1974 MV4 of similar power). This weight did not include the watercooling system or the essential exhaust system. The 135 kg A7-20 motorcycle sold for about £4,000 (£24,000 in 2012 money) and, as stated by Phil Read who bought one "…all it needed was a change of tyres to be instantly competitive with Agostini and the MV" (ref. 19).

MV Agusta, realising the situation, effectively retired from full works participation after 1975. They took into consideration an FIM ruling to take effect in mid-1976 that silencers down to a specified level would have to be fitted which they believed would drop the power of their megaphone-exhaust engines by 15% (ref. 11)(2-strokes with the mufflers fitted after the *convergent* portion of their exhausts would not lose so much; Suzuki lost 4½ % (ref 2)). As Yamaha had also retired at the end of 1975 MV did supply some improved machines in 1976 to Agostini to run privately where he thought they might have an advantage over his production Suzuki. This did produce the last premier class race win for a 500cc 4-stroke at the Nurburgring. It was also Agostini's last Grand Prix win.

Another "last" in 1976 was that the Isle of Man TT was included in the motorcycle World Championship for the final time, the FIM excluding it thereafter for safety reasons. In fact MV had banned it post 1972. It is worth noting that whereas the IoM Snaefell circuit tested 500cc bikes and riders over 226 miles the average of the other Championship races that year was only 39% of that distance.

Two-stroke domination

After 1975 no 4-stroke would ever again win a 500cc Championship. This situation, long foreshadowed since the first 50cc 2-stroke Championship in 1962 followed by the gradual conquering of all larger classes and helped by the FIM limits on cylinder number, was somewhat analogous to the 1959 displacement in Grand Prix car racing of the front-engined chassis by the mid-engined. In each case there were many conservative onlookers who regretted the change, especially in motorcycle racing as the throaty roar of the expensive 4-stroke was replaced by the squeal of the cheap 2-stroke, just as some people had lamented the cheap-and-cheerful Cooper defeating the expensive Ferrari!

3rd era: 27 years 1976-2001: 2-strokes supreme

The rise of the 2-stroke 1962-1974

Before reviewing the details of the 27 2-stroke machines on which the Champion was mounted, the "Bikes-of-the-Year" (BoY), from 1975 until the FIM changed the rules for 2002, it is worth considering *how* the 2-stroke came to be dominant. Tables have been included previously to show that this came about gradually from the smallest class to the largest over 13 years, 1962 to 1974, as, with concentrated development, the 2-stroke *disadvantage* of "breathing through its bottom" was overcome and the *basic advantage* of an expansion stroke every revolution instead of every second came to the fore There are physical reasons for this gradual progress in superiority by cylinder size. The first is the "Inverse Stroke (1/S)" effect described earlier, which produces higher HP/Litre as S is reduced (which applies to 4-strokes equally). The second is that the ratio Cylinder Wall Area/Cylinder Volume increases with "Inverse Bore (1/B)" and so the 2-stroke Port Area/Volume ratio which governs its breathing improves as B is reduced. Simultaneously the cooling is improved, a very important consideration with a power stroke each crank revolution. Together these effects mean that a smaller cylinder at a given state of technology generates higher volume-specific 2-stroke power more reliably than a larger.

These *physical* features, which mean that the 2-stroke first began to compete with the 4-stroke at the smallest size, was also coupled initially with the *commercial* desire of the Japanese 2-stroke manufacturers to race small-capacity machines like those they were selling in volume (the 50cc class introduced in 1962 was a gift to Suzuki) .Hence the development funds made available by them for racing. It had also meant that Suzuki assisted Ernst Degner to move to the West with his knowledge of MZ 2-stroke technology (ref. 2).

Success in the smaller classes and the steady improvement in BMEP with development then led Suzuki and Yamaha with their growing expertise to challenge in the premier 500cc class for reasons of prestige.

A table illustrates further the spread of 2-stroke success as their technology was improved.

Manufacturers' Championship
Dates at which 2-strokesfinally superseded 4-strokes

Class	50	125	250	350	500
Year	1966	1967	1970	1973	1974
Make	Suzuki	Yamaha	Yamaha	Yamaha	Yamaha
Type	RK67	RA31	TD2	TZ350A	OW23
No. Cyl.	2	4	2	2	4
B/S	32.5/30	35/32.4	56/50	64/54	54/54
	= 1.083	= 1.080	= 1.12	= 1.185	= 1
1 Cyl. Vol.cc	24.89	31.17	123.15	173.72	123.67

It is arguable that in the 250 class the supersession would have been in 1969 with the developed 1965-1968 Yamaha RD05 4-cylinder, unit volume 62.35cc, defeating a planned 8-cylinder 4-stroke Honda, if the FIM announcement of a 1970 limit to 2-cylinders for that class had not caused both Yamaha and Honda to withdraw from works participation.

As it was, Yamaha proceeded on a completely different tack. This produced in 1969 simpler 2-cylinder types of 250 and 350 2-strokes for private owners, developed from street bikes, which began a new line of development leading on to the 500 class (and also to the 750 class, although this did not figure in Grand Prix racing). Instead of the disc inlet valves of the RD05 these new engines had the usual 3 plain-piston-controlled ports but introduced an extra pair of transfer ports. These were the "Kaaden MZ boost port" divided into two, as pioneered by Hermann Meier in the 1965 Royal Enfield GP5 (ref. 21) because, unlike the disc-valved MZ, the intake port occupied the rear cylinder wall.

The improved effectiveness of these simple engines was a source of wonder to Walter Kaaden himself, vividly described in ref. 22; at the 1969 West German GP at (the original) Hockenheim "a track which shows up any speed differential….His MZs had met a match in the 246cc TD2 Yamaha….For the aircooled piston-ported 5-speeders to be as fast as the disc-valve watercooled 6-speed MZs would have seemed inconceivable a year ago". The race was won by Kent Andersson, the 1st success of the TD2. He went on to take 2nd place in the 1969 250 Riders' Championship (the winner rode a 4-stroke 4-cylinder Benelli). The price of the TD2 was only £800 (£11,000 in 2012 money)! Three more years of development led to doubling-up to a 4-cylinder 500 and a further two years would see that larger machine help to win the Manufacturers' title (together with the points gained by its 2-cylinder over-bored 350 cousins). Another season plus Agostini's genius and it was the 1st 2-stroke "Bike-of-the-Year" in 1975.

An overview of the "Bike-of-the-Year" in the 2-stroke years

The reader is asked to revisit Figure 1, Maximum Power versus Date for the "Bikes-of-the-Year" so as to appreciate again the remarkable way 500cc Grand Prix motorcycle engines doubled in output over the 26 years of the 4-stroke eras, 1949-1974 inclusive (approximately 50 to 100HP) and then nearly doubled again in 23 years of the 2-stroke era, 1975-1997 inclusive (approximately 100 to 200HP). All these engines were Naturally-Aspirated and running on petrol, initially 72 Octane Number (ON) in 1949, then 80 ON until 100 ON was available in 1956. This grade was then used until "Low-lead" fuel was mandated in 1993, followed by "No-lead" in 1998. This latter required a drop in compression ratio, so producing somewhat lower power over the final 4 years of the 2-strokes to 2001. The machines from mid-1976 also had to have silencers fitted to reduce noise to a specified 110dBA at a given RPM at a given distance which may have cost 5% of power (ref. 2). It is very probable that powers quoted exclude that effect.

All the 2-stroke machines were watercooled 4-cylinder, the FIM limit, except for a Honda 3-cylinder in 1983.

All the BoY machines 1976-2001 were from 3 Japanese manufacturers:-

- Yamaha:- 10 Riders' Championships with Giacomo Agostini; Kenny Roberts (3); Eddie Lawson (3); and Wayne Rainey (3).They also took 9 Manufacturers' titles. A8-22
- Suzuki :- 6 Riders' Championships; Barry Sheene (2); Marco Lucchinelli; Franco Uncini; Kevin Schwantz; Kenny Roberts Jr.). They gained 6 make titles.

- Honda, once they had tried very hard over 1979-1981 and failed to win with a "Trade-mark" 4-stroke (with "oval" pistons, described below); 11 Riders' titles; Freddie Spencer (2); Eddie Lawson ; Wayne Gardner ; Mick Doohan (5); Alex Criville; Valentino Rossi. They totalled 12 Manufacturers' Championships.

[The Honda NR ("New Racing") 500

Honda re-entered premier 500cc motorcycle racing in 1979 after a 12 year absence with a 4-stroke in a class which had been dominated by 2-strokes for the previous 4 years. To secure sufficient power required ultra-high RPM and therefore ultra-short stroke (36mm, ref.6). As the rules permitted only 4 cylinders –Honda chose a watercooled 100^0V4 - and a huge Bore/Stroke ratio was then thought not to be feasible, lateral thinking led to the distribution of the needed piston area into "oval" bores. The required valve area and freedom from valve bounce was then provided by 8 valves (4 inlet, 4 exhaust). Each piston required 2 con-rods. How the pistons were sealed only Honda and Heaven knew! Initially 113HP was obtained (ref. 23). Honda developed this engine for 3 years, redesigning it as a 90^0V4, and got it up to 134HP @ 19,500RPM (ref.15)(BMEP = 12.3 Bar @ MPS = 23.4 m/s) but it never looked like beating the rival 2-strokes in major races (a novel monocoque chassis had something to do with that initially). In its last GP race, the 1981 British, Freddie Spencer was 2.3% slower than the Suzuki RG500 on pole (ref.24). It seems that inferior power/weight ratio was its handicap (refs. 24,25).Having lower fuel consumption the machine did win a 1981 Japanese non-Championship 200 km race by running non-stop where the 2-strokes had to refuel (ref. 25).

Honda abandoned their very-costly 4-stroke adventure and joined the 2-strokes in 1982. They produced a 3-cylinder which was immediately competitive and Spencer won the Championship – their first – in 1983.]

BMEP and MPS

Figure 3 of BMEP versus Date shows that 2-stroke BMEP rose from 7.8 Bar in 1975 to 14.2 in 1997 (+82%) after which no-lead petrol pulled it down by 5%.

When Figure 3 and Figure 4 MPS versus Date are examined by makes the following is shown:-

	BMEP Bar	MPS m/s
• Yamaha over 18 years 1975-1992 (pre no-lead)	7.8 to 12.6 (+61%)	19.8 to 19.8 (0)
• Suzuki over 25 years 1976-2000 (post no-lead, which depressed the final BMEP)	9.4 to 13.2 (+40%)	19.8 to 22.5 (+14%)
• Honda over 15 years 1983-1997 (pre no-lead)	10.2 to 14.2 (+39%)	19.8 to 21.8 (+10%)

The striking points are the large increases in BMEP with little or no increase in MPS.

