The Development of the Piston Engine for Motor Cars

Anders Ditlev Clausager
Chief Archivist Jaguar Heritage, Secretary SAHB

The paper discusses the development of the internal combustion piston engine from its first practical use in a wheeled vehicle in the latter part of the nineteenth century until around 1950. The initial challenge was to adapt existing stationary gas engines to be portable and self-contained for use in vehicles. This was successfully achieved by 1886 and development from then on concentrated on making engines more powerful, and more efficient. The quest for performance was spurred on by motor racing, and many useful features first appeared on high-performance engines. In Britain the peculiarity of the horsepower tax had a stifling influence on engine design between the wars. An important influence on the modern car engine was the development of high-octane fuels in the 1920s, which led to more efficient engine designs. Many other inventions eventually turned out to lead into blind alleys, but merit discussion in the context of their time, and examples are given of both successful and less successful developments. By 1950 several designs had appeared with features which today we take for granted in car engines. The paper concludes with a brief reference to some of the more important post-1950 developments.

KEYWORDS: Motorcar developments (early, inter-war, post war, later), taxation problems.

Introduction

Of the many inventions which have proceeded from and relied upon the invention of the internal combustion piston engine, I believe that none has had a greater impact on society, on the environment, and on our daily lives, than the motor car. Obviously, this is proposed from the point of view of an automotive historian… but if considered in the totality of the concept “motor car” and stretch it to include other road vehicles such as commercial and public transport vehicles, never mind the agricultural tractor, you may agree, even if you are not a car owner or user.

This is not to overlook other modes of transport which use internal combustion piston engines, such as rail locomotives, ships or aircraft. However, rail transport has equally successfully made use of steam or electrical power, and except for small aircraft, the skies have long since been dominated by the jet engine. Only in marine transport does the piston engine still hold the same pre-eminence as it does in the motorcar.

By 2009, there were in round figures 700 million motorcars on earth, or nearly one for every ten human beings, while in the most fully motorized countries there was around one car for every two people. Annual world production of new cars now stands typically around 50 million.[1] Not surprisingly, the motor industry and the entire infrastructure surrounding the motor car provide millions of people with employment. The widespread ownership or use of motor cars stretching back over decades has shaped the topography of many countries and has fundamentally altered our way of life, by giving us previously unheard-of freedom and choice in where and how we live, work, shop, send our children to school, or go on holiday.

However, like other forms of transport which rely on the burning of fossil fuels, the motor car has come to be seen as a major contributor to pollution, and to global warming. Since fossil fuels are finite, if we are to preserve the advantages afforded to us by personal mobility, we will in the future have to accept radical changes in the science and technology of the car. In 2011, I suspect that the motorcar powered by an internal combustion piston engine is already past its prime; it has lasted 125 years, but is unlikely to last as long again.

These thoughts were clearly far from the minds of the early inventors who in the closing years of the nineteenth century struggled to realise the dream that "carriages without horses shall go",[2] and to whom I shall now turn my attention, going on to provide an historical outline of how the motorcar engine developed from then onwards, up to around 1950.

From stationary engine to motive power for vehicles

It is not necessary here to examine in detail the many claims and counterclaims as to who actually invented the internal combustion piston engine or the motor car, so instead I shall simply sketch out the sequence of events which led directly to the most successful outcome (but see also the Appendix). In 1862 the French inventor Alphonse Beau de Rochas described the theoretical working cycle of a four-stroke internal combustion piston engine and published this in the form of a pamphlet; according to some sources a patent was issued to him. He did not actually build such an engine, but the fact that the theory was in the public domain was later to assume great importance.

In the same year of 1862, Nikolaus August Otto (1832-91) of Cologne in Germany built a free-piston atmospheric (i.e. compression-less) gas engine. This functioned so well that Otto and the engineer Eugen Langen set up a company to manufacture these engines. An improved design of engine was patented in 1866 and it deserves mention that in 1869 Crossley Brothers in Manchester obtained a licence to make the Otto & Langen engines. By 1872 the company became the Deutz Gas Engine Factory. In the same year, they appointed Gottlieb Daimler as works manager.[3]

Daimler (1834-1900) was an experienced mechanical engineer who previously had been in charge of the engineering workshop of the orphanage at

Reutlingen. Here he met Wilhelm Maybach (1846-1929), who had lived there from the age of ten. Maybach became Daimler's apprentice and protégé, and was to follow the older man when he moved to an engineering factory at Karlsruhe, and later to the Deutz factory.[4]

In 1876, Otto designed a new much-improved engine, using compression and working on the four-stroke principle, for which he was granted German patent number 532. This was a far more efficient design, which developed more power with a reduced fuel consumption. In the period 1877-79 the Deutz Company considered adapting gas engines for use in boats and trams. However, these attempts remained unsuccessful, as the stationary type of gas engine could not be used in a vehicle without substantial modification. It might be added that in the early years of the twentieth century, Deutz did make some cars.