Some more generalities

Five major cylinder configurations were tried for BoY engines:- transverse 4 in-line (IL) (Yamaha 4 times in early years); geared-crank square 4 (Suzuki 4 times in early years ; 100^0 V3 (Honda once); geared-crank 2 x transverse IL2 with various angles between banks (60^0, 70^0, 80^0) (Yamaha 6 times, Suzuki 2 times);V4 (90^0 and 112^0) (Honda 10 times). Generally the 1-crank engines rotated in the opposite direction to the wheels by means of a jackshaft, so as to oppose wheel gyro effect. Although the early square 4 Suzukis had both cranks rotating the same as the wheels, all later 2-crank engines had them rotating in opposite directions to each other to cancel internal gyro. When Honda introduced the "Big-Bang" engine in 1992 (see below) they had to incorporate a balance shaft to reduce vibration

A8-23

For the first 10 years designers varied in choice of inlet-to-crankcase arrangements between no valves, reed valves to prevent blowback and disc valves to extend the open period but after 1985 the choice was always reed. On the exhaust side, to extend the useful power to lower speeds Yamaha introduced a variable port height valve in 1978. At first this was a rotating cut-away cylinder but later a "guillotine" was used. With the exception of Honda using a variable-volume exhaust system over 1983-1985 all BoY engines after1982 used the port height variation method.

The 1991 Yamaha introduced an "airbox" around the carburetters with a duct from the outside so as to provide them with cool air. This formed part of the tuned inlet system and could also convert forward speed into pressure. Airboxes were a standard feature thereafter.

Tuned divergent-convergent exhaust systems with an "extractor-repulsor" effect to raise BMEP had been known and refined since first used by DKW in 1955 (ref. 26) and any improvement was easily seen and copied. The Honda NSR500 of 1997 type, which was the most powerful 2-stroke before no-lead fuel was imposed, had a diffuser of area ratio 1 : 6 with an *average* included angle of 15^0 (the wall angle increased along the length). This was followed by a plain pipe section 28% of the diffuser length. Then came a convergent "repulsor" cone of area ratio 1 : 0.05 at an included angle of 30^0 (the regulation silencer was fitted aft of that) (shapes scaled from an illustration in ref. 27). This system used the exhaust exiting pressure pulse as a reciprocating pump, first sucking new charge into the cylinder *and* the diffuser then, by reflection of the pulse from the convergent cone, blowing it back from the diffuser into the cylinder. The engine was, in effect, supercharged. Clearly this resonating system worked best at only one RPM hence the range between peak power and maximum torque RPMs was only about 5%.

A7-21
A8-24

Transfer port designs in terms of number, radial and vertical inflow angles could not be seen and copied and these contributed much to the BMEP gains which have been listed above. Very little is known but it amounts to the following:- Yamaha in the 1st champion 2-stroke is reported to have had 7 cylinder ports (ref. 28) although its derivation from 2 x YZ250 twins would suggest 5; the 1976 Suzuki RG500 had 6 ports: 1 x exhaust, 2 x front and 2 x rear main transfers plus a "Kaaden boost port" (ref. 6); by 1979 the developed Suzuki RGB500 had 8: 1 x exhaust, 2 x front, 2 x middle, 2 x rear main transfers plus the boost (ref.2); the 1990 Yamaha is reported to have had 11: 1 x main plus 2 sub- exhaust ports, 6 transfers plus 2 x boosts (ref 1). Moving to the last of the 2-strokes in 2001, ref.1 reported that the Honda had only 7 ports: 2 x exhaust, 4 x transfers plus boost.

Port timing is another important detail rarely given in any 2-stroke GP engine reports, although it cannot vary so much as port design. The inlet, if plain, was probably around 190^0 crank angle period (opening 95^0 Before Top Dead Centre (BTDC) and closing 95^0 After TDC). If a disc valve attached to the crankshaft was fitted the opening might be advanced to 140^0 BTDC but closed earlier at 75^0 ATDC for an increased period of 215^0, the maximum opening being at 32.5^0 BTDC. Transfer and boost ports might open at 112^0 ATDC and close at 112^0 BTDC, period 136^0; exhaust opening 90^0 ATDC, closing 90^0 BTDC, period 180^0. The "blow-down gap" between exhaust and transfer openings would then be 22^0.Sometimes transfer ports and boost port might be timed differently, a later timing for the boost giving lower power but a wider power range. Inlet timing before 1984 had to take into account rider push starting off the grid. The adoption of starts then with engine running after a parade lap enabled inlet timing to be increased for more power.

<u>Torque control and the "Big-Bang" engine</u>

In the late 1980s there had been many "high side" crashes caused by insufficient control of torque while banked in a corner. A tyre was asked to give more grip than it could provide, slipped, the rider reacted by closing the throttle, the tyre suddenly regained grip and the motorcycle jerked upright and threw the rider off. The sudden rise of torque versus RPM of the tuned 2-stroke and the narrow grip range of the new radial tyres were contributory factors. Honda in mid 1990 had even proposed that power should be reduced by cutting the capacity to 375cc (ref. 24) but the FIM turned this down. There were actually already steps in 1990 to ease the situation. Electronics were applied to limit torque to the back wheel. Honda had copied for its true V4 the ignition timing used by Yamaha's 2 x IL2 of firing *pairs of cylinders at* 180^0 *apart* instead of at 90^0 intervals, which for a then-unknown reason had given somewhat better torque control. It was known that Harley Davidson big twins on US dirt tracks, i.e. on low-grip surfaces requiring delicate throttle control, had benefitted by firing the cylinders close together.

After another couple of years Honda then introduced the "Big Bang" engine. Their 112^0V4 was fitted with a crank having pairs of cylinders at 180^0 so that the second pair reached TDC and fired $180^o - 112^0 = 68^0$ after the first pair. That the new idea worked well was soon proved – in 1992 the NSR500 ridden by Mick Doohan won 5 races and took 2 x 2nd places in the first 7 events. Only a crash and bad injury then prevented him gaining the season's Championship. Furthermore, a rookie 500cc rider, Alex Criville, won a race on the "Big Bang" Honda, showing the degree to which it had been tamed. All rivals during the year had to produce their own versions of the Honda innovation.

An experienced racing journalist who had ridden previous Hondas – with considerable trepidation - , trying the "Big Bang" machine at the end of the season found he was able to pull a "big wheelie" when still well banked over while exiting a fast curve (ref. 29).

While various theories about tyre slip and grip were aired to explain the undoubted fact of greatly improved controllability, it was not until 2007 after MotoGP experience that Masao Furusawa, effectively chief racing engineer for Yamaha, was able to give an explanation of "Big Bang" success (ref.30). His theory was related in detail to 4-strokes but is adapted here to the preceding GP 2-strokes. Torque reaching the wheel is a mixture of that from combustion (he designated this as "Signal", which is what the rider wants to control) and that from the inertia of the reciprocating parts which fluctuates between positive and negative according to those parts having to be decelerated or accelerated. This inertia torque (which he called "Noise ") rises as the square of RPM. In the 500cc 4-cylinder 2-stroke engine with conventional 90^0 firing at half maximum speed (6,000 RPM), when the rider wants *some* torque to his wheel banked over at 45^0, Noise obscures Signal and prevents the rider from having a good connection between the throttle angle and the driving torque at the wheel. Firing all the cylinders close together multiplies the Signal to Noise ratio and a good throttle to wheel torque connection is obtained.

<u>FIM changes the rules for 2002</u>

In order to show a "greener" aspect to a world critical of smoky emissions and allegedly careless use of fossil fuel generating CO_2 for sport, the FIM in 1999 changed the rules of the premier class for 2002. While 500cc 2-strokes could still compete a new class of 990cc 4-strokes was specified. These 4-strokes would not have the petroil-fuelled emissions and with higher efficiency would have lower fuel consumption. In fact, the 2002 rules restricted the 990cc 4-strokes to a maximum petrol consumption of 24 litres, only 75% of the 32 litres allowed to the 500cc 2-strokes.

Noise rules were relaxed for the new 4-strokes to 130 dB – it will be be recalled that MV in 1976 had stated that the new noise rule of 110 dB would cause a power loss of 15%. The 2-stroke noise limit was to be 113 dB.

A sliding scale of cylinder number versus minimum machine weight was also introduced:-

No. of Cylinders	kg	
	4-stroke	2-stroke
2		100
3	135	115
4 or 5	145	130
6 or more	155	

Grand Prix motorcycle racing was to be "rebranded" as "MotoGP".

New 990cc motorcycles for 2002 from Yamaha (transverse IL 4 cyl.) and Honda (75.5^0 V5) were on track test by mid-2001.

<u>Success of the Honda NSR500</u>

In Grand Prix motorcycle racing history the Honda NSR500 stands in a similar status to the Cosworth DFV for number of wins relative to those possible. Not counting the 3 years 1984 – 1986 when this true V4 engine was 90^0 bank angle and obtained 15 wins, the 112^0 V4 introduced in 1987 and continuing without major change to 2001, won 116 races, 52.5% of the possible. The DFV over 1967 -1982 won 154 races, 65% of the possible. In both cases there was severe competition unlike the 13 years of MV successes, 1958 – 1965 with the original 4 cylinder and 1968 – 1972 with the 3 cylinder.

Before low-lead fuel led to power drop the 1997 version of the NSR500 is stated by the descriptive label on the machine exhibited at Honda's Motegi museum (ref. 27) to have had 185PS @ 12,000RPM, i.e. 182.5BHP or 365HP per litre.

4th era: 7 years 2002 – 2008 (and counting): MotoGP 4-strokes

A cautionary note to introduce the 4th era: engine data in this period is rather limited. In most cases there are no official figures even for the Bore and Stroke. While Gilera and MV Agusta in the 1st era revealed little or no internal details at least they did not deprive analysts of that basic information! Accordingly ref. 1 has resorted to estimates although there is some back-up to these found by this author.

The reader is asked to refer back to the section on “Common features of engines in 1949 and onward” so as not to repeat some details of this era.

The FIM in allowing 990cc 4-strokes to compete with 500cc 2-strokes in 2002 probably expected similar performance. This proved to be unfounded from the start. With 200HP to 180 and a much wider torque range (about 15% between peak power and maximum torque RPMs versus only 5% for 2-strokes) and with about the same loaded power/weight ratio the new machines won all the 2002 races.

Relative Thermal Efficiencies: 4-strokes versus 2-strokes

Assuming each type used all its fuel ration the 4-stroke Thermal Efficiency in relation to the 2-stroke was close to:-

(200HP/24Litres fuel) / (180/32) = nearly 1.5.

If the 4-stroke actual Thermal Efficiency was 30% (judged from ref. 31) then the 2-stroke was only 20%. One reason for the difference was that the hotter 2-stroke piston limited the true compression ratio to about 8 where the 4-stroke could use as much as 13.

The FIM intention to show better use of fossil fuel was therefore achieved. The smoky petroil-fuelled emissions of the 2-stroke were, of course, no longer seen from the winners.

2002 -2003

Winning mount: Honda RC211V

Honda, ready as always to innovate, produced in 2002 a 5-cylinder 4-stroke engine to take full advantage of the 145 kg minimum weight. This had 3 cylinders leaning forward at 45^0 and 2 backwards at 30.5^0, the bank angle being 75.5^0. They had developed their 90^0 V4 RC45 750cc Endurance and Superbike racing engine with B/S = 72/46 = 1.565 over many years up to an output of 175HP @ 14,500RPM (ref. 32) (BMEP = 14.4 Bar @ MPS = 22.2 m/s). It only required a bore increase of 2 mm and a 5th cylinder to produce a MotoGP engine with B/S = 74/46 = 1.609 and 989.2 cc. Official data quotes ”over 200HP” (ref.27). Ref. 1 gives an estimated 220HP @ 15,500RPM which represents BMEP = 12.8 Bar @ MPS = 23.8 m/s. The MotoGP engine was required to race over only 120 km so could use a higher MPS compared to the Endurance RC45. A9-25

Details (from ref. 33) included:- narrow VIA (about 26^0) valve gear which used a steel coil-spring return system (CVRS) with inverted cup tappets although Honda had in its F1 car engines pioneered a return to finger followers in the 80s and adopted Pneumatic Valve Return Systems (PVRS) ,following Renault, in the 90s. With B/S of 1.6 the Mean Valve Speed (MVS) with *all* valves in titanium-alloy was not high enough to make these refinements necessary. Later titanium-aluminide would be used for valves, being 9% less dense than the previous Ti6Al4V and retaining strength to higher temperature (ref. 41). The particular 5-cylinder configuration, with the front central cylinder’s crank 180^0 behind the other two throws each driven by a front and rear pair of cylinders, did not need a balance shaft. From their 1992 “Big Bang” experience with the V4 NSR500 Honda chose an irregular firing order with intervals of:- 75.5^0; 104.5^0; 180^0; 75.5^0; 284.5^0 instead of the regular 144^0. The firing order was:- front (F) 1; back (B) 5; F2 (centre); F3; B4. Because of this pattern a flywheel was fitted, its inertia being varied to suit the rider’s wishes. The inertia torque was near zero (ref.34). Initially the 3-branch exhaust system (paired cylinders plus a separate central pipe) was plain.

With the high compression of the 4-stroke it was necessary to introduce a “slipper” clutch so that closing the throttle while braking did not cause too much rear wheel braking when weight was being transferred to the front wheel.

For a comparison of performance, at this date a good, but not Champion, F1 engine, the V10 3 litre BMW P82 had B/S = 95/42.3 = 2.246, with a MVS made possible by PVRS, and gave at mid-season a BMEP of 14.25 Bar @ MPS = 26.1 m/s (ref. 35).

Valentino Rossi, the Champion, won 11 races on the RC211V in 2002 and three other wins were obtained so the season score was 14/16= 87.5% of the possible. The 4-stroke Yamaha M1, of which more under 2004, took the other 2 races.

Having won the 2002 Championship in overwhelming fashion Honda had no need to make much change to their RC211V, although the Italian Ducati had now joined their Japanese rivals. Ref. 1 estimates that power was slightly higher at 230HP @ 15,800RPM, possibly because of a megaphone exhaust (ref.33). Since the official Honda figure for their 2004 machine was "over 240HP" the above seems likely. The result was even greater supremacy, 15 wins out of 16 races (93.7%), Rossi achieving 9 of these. This result calls to mind the 1988 season of the turbocharged Honda-engined F1 McLaren which also won 15 out of 16 races.

<u>2004 – 2005</u>

<u>Winning mount: Yamaha YZR M1</u>

Yamaha, who had won only 2 races in 2002 and none in 2003 with their transverse IL4 5 valves-per-cylinder (5v/c) engine, made two important changes for 2004:- they revised the engine completely and they secured the services of the triple premier-class World Champion Valentino Rossi. The latter joined them to see if he could show that his Honda successes were at least as much due to his skill as to their technology. He brought with him his very experienced crew chief Jerry Burgess, who had also worked previously with Mick Doohan. The technical changes to the M1 OWR4 under the direction of Masao Furusawa involved discarding the "Trademark" Yamaha 5 v/c and adopting 4 v/c like everyone else. Camshaft primary drive was still by chain. There may have been different B/S dimensions – ref. 1 estimates they were 84/44.6 = 1.883. This ratio was much less than in F1 engines because frontal area and a banking angle of 55^0 had to be considered but, as noted for the RC211V, it enabled CVRS to be used. Although there was an extreme inlet downdraught angle of 40^0 the exhausts from the engine leaning forward at 25^0 were very cramped – the flow turned through about 170^0 in a very small space. Power was 235HP @ 15,500RPM (ref. 36) (BMEP = 13.7 Bar @ MPS = 23 m/s). This was actually only 5HP more than the preceding 5v/c engine. A9-26

A9-27
A10-28
A10-29

Furusawa, who had developed the theory accounting for the success of "Big Bang" engines which has been mentioned earlier (although it was not disclosed until 2007, ref. 30), gave the OWR4 a "cross plane" crankshaft to obtain the desired irregular firing. This had the pins at :- 0; $+90^0$; -90^0; $+180^0$ (which, coincidentally, was the crank introduced in the 1932 Ford V8 to eliminate secondary unbalances compared to a flat crank). The firing intervals were:- 270^0; 180^0; 90^0; 180^0 instead of the regular even 180^0, giving a firing order of:- 1, 3, 2, 4. This was stated to have nearly eliminated inertia torque (ref. 30). The M1 already had a balancer shaft. Rossi tested engines with the original 180^0 and with the 90^0 crank before choosing the latter.

Whatever the share of credit between the engineers and the rider the M1 fortunes were transformed in 2004 with 9 wins out of 16 races, all to Rossi, and the titles.

In 2005 the fuel ration rule was tightened to 22 litres (-8.3%) and Yamaha adopted a "ride-by-wire" electronic control system to improve efficiency. This had electronic control of two of the throttles but left two manual. Despite the reduced fuel, power of this OWP4 was increased to 240HP @ 16,250RPM (ref. 36) (BMEP = 13.4 Bar @ MPS = 24.2 m/s). The cam drive by chain had to be replaced by all-gear at the higher RPM.

The 2005 season was even more satisfactory to Yamaha, Rossi winning 11 out of 17 races and, of course, the titles again.

2006

Winning mount: Honda RC211V

This was the last year of the 990cc machines as the FIM had decreed that in 2007 the capacity would be cut to 800cc to reduce speeds, with a 4-cylinder minimum weight of 148 kg and a maximum fuel ration lowered to 21 litres (-4.5%).

Honda had apparently altered their engines dimensions in 2005, the most likely estimate for these being a 2mm bore increase to give B/S = 76/43.6 = 1.743 (ref. 33). Power (from ref. 1) was believed to be 250HP @ 16,500RPM (BMEP = 13.7 Bar @ MPS = 24.0 m/s). There was now a full electronic control system. A10-30 A11-31

Yamaha had also increased their B/S ratio and had equal power but had some engine failures (ref. 36). Consequently although Rossi won 5 races, 3 more than Nicky Hayden on the Honda, the latter's consistency won him the Championship. Altogether Honda riders won 8 times out of 17 races. Ducati had their best season since their 2003 debut with 4 wins.

The 800cc formula

2007

Winning mount: Ducati GP07

Ducati began MotoGP competition in 2003 with a 90^0 V4 having their "Trademark" desmodromic valve return system (DVRS), i.e. the valves being returned to their seats not by springs but by direct mechanical action. DVRS, compared to CVRS is a means of increasing the Mean Valve Speed (MVS) of an engine, where:- A11-32

$$\text{MVS is proportional to } \frac{\text{(Maximum Valve Lift) x (RPM)}}{\text{Valve Open Period}}$$

Where MVS is originally on the limit a higher value can be used to either increase Lift and/or RPM and raise power; or, Valve Open Period can be reduced with higher acceleration so as to cut overlap and widen the useful power range.

The parameter Bore Speed (BN) = B x RPM can be used as a surrogate for MVS where details are not known. The 2007 Ducati with DVRS had BN = 81mm x 19,000RPM = 25.7 m/s compared to the 2006 Honda with CVRS at 76 x 16,500RPM = 20.9 m/s.

More details of the theory behind MVS and BN can be found on the website "grandprixengines.co.uk" at Note 13 Part III.

Ducati claimed that DVRS reduced friction in the valve gear, particularly at lower speeds (ref. 42).

During 2003 to 2006 the Ducati had been considered to be more powerful than its rivals but this had not produced many wins. In those 4 years the results had been:- 2003, 1 win; 2004, none; 2005, 2; 2006, 4. However, in 2007 under the 800cc formula and with a new rider, Casey Stoner, their fortunes came good. The Championship was taken with 10 wins from 18 races.

The GP07 engine was B/S = 81/38.8 = 2.088 (ref. 37) where the 990cc GP06 had been 86/42.56 = 2.021 (ref. 38). To judge from the 2007/2006 top speeds quoted later, 330 kph versus 340 (ref. 39), maximum power was probably around 230HP @ 19,000RPM (BMEP = 13.5 Bar @ MPS = 24.6 m/s) but Ducati had a fuelling control which ran lean on corners so as to save fuel and rich only along the straights (ref. 34). This was necessary because the fuel ration had been cut from 22 litres to 21 (-4.5%). The scope for fuel saving in this way is shown by some circuit operational data given later by Furusawa of Yamaha (ref.39). At Mugello, a track with a race speed around 170 kph (105 mph), he stated that the throttles were wide open only 25% of the time. For a third of the lap only 10% throttle was used. A11-33

Some details from ref. 38 for the replica of the GP06 engine probably also applied to the GP07, as follows. There was a "Twin Pulse" firing pattern, having crank pairs separated by 70^0 with firing intervals of 0; 90, 290; 380, the cylinder order being 1, 3, 2, 4. Compression ratio was the high figure of 13.5 despite the high B/S ratio. Pistons were slipper type as usual, the height being only 80% of the stroke. Bores were linerless with a Nikasil coating. Crank webs were knife-edged to reduce windage.