An engine for a vehicle had to be much smaller and lighter to be portable, yet had to develop enough power to move the vehicle. It had to be completely self-contained, with systems for ignition and cooling, apart from carrying its own fuel supply on the vehicle. This dictated the use of a liquid rather than a gaseous fuel, and Otto did in fact experiment with both paraffin and petrol for his stationary engines. The Deutz Company also developed an electrical low-tension ignition system and applied for a British patent in 1878. By 1885, Deutz exhibited a stationary engine that used petrol and featured electric ignition.

At the end of 1881, following disagreement with Otto and Langen who were the directors of the Deutz Company, Daimler was sacked. Having accumulated enough capital to set up on his own, he moved to Cannstatt near Stuttgart where he bought a house with a large garden containing a greenhouse which became his laboratory and workshop. After a few months, Maybach joined him.

They continued to develop the four-stroke Otto type engine, but with the intention of producing an engine suitable as a motive power for vehicles. Not only did such an engine need to be much smaller than the stationary gas engines, but also it needed to run at a higher speed to develop sufficient power. In 1883 their first experimental engine ran; it had a single horizontal cylinder of 42mm by 72mm and a capacity of just about 100cc. Where large stationary engines ran at 180-200rpm, this tiny engine ran at 600rpm. The engine used a form of hot-tube ignition and Maybach's newly invented float chamber carburettor. The overhead inlet valve was of the automatic type, while the exhaust valve was operated by a pushrod from a half-speed eccentric on the crankshaft. In 1884, Daimler was granted a patent for a gas engine, although some of its features were impractical. It is debatable how much novelty there was in this design, and it apparently only avoided rejection by some careful wording.

To avoid conflict with Otto's patent, many other inventors of the period designed engines that worked on the two-stroke principle, notably Karl Benz of Mannheim in Germany whom I shall discuss below. However, in 1884 a German court declared that Otto's original patent for the four-stroke cycle of 1876 was invalid, since the principle had been published by Beau de Rochas in 1862, and had also been used by Reithmann in Austria. The court decision meant that Daimler and Maybach could proceed to develop their four-stroke engine. In a subsequent patent, they described a mechanically operated inlet valve but did not yet exploit this in practice. Their next designs were vertical single-cylinder engines which were some times called “grandfather clocks” from their shape. In 1885, such an engine was fitted in a two-wheeled “riding car” – in effect, a motorcycle – which was patented.

At this time, Daimler and Maybach were primarily interested in engines, rather than in complete vehicles. In 1886, they fitted one of their engines in a carriage. This was followed in 1887 by a motorboat, and soon Daimler engines were fitted in trams, light locomotives, and rail cars. A Daimler engine was even fitted in a dirigible balloon in 1888. Maybach designed a V-twin engine with the cylinders at an angle of 17 degrees that was patented in 1889. A four-cylinder in-line engine with overhead valves followed in 1890, intended for marine use.

Daimler continued to take out patents for his and Maybach’s inventions which by 1893 included a spray carburettor. They were successful in selling patent rights to several foreign licensees, including a newly-formed Austro-Daimler company in Vienna, the French partnership of Panhard & Levassor and, rather unlikely, the Steinway piano company of New York. Frederick Simms acquired the Daimler rights for the British Empire but within a few years he sold them on to H.J. Lawson’s syndicate, which in 1896-97 set up a factory in Coventry and began to make Daimler cars.

The other important German pioneer was Karl Benz (1844-1929). He was a trained engineer who established a mechanical workshop at Mannheim in 1871. A few years later, he began to experiment with gas engines. To avoid infringing Otto’s still apparently valid master patent on the four-stroke cycle, Benz designed an engine working on the two-stroke cycle, although different from Dugald Clerk’s two-stroke engine which had been patented in 1878. In 1882, Benz was able to patent certain improvements in gas engines and in the same year his company became the Mannheim Gas Engine Factory. When the Otto patent was declared void, Benz adopted the four-stroke principle.[5]

In many ways, the thoughts, ideas and designs of Benz progressed almost in parallel to those of Daimler and Maybach, but an important difference was that Benz decided to construct a fully-fledged complete motor vehicle, rather than designing an engine with several different applications. His 1886 patent was for a “Vehicle driven by a gas engine” and the first Benz three-wheeler which was successfully demonstrated in the summer of that year, followed the patented design almost exactly. Unlike the hot-tube ignition of the Daimler engine, Benz used electric ignition with a battery and trembler coil. Both engines used a rudimentary form of water-cooling.

Developments to the early 1900s

By 1886, the motorcar had become a practical proposition. Most early motorcars and their engines followed the designs of either Daimler, or Benz. Unlike their many predecessors and other contemporary pioneers, these two German inventors saw their efforts crowned with success. Their 1886 vehicles began the gradual dissemination of the idea of a self-propelled vehicle, and led directly to commercial production. France was especially quick to adopt the motorcar, with Panhard and Peugeot both making cars from the early 1890s onwards, and many significant developments would occur in this country.

There were however many problems to overcome. While internal combustion piston engines had proved themselves for stationary use, they required many adaptations to become efficient power units for vehicles. One fundamental requirement was that a car engine had to be able to run at different speeds, rather than at one ideal constant speed, as is mostly the case for stationary engines. This was achieved primarily by various means of altering the composition and amount of the air-gas mixture admitted to the engine, and later by variable ignition timing, while the adoption of variable gearing helped to adjust engine speed to various road speeds. Above all, there was the desire to increase the power output of engines to improve the overall performance of motorcars, spurred on by the early use of cars in competitive speed trials. This could be done simply by making engines larger, or by improving their efficiency.

Multi-cylinder engines quickly appeared. Daimler's V-twin engine of 1889 was soon followed by a parallel twin. By 1896, horizontally opposed twins were developed by Benz in Germany and Lanchester in England. As mentioned, Daimler had a four-cylinder boat engine in 1890, and four-cylinder engines were fitted to cars by Panhard and Daimler around 1895-96. Engine sizes grew as well. The 1886 Benz had an engine of 91mm by 150mm, or 975cc, and developed around 0.8bhp at 400rpm. Daimler's four-cylinder boat engine of 1890 was of 80mm by 120mm or 2413cc and developed 5bhp at 620rpm. The French inventor Fernand Forest is credited with designing an in-line six-cylinder engine with a single overhead camshaft (operating the exhaust valves; the inlet valves were automatic) in 1888, and together with Galicier patented a four-cylinder "compound" engine in 1890.[6]

In 1895, the French partnership of de Dion and Bouton turned their attention from steam-propelled vehicles to small petrol engines. Apparently to M. Bouton's surprise, the first prototype of 137cc ran satisfactorily at a speed of 3000rpm rather than its intended 600rpm. The higher speed caused problems for both the automatic inlet valve and the trembler coil ignition, and later production versions ran mostly at 1500rpm which was still considered a very high speed. The design became a tremendously successful power unit in motorcycles, tricycles and small motorcars called "voiturettes", whether made by de Dion-Bouton or by other manufacturers to whom they sold engines, apart from licensed production or simple copying.[7]

It is said that most early engine designers did not fully understand the science and the laws of physics which underlay the internal combustion engine but simply proceeded by trial and error and then developed any feature which seemed to promise some improvement, whether in efficiency and performance, in reliability and ease of operation, and soon also in refinement, as well as in simplicity, for cheapness of manufacture and ease of maintenance. Bouton's inadvertent discovery of the possibility of higher-speed engines was a classic case in point. Higher outputs could be achieved by making engines run faster, but primitive features such as hot-tube ignition and automatic inlet valves then proved unsatisfactory.

The petrol-engined motorcar also still faced competition from steam and battery-electric cars. While a steam car was complicated to operate, it was quiet and refined, and had astonishing torque and power literally from zero rpm. The electric car was simplicity itself to operate; it was similarly noiseless and blessed with excellent torque but was ultimately handicapped by its lack of power and limited range. Both of these propulsion systems obviated the need for a gearbox. It is however significant that, in the early years, at one time or other both an electric car and a steam car held the world's land speed record.