2008

Winning mount: Yamaha YZR M1

In trying to combat the high-revving desmodromic Ducati in 2007 Yamaha had fitted a Pneumatic Valve Return System (PVRS) for the 13th race at Misano. PVRS had been in use in Champion F1 engines since 1990 to enable B/S to be pushed eventually well over 2 and so permit higher RPM at constant MPS. The advantage of PVRS over CVRS was the virtual absence of the mass in the springing medium which caused steel coil springs to "surge" and fail in fatigue at *average* stresses below critical. PVRS therefore allowed an increase in MVS. It was also lighter. It was also cheaper since it was no longer necessary after every race to discard very-expensive fatigued wire springs with worn-out inter-coil damping interference.

The M1, according to ref. 1, reached B/S = 82/37.8 = 2.17 (although this is unconfirmed). A big end failed in the Misano race (ref. 43). The new valve gear was tried again in the next race at Estoril and Rossi beat Pedrosa on a Honda RC212V and Stoner on the GP07 Ducati. However, another bottom-end failure occurred in practice for the following race so the revised engine was not used again in 2007.

For 2008 the oil system was improved by a centre feed into the crank (ref. 43) (something fitted to the Rolls-Royce Merlin in 1944). Rossi had no DNFs in the season. PVRS was standardised. Yamaha claimed the gear was 40% lighter than CVRS. They seem to have taken the advantage in MVS by using higher accelerations to permit lower valve timing overlap and save fuel, because the RPM were "only" 18,000RPM where ref. 1 believes that 230HPwere produced (BMEP = 14.3 Bar @ MPS = 22.7 m/s). The output was claimed to be 12% above that of the last CVRS engine (ref. 43).

With reliability now established Rossi regained the Championship with 9 wins. The rookie Jorge Lorenzo won another to total 10 wins to Yamaha from 18 races. The Ducati GP08 ridden by Stoner was 2nd with 6 wins.

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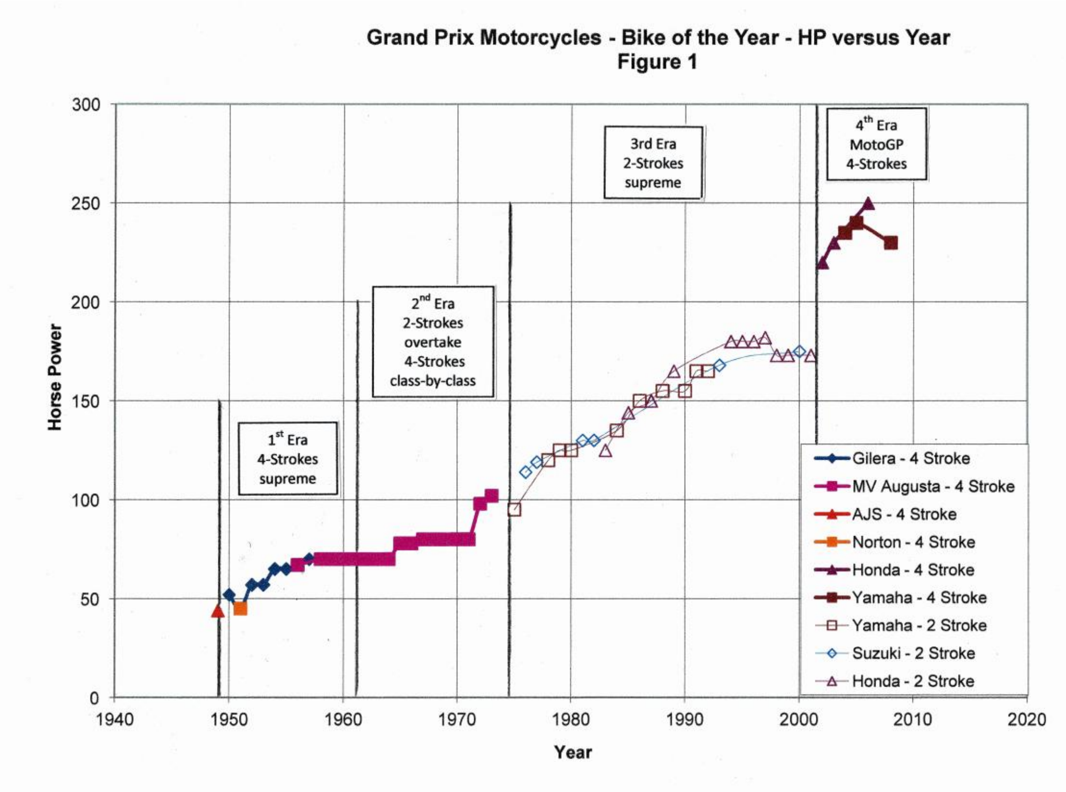
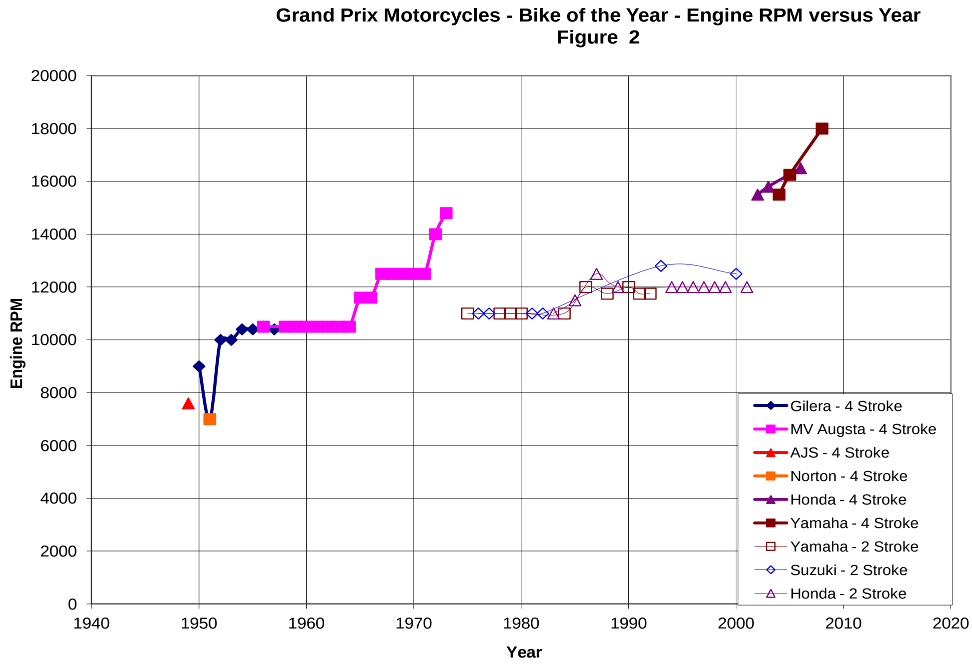
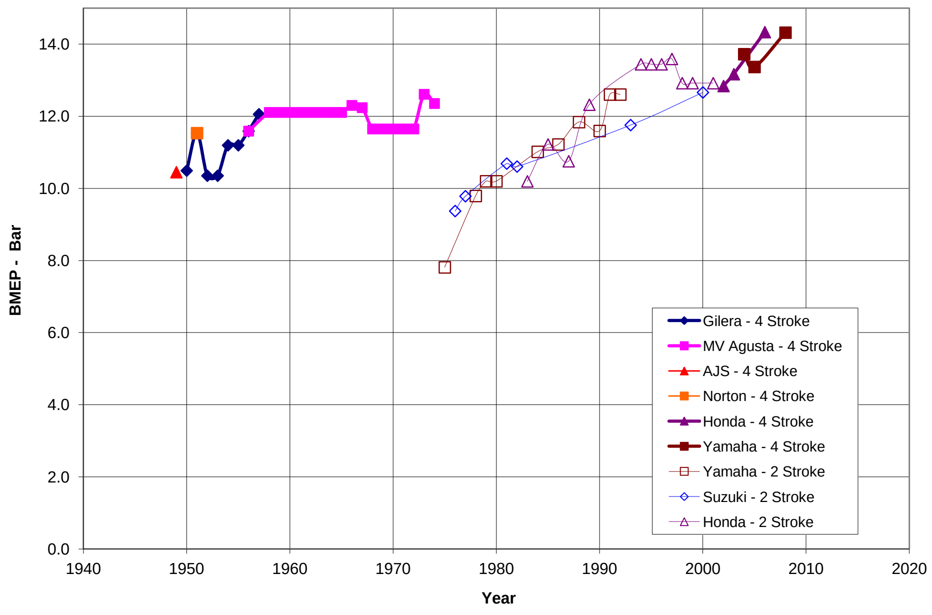
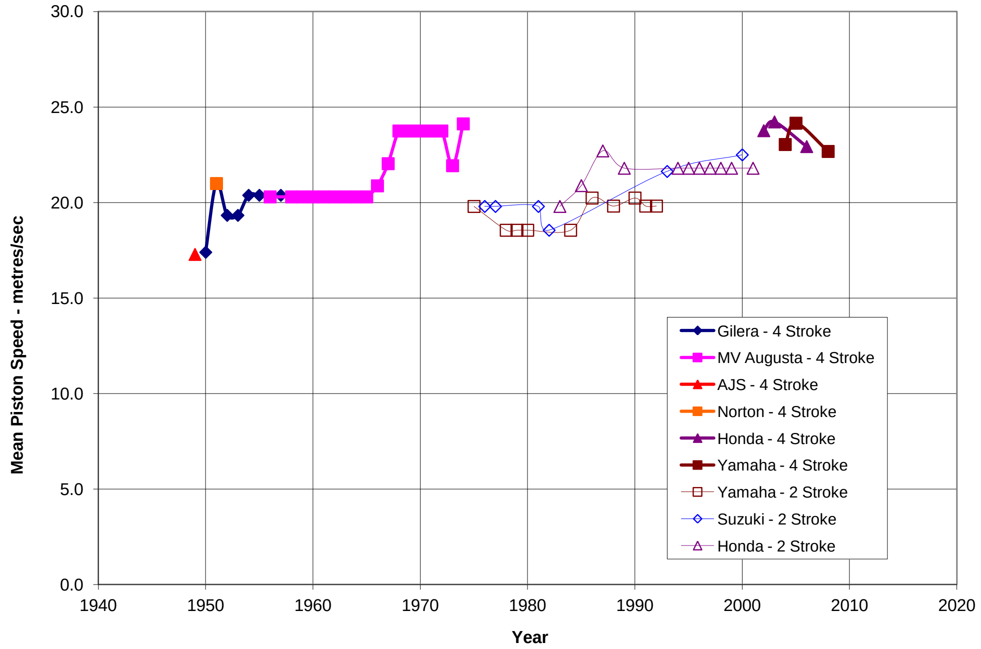

Grand Prix Motorcycles - Bike of the Year - HP versus Year
Figure 1
Horse Power
Year
1st Era
4-Strokes
supreme
2nd Era
2-Strokes
overtake
4-Strokes
class-by-class
3rd Era
2-Strokes
supreme
4th Era
MotoGP
4-Strokes
Gilera - 4 Stroke
MV Augusta - 4 Stroke
AJS - 4 Stroke
Norton - 4 Stroke
Honda - 4 Stroke
Yamaha - 4 Stroke
Yamaha - 2 Stroke
Suzuki - 2 Stroke
Honda - 2 Stroke

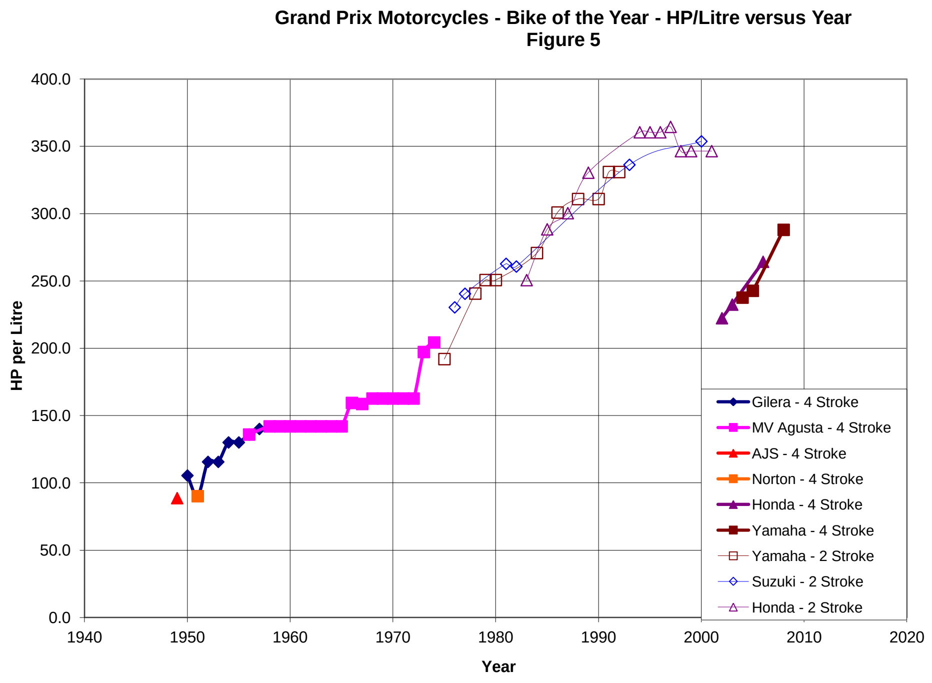

Grand Prix Motorcycles - Bike of the Year - Engine RPM versus Year
Figure 2
Engine RPM
Year
Gilera - 4 Stroke
MV Augusta - 4 Stroke
AJS - 4 Stroke
Norton - 4 Stroke
Honda - 4 Stroke
Yamaha - 4 Stroke
Yamaha - 2 Stroke
Suzuki - 2 Stroke
Honda - 2 Stroke

Grand Prix Motocycles - Bike of the Year - BMEP versus Year
Figure 3



Grand Prix Motorcycles - Bike of the Year - Mean Piston Speed versus Year
Figure 4

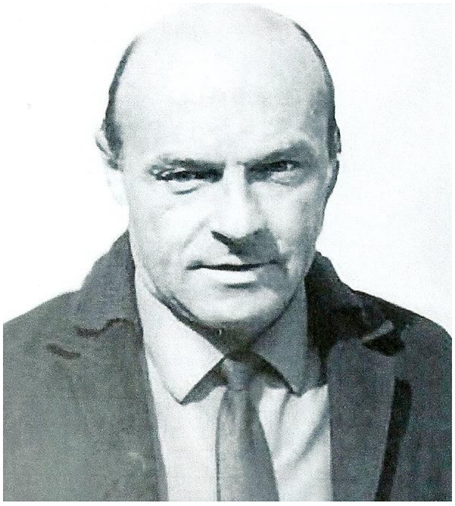



Grand Prix Motorcycles - Bike of the Year - HP/Litre versus Year
Figure 5
HP per Litre
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
1940
1950
1960
1970
1980
1990
2000
2010
2020
Year
Gilera - 4 Stroke
MV Agusta - 4 Stroke
AJS - 4 Stroke
Norton - 4 Stroke
Honda - 4 Stroke
Yamaha - 4 Stroke
Yamaha - 2 Stroke
Suzuki - 2 Stroke
Honda - 2 Stroke

Appendix of Illustrations

Index of Abreviations in captions
2st/4st = 2- or 4-stroke engine cycle.
NA = Naturally-Aspirated. MSC = Mechanically-SuperCharged.
AC/WC = Air- or Water-Cooled.
Configurations:- ILx = Transverse In-Line, x no. of cylinders;
y ^{0}Vx = Transverse Vee at y ^{0} bank angle, x no. of cylinders;
HOx = Transverse Horizontally-Opposed, x no. of cylinders.
SOHC/DOHC = Single or Double Overhead Camshafts per cylinder.
2/4 v/c = 2 or 4 valves per cylinder.
B = Bore (mm)/S = Stroke (mm) and B/S ratio.
V = Swept Volume (cc).
Italics indicate approximate figures.

A1-1. (P.2). Walter Kaaden. 1919 – 1996. The engineer who began the unstoppable advance of the 2-stroke engine in motorcycle racing.



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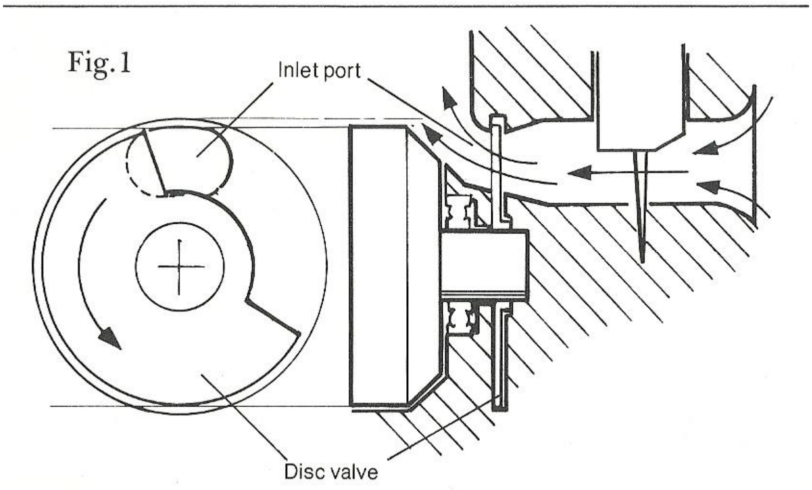
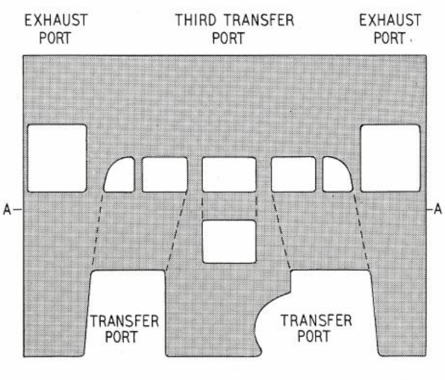
A1-2. (P.2). Disc inlet valve for 2-stroke engines.
Introduced into modern racing 2-strokes by Walter Kaaden of the East German firm of MZ in 1953 (but note that Alfred Scott had a rotary inlet valve on his successful 2-stroke engines in 1912!).



Ref. 20

A2-3. (P.2). The 3rd Transfer Port for 2-strokes.
Introduced by Walter Kaaden in 1959.

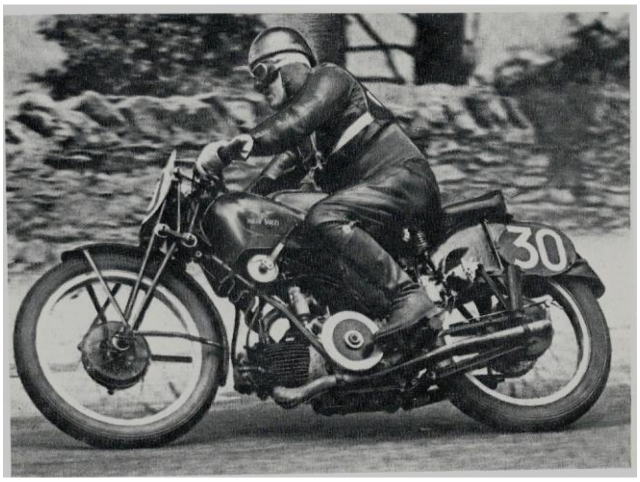
This diagram, from ref. 6, had the explanatory caption as follows:-
"*MZ cylinder liner split vertically through exhaust port bridge and 'unrolled'. Main transfer* [ports] *are also bridged to prevent ring trapping. Their gas streams converge on front cylinder wall at included angle of 124 degrees and slightly upward. Middle transfer* [3rd port] *stream is much faster and directed steeply upward*".



A2-4 (P.4). 1913 Scott. 2st. NA. WC cylinders; AC heads. IL2. B 70/S 63 = 1.11. V = 485.
Rotary inlet valve. 2 spark plugs per cylinder.

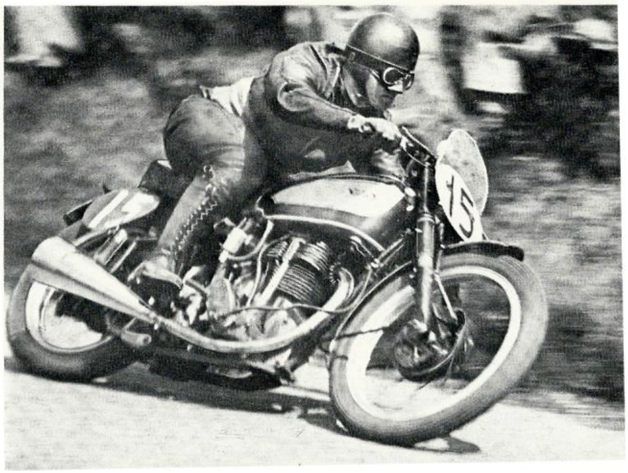
www.nationalmotorcyclemuseum.co.uk

A2-5 (P.4). 1935 Moto Guzzi. 4st. NA. AC. 120^0 V2. SOHC. 2 v/c. B 68/S 68 = 1. V = 494.
Stanley Woods riding. Note the external flywheel. The 2nd cylinder is hidden behind the rider's boot.