The state-of-the-art engine design of the early 1900s was typified by the 1901 Mercedes, designed by Maybach for the German Daimler Company. This was a substantial four-cylinder in-line engine which incorporated mechanical rather than automatic inlet valves, with inlet and exhaust valves arranged on opposite sides of the engine, operated from two camshafts in the crankcase: this became known as a T-head. Rather than a simple arrangement of finned or gilled tubes, the Mercedes had a proper radiator in front of the engine for its water-cooling system, and ignition was by Bosch's magneto system introduced in 1899. The car was a huge success both commercially and in competitions, and set the pattern for numerous imitators.

The first Mercedes had an engine of 5.9 litres developing around 35bhp at 950rpm. However, already in 1902 there was a 9.2-litre version with 70bhp at 1200rpm. Under the influence of early motor races and the search for higher performance, some engines grew to nearly grotesque sizes as may be gauged from the list of competitors in the Gordon Bennett races from 1900 to 1905. Already in 1900 there was a 10.6-litre engined car; 1901 saw a 17.1-litre Napier; the 1904 participants ranged from 9.9 to 17.8 litres; and the monstrous Dufaux of 1905 had an engine of 26.4 litres, still of four cylinders, and supposedly 150bhp.[8] Specific power outputs of 6-9bhp per litre were the order of the day. Inevitably the trend towards larger engines was self-defeating, since their bulk and weight were incompatible with contemporary primitive chassis, while the weight of the reciprocating parts limited the speed of such engines.

Apart from making larger four-cylinder engines, there was soon a trend towards engines with more than four cylinders. Six-cylinder in-line engines with their inherently better balance offered potentially greater refinement, but many early sixes were beset by problems of crankshaft whip, partly remedied by dampers, ultimately by more rigid crankshafts. Six-cylinder engines however became popular especially after they were taken up by Napier in 1904 and soon came to dominate the luxury market.

The French company CGV showed an eight-cylinder in-line engine in 1902, believed to be the world's first straight eight. Ader made a V8 for a racing car in 1903, which apparently had its roots in their V-twin engine, and Darracq also in France made another racing V8 in 1905, unsurprisingly of 22.5 litres and developing 200bhp. Rolls-Royce made of handful of V8 engines in 1905 for the "Legalimit" model, which was also an early exponent of a pressure lubrication system. De Dion-Bouton had a V8 in series production in 1910 but it is worth noting that the V8 found more ready acceptance as an aero engine and quite a number had been made by 1909, including by companies such as Renault and Wolseley, while Antoinette apparently coupled two together to make a V16, and Gobron-Brillié had an X8.[9] The de Dion-Bouton V8 is said to have influenced the American Cadillac engine of 1914 which began "the battle of cylinders" in the USA and was followed by Packard's V12 in 1915, the first series production car with a V12 engine. Most V8 engines were angled at 90 degrees, V12 engines at 60 degrees, and V16 engines at 45 degrees, following the precept that a the angle of a V-engine should be 720 divided by the number of cylinders with even firing intervals for smother running and better balance.[10]

Rather than simply making larger engines or engines with more cylinders, efforts soon began to improve the efficiency of engine designs, which typically concerned the cylinder head, the shape of the combustion chamber, the arrangement of valves, and the gas flow in and out of the combustion chamber. Some of the early engines showed scant regard for the shape of the combustion chamber, while side valves whether in a T-head or L-head clearly imposed their own limitations. The ideal might be a spherical combustion chamber but this could not be readily achieved. A hemispherical chamber was possible if overhead valves were used. To suit the hemispherical shape of the chamber, overhead valves should ideally be arranged so that inlet and exhaust valves were at an angle on opposite sides of the cylinder, and this led to early experiments with overhead camshafts, which might operate the valves directly, or through short rocker arms.

Of several early experimental designs, Loutzky's Daimler marine engine of 1902 had a cone-shaped combustion chamber with vertical inlet valves and near-horizontal exhaust valves operated by a single overhead camshaft and rocker arms. The Pipe and Welch car engines of 1904 had proper hemi-heads – in the case of Welch with an overhead camshaft – as did the Weigel and Clément-Bayard of 1908, and similar solutions began to appear on aero engines and even on stationary or marine Diesel engines. The engine which clinched the argument in favour of a hemi-head twin overhead camshaft design with four valves per cylinder was the Peugeot Grand Prix racing engine of 1912, usually credited to Ernest Henry.[11]