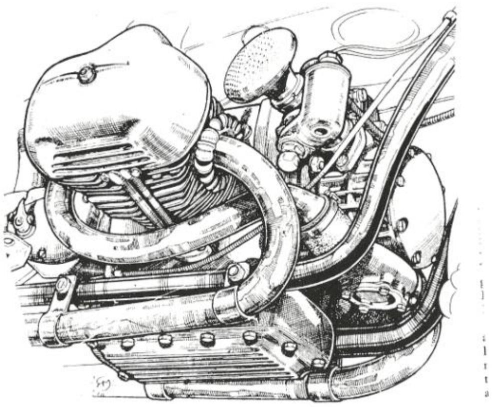
Ref. 6

A3-6 (P.4). <u>1938 Norton</u>. 4st. NA. AC. 1-cylinder. DOHC. 2 v/c. B 82/S 94.3 = 0.87. V = 498.
Harold Daniell riding. Note the very large “megaphone” exhaust.



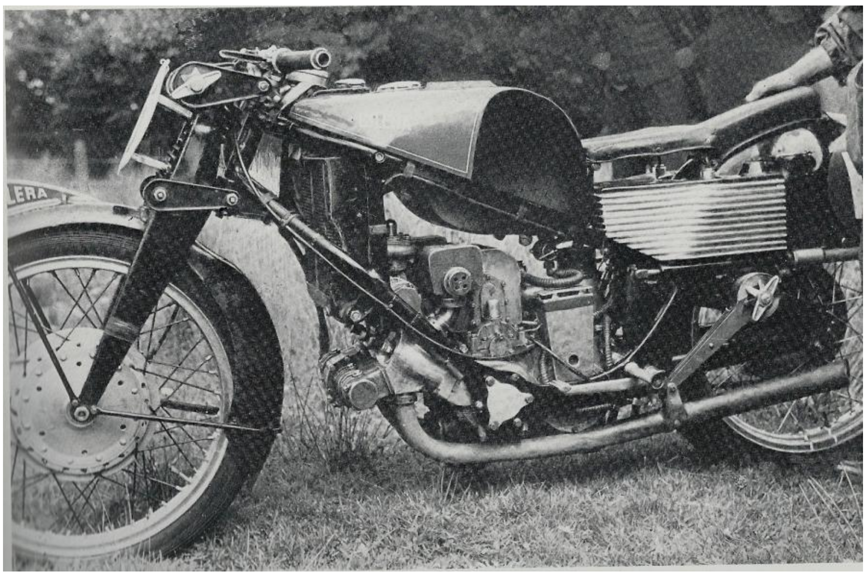
Ref. 6

A3-7 (P.4). <u>1938 BMW</u>. 4st. MSC. AC. HO2. DOHC. 2 v/c. B 66/S 72.= 0.917. V = 493.



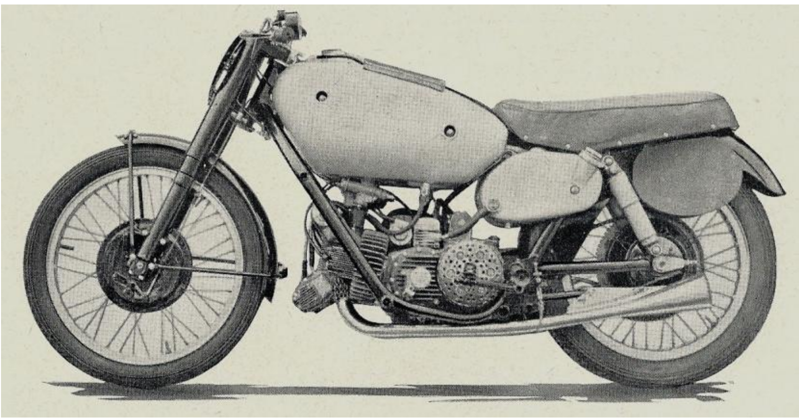
Ref. 6

A3-8. (P.4). <u>1939 Gilera</u>. 4st. MSC. WC. IL4. DOHC. 2 v/c. B 52/S 58 = 0.897. V = 493.



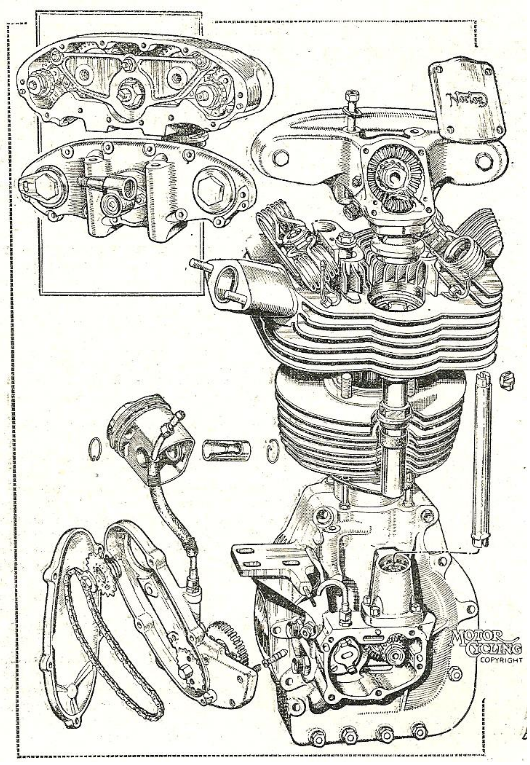
Ref. 6

A4-9 (P.5). <u>1949 AJS E90</u>. 4st. NA. AC. IL2. DOHC. 2 v/c. B 68/S 68.25. = 0.986. V = 496.
Picture is of the original 1947 machine. The 1949 type was the same except for carburettors mounted more nearly horizontal.



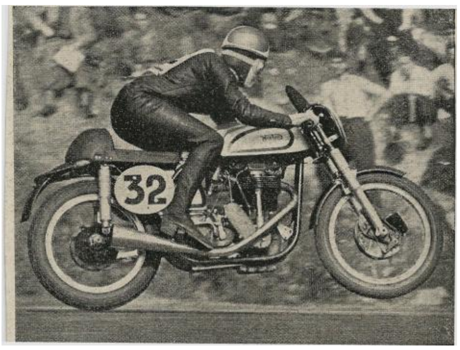
Famous Racing Motorcycles. J. Griffith. Temple Press. 1961.

A4-10. (P.6). <u>1951 Norton</u>. 4st. NA. AC. 1-cylinder. DOHC. 2 v/c. B 84/S 90 = 0.933. V = 499.



Motor Cycling 21 June 1951

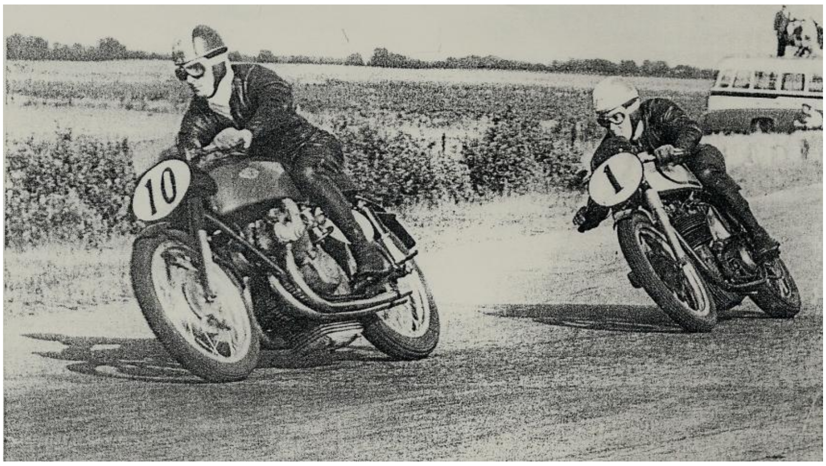
A4-11. (p.6). <u>1951 Norton. Geoff Duke riding</u>.



Motor Cycling 5 July 1951

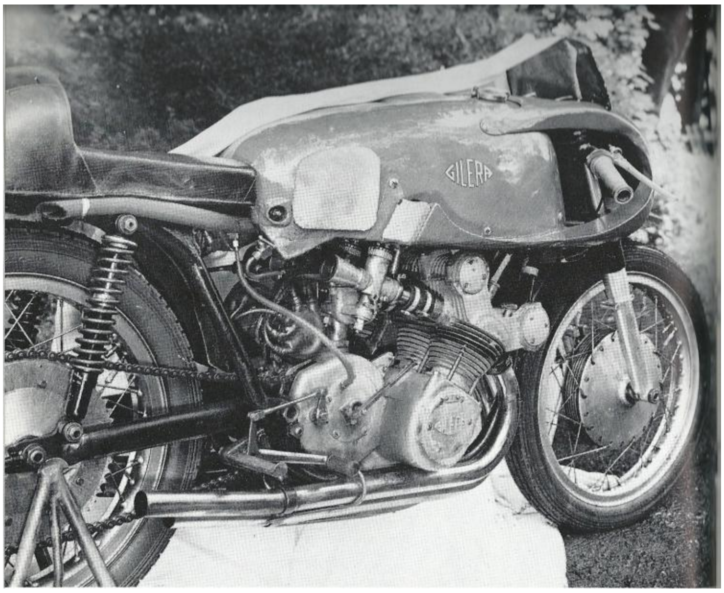
A5-12 (P.6). <u>1952 Gilera versus Norton</u>. The end of the single cylinder engine in Championship racing.

1952 Dutch Senior TT. Umberto Masetti, the 1950 Champion on the 4-cylinder Gilera leads Geoff Duke, the 1951 Champion on the 1-cylinder Norton. Masetti won the race and later the 1952 Championship. Duke joined Gilera for 1953 and won three consecutive Championships with them.



A5-13. (P.6). <u>1954 Gilera</u>. 4st. NA. IL4. AC. DOHC. 2 v/c. B 52/S 58.8 = 0.884. V = 499.

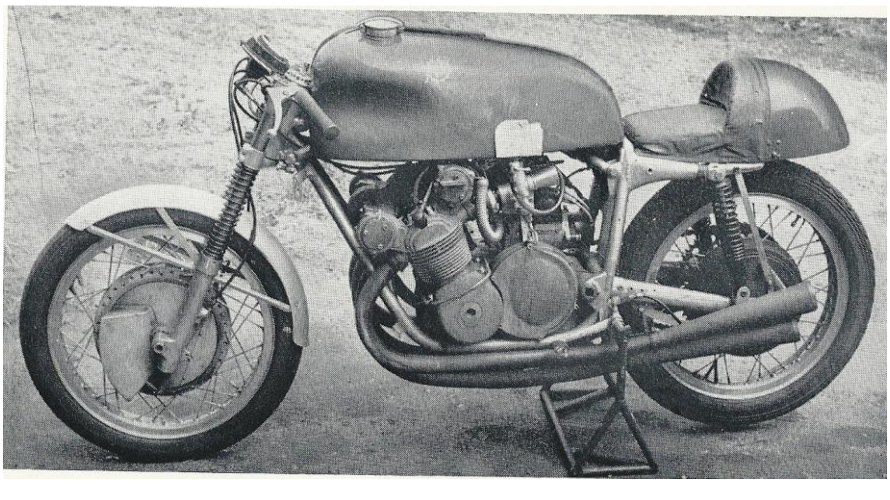
In 1956 megaphones were added to the exhausts.



Ref. 9

A5-14. (P.7). <u>1958 MV Agusta</u>. 4st. NA. AC. IL4. DOHC. 2 v/c. B 52/S 58 = 0.897. V.=493.

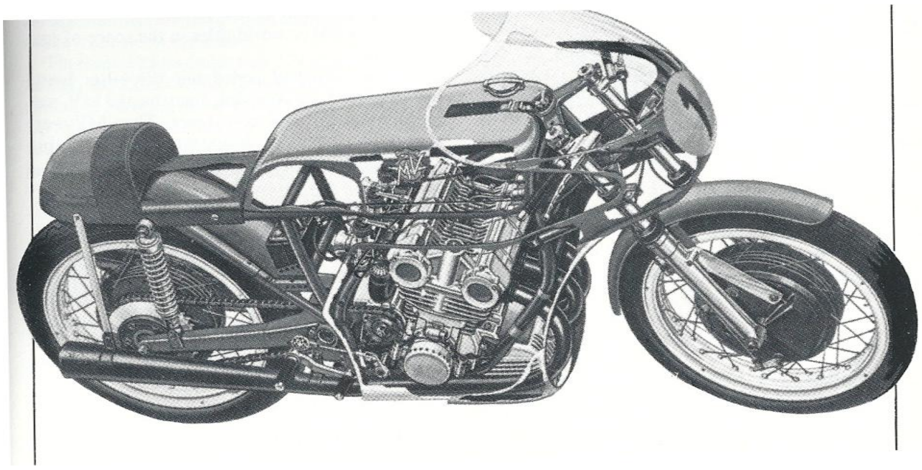
The picture is of a 1961 machine but the data and picture source (*Built for Speed.* J Griffith. Temple Press. 1962*)* reported the works statement that they had done "*very few or no modifications*" since the engines were built in 1952. Development had been mostly on the chassis.



A6-15. (P.9). Piero Remor. 1896 – 1964. The "father" of the Transverse 4-cylinder racing motorcycle.

Ref. 11

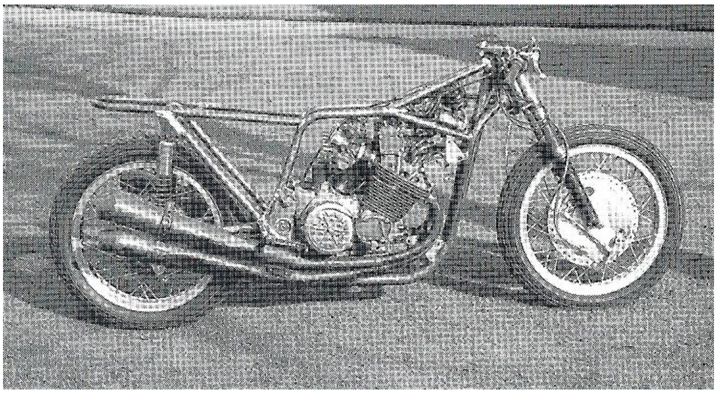
A6-16. (P.9). 1966 MV Agusta. 4st. NA. AC. IL3. DOHC. 4 v/c. B 62/S 54 = 1.148. V = 489.



Ref. 11

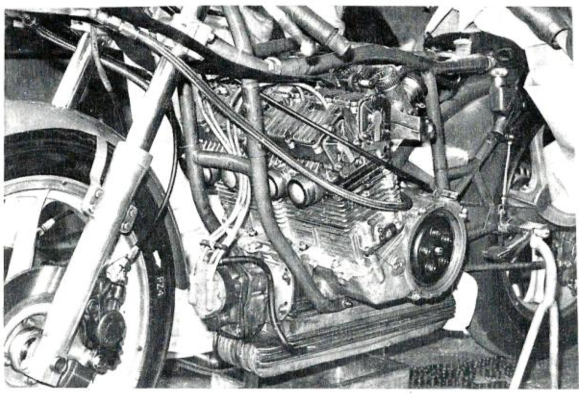
A6-17. (P.9). 1967 Honda. 4st. NA. AC. IL4. DOHC. 4 v/c. *B 59.6/S 44.7 = 1.333. V = 499.*
The engine is shown mounted in the special frame built by Ken Sprayson for Mike Hailwood in 1968 when he wanted better roadholding, after the works Hondas had been retired.. He raced the bike at minor Italian events at Rimini (2nd) and Imola (1st, with a 1966 engine).

Note the inverted cones at the end of the megaphones to widen the power range.



Ref. 24

A6-18. (P.11). 1973 MV Agusta. 4st. NA. AC. DOHC. 4 v/c. B 58/S 47 = 1.234. V = 497.



Ref. 6

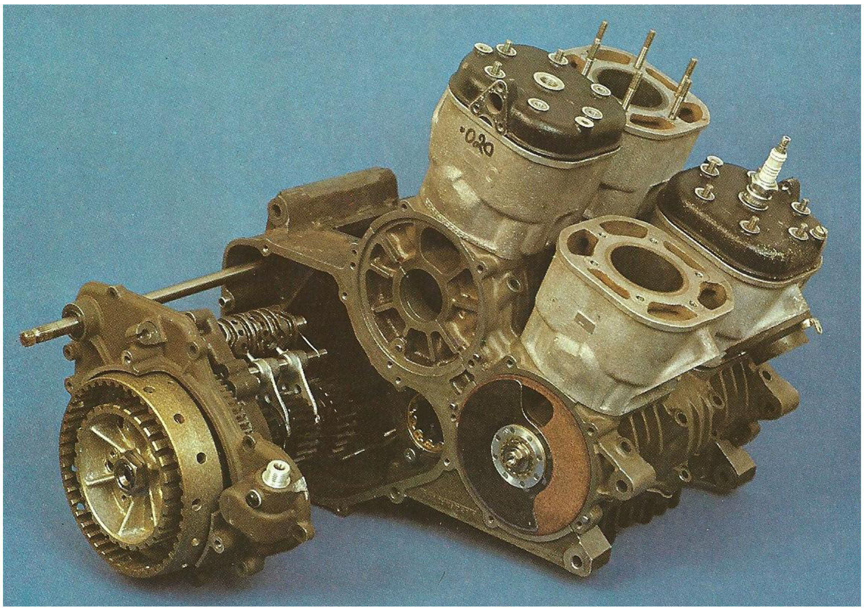
A7-19. (P.11). <u>Representing 1975 Yamaha OW23</u>. 2st. NA. WC. IL4. Piston-ported. B 54/S 54 = 1. V = 495.

The picture is of the 1979 development of the 1975 machine, having B 56/S 50.6 = 1.107. V = 499. The external difference, visible in the picture where two cables lead to the mechanism from the tachometer, is that the 1979 had a feature to reduce the exhaust port height which extended the useful power range to lower RPM when operated automatically.

Ref. 6

A7-20. (P.11). <u>Representing 1976 Suzuki XR14</u>. 2st. NA. WC. "Square-four", actually 2 x IL2 geared together
with parallel cylinders. Disc valves. B 54/S 54 =1. V = 495.

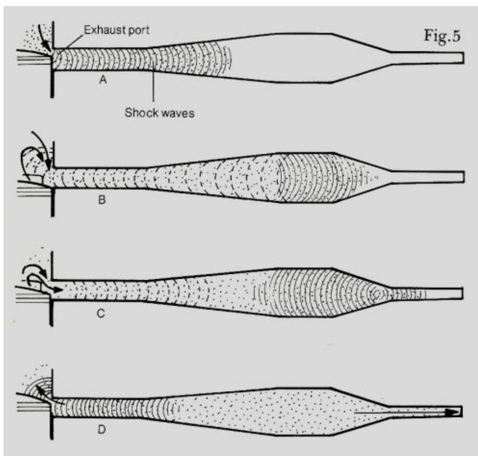
The picture is of a 1979 XR27B which had the front pair of cylinders lower than the rear.



Ref. 2

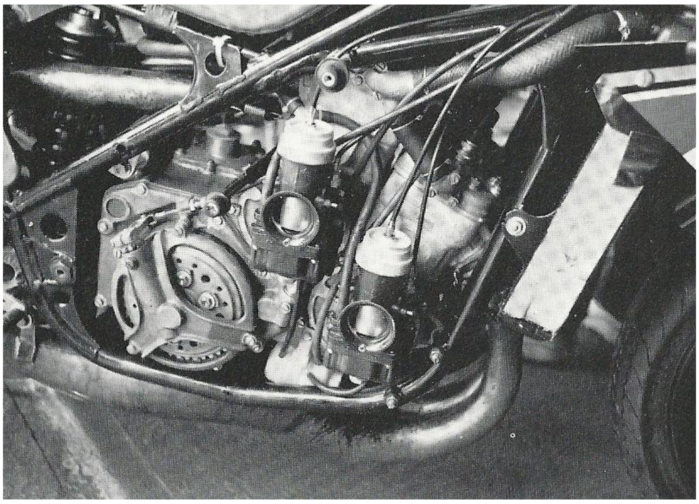
A7-21. (P.15). <u>Divergent/Convergent exhaust system for 2-strokes</u>.

The diagram illustrates the principle of the "Extractor/Repulsor" exhaust, as described on P.15, which assisted in increasing the 2-stroke BMEP by a factor of nearly 3 (ref. P.2) over 3½ decades of development.



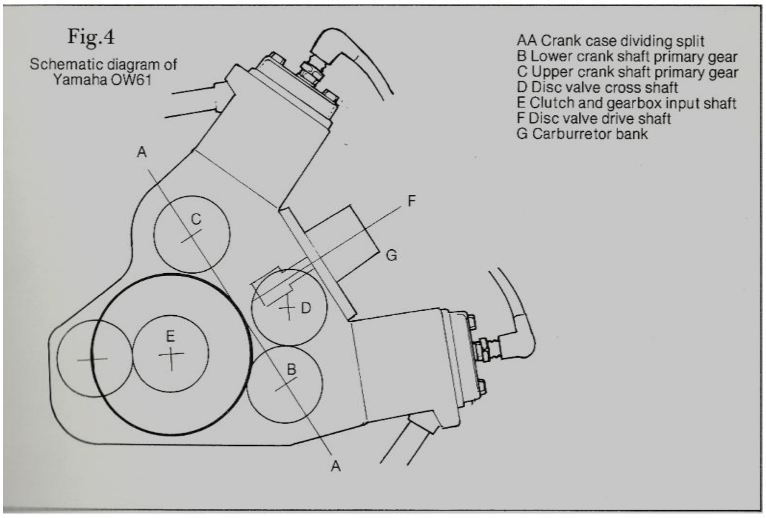
A8-22. (P.13). <u>1981 Suzuki XR35</u>. 2st. NA. WC. “Square-four”. Disc valves. B 54/S 54 =1. V = 495.

Ref.20

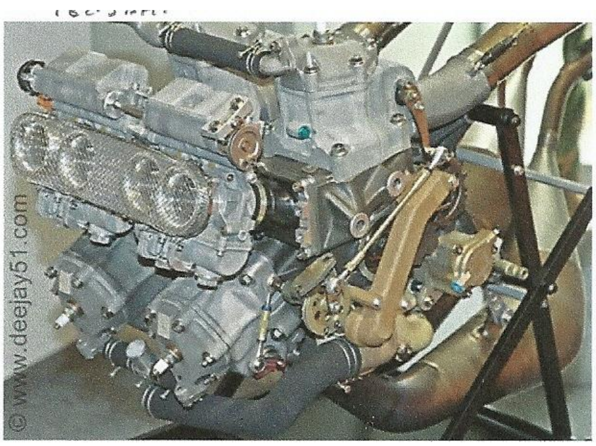


A8-23. (P.14). <u>1982 Yamaha OW61</u>. 2st. NA. WC. “V4”, actually 2 x IL2 geared together at an angle of 45^0.
Disc valve in the vee. B 56/S 50.6 = 1.107. V = 499.
The 1st engine of this configuration in 500cc GP motorcycle racing.

Ref.20

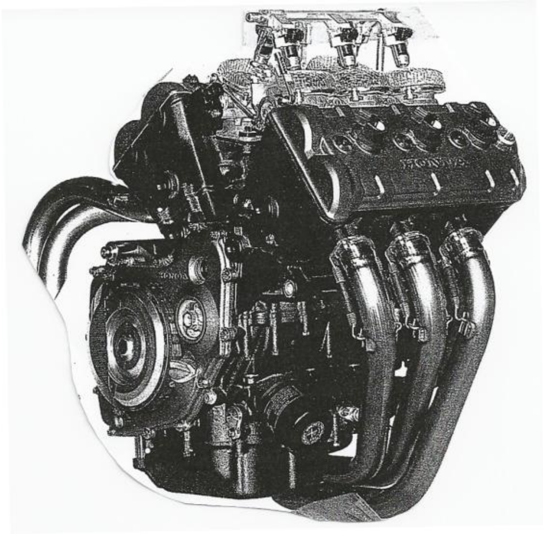


A8-24. (P.15). <u>1997 Honda NSR500</u>. 2st. NA. WC. 112^0 V4. Reed valves. B 54/S 54.5 = 0.991. V = 499.
Note the reed valves in the vee. The cylindrical final parts of the exhausts are silencers to meet FIM rules.



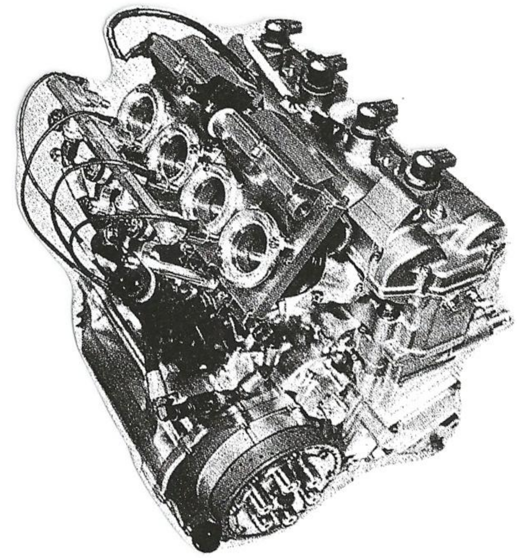
deejay51.com

A9-25. (P.17). 2003 Honda RC211V. 4st. NA. WC. 75.5^0V5. DOHC. 4 v/c. *B 74/S 46 =1.609*. V = 989.
Note the fuel injectors outside the inlet trumpets (a layout pioneered by the Grand Prix Renault in 1993).



Performance Bike
Feb. 2004

A9-26. (P.18). 2003 Yamaha YZR MI. 4st. NA. WC. IL4. DOHC. 5 v/c.
B ?/S ? V = "990".
Also with fuel injectors outside the inlet trumpets.

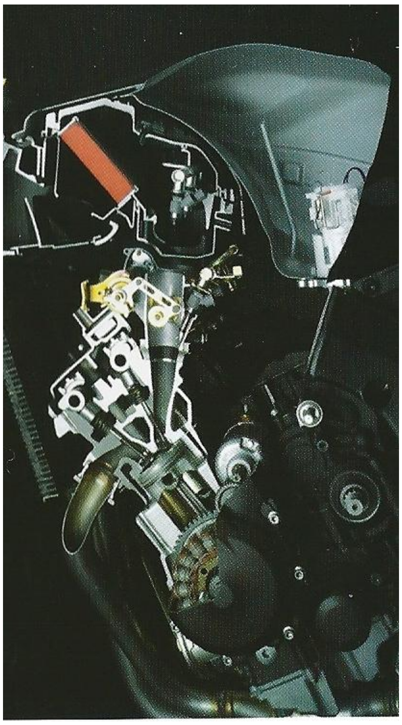


Performance Bike
Feb. 2004

A9-27. (P.18). 2004 Yamaha YZR M1. 4st. NA. WC. IL4. DOHC. 4 v/c. *B 84/S 44.6 = 1.883*. V = 989.
This was the redesigned engine which powered Valentino Rossi to two Championships.

Ref. 36

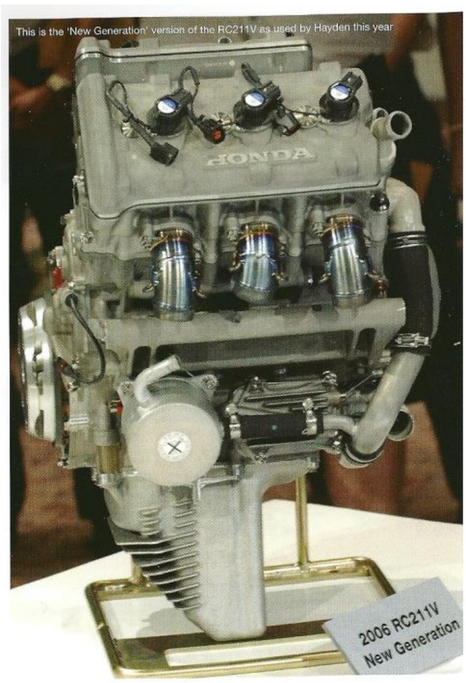
A10-28. (P.18). 2006 Yamaha YZF-R6. 4st. NA. WC. IL4. DOHC. 4 v/c. B 67/S 42.5 = 1.576. V = 599.4. This production fuel-injected engine section is included because it appears to be very similar externally to the YZR M1. The inlet downdraught is notable and the engine is forward-inclined like the M1. On the other hand, the exhaust is cramped.



RET 014
May 2006

A10-29. (P.18). Masao Furusawa. The leading engineer in the Yamaha M1 series of engines.

www.motorcyclenews.com



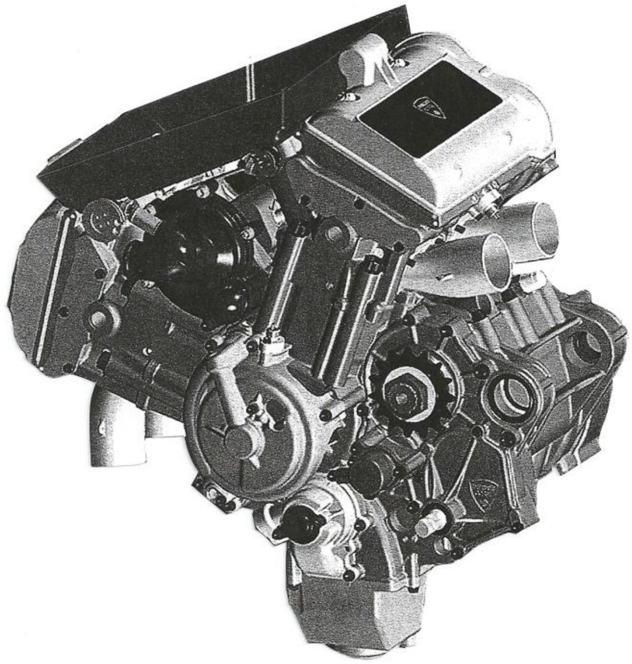
A10-30. (P.19). 2006 Honda RC211V. 4st. NA. WC. 75.5^{0}V5. DOHC. 4 v/c. *B 76/S 43.6 = 1.743. V = 989*.

Ref.33

A11-31. (P.19). Kyochi Yoshii. The leading engineer in the Honda RC211V series of engines.

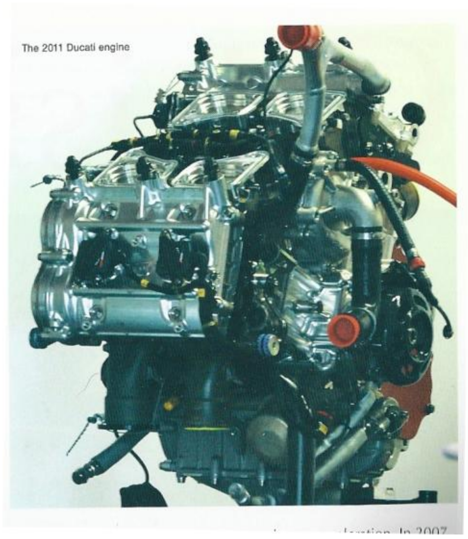
Ref. 33

A11-32. (P.19). 2003 Ducati GP03. 4st. NA. WC. 90^0V4. DOHC with Desmodromic Valve Return System (DVRS). 4 v/c. B 86/S 42.56 = 2.021. V = 989.



Performance Bike
April 2002

A11-33. (P.19). 2011 Ducati GP11. 4st. NA. WC. 90^0V4. DOHC. 4 v/c. B 81/S 38.8 = 2.088. V = 799.7. Representing the GP07 which powered the 2007 Champion.



Ref. 37