However, while such an engine was highly suitable for racing (and would influence many aero engine designs in the coming World War) it was as yet too complex and costly for everyday motoring. Mass-production engines were more conservative and evolved more slowly. In 1908 the Ford company introduced the Model T with a simple four-cylinder engine with a combination of features which would remain standard practice until the Second World War and even after, such as a single casting for the cylinder block rather than separate or paired cylinders; a detachable cylinder head; and a single camshaft operating side valves all on the same side of the engine, the so-called L-head. With a compression ratio of about 4:1, this 3.6-litre engine developed around 20bhp. The simplicity of the design combined with Ford's mass-production methods made the Model T an affordable and practical car for everyman. Around the same time, European attempts at providing cheap popular cars resulted in the so-called cyclecars, which were notable for their use of air-cooled one or two cylinder engines of motorcycle type. They enjoyed a short-lived boom which ended soon after the First World War, when European manufacturers embraced mass-production methods to offer proper light cars or small cars designed on the lines of bigger cars (Morris, Austin, Citroën, Opel and Fiat).

One recurring criticism of early piston engines with poppet valves was that they were noisy. The American Charles Yale Knight came up with the alternative of a double-sleeve valve engine, where valve ports in the cylinder wall were uncovered at the appropriate times by synchronised up-and-down movements of two concentric sleeves running between the piston and the cylinder wall, operated by connecting links from a half-speed crankshaft. This "Silent Knight" engine was fairly widely adopted by luxury car makers such as Daimler in Britain. Among its advantages were that the combustion chamber could be shaped closer to the ideal and the possibility of large port openings promised high efficiency, but oil consumption was often high and engine speed was restricted by the original heavy cast-iron sleeves, later replaced by lighter steel sleeves. A few companies (Panhard and Voisin) used such engines through the 1930s but then abandoned them. The alternative single-sleeve valve design by Burt McCollum had sleeves that partially rotated, as well as moving vertically. Single-sleeve valves were widely used on aero engines with great success, until superseded by jet engines.

Alongside the basic design of engines, their associated systems were much improved in the years before the First World War. Apart from a few small cars, water-cooling had become universal, with the honeycomb radiator first seen on the 1900 Mercedes and a cooling fan, but not yet always with a water pump. Pressurised lubrication systems with an oil pump were beginning to replace drip-feed total loss or "splash" systems. Ignition was usually by high-tension magneto and most carburettors were of the spray or jet type. Charles F. Kettering in the

USA invented an electric self-starter, which was at first fitted to Cadillac cars in 1911, and obviated the need for starting the engine using a manual handle. Kettering also came up with an improved battery and coil ignition system, and fitted the engine with a dynamo to keep the battery charged. This opened the way for equipping cars with electric lighting and many other accessories.

A British problem: horsepower rating and taxation

The original formula for determining the rated horsepower of a car engine had been developed by the Royal Automobile Club in 1906. While "the formula was not intended to be a scientific statement of horse-power … manufacturers were asked to adopt the rating for the purposes of catalogue description".[12] The intention was to guide potential car buyers, seeking to compare cars of different prices.[13] In working out the formula, the RAC had made a number of assumptions, reflecting the then-current state of engine design, and therefore assigned fixed values to such factors as piston speed, mean effective pressure, and average mechanical efficiency. Cancelling out the numerical values gave as the end result the following formula:

$$hp = D^2N/constant$$

where D was the bore of the cylinder, and N was the number of cylinders; if the bore was measured in inches, the dividing constant was 2.5, and if measured in millimetres, it became 1612.9. As the formula included the square of the bore, it became effectively an expression of the piston area of an engine. The reason why the stroke of the cylinder was not included was that in the 1906-07 period, most car engines in Britain tended to have nearly "square" dimensions, with bore and stroke of approximately the same size. It was found that of sixty-nine cars in 1907, the stroke/bore ratio was on average 1.16, and for British cars the average was 1.12.[14]

It seems probable that the RAC formula already at the time it was devised gave a somewhat conservative estimate of actual power output of many car engines, and technical developments soon left it hopelessly behind as even an approximation of brake horsepower. In 1909, however, the Chancellor, Lloyd George, seeking to increase taxation on motor vehicles to finance the road board, adopted a sliding scale of annual tax on cars, based on the RAC formula (he also introduced the first petrol tax of 3d per gallon). The scale of taxation implemented was not yet entirely proportional to the actual RAC hp rating of engines but was as shown in Table 1.[15]

In practical terms, this scale meant that most of the cycle cars which began to emerge from 1910 onwards, and which had small single or twin-cylinder engines, fell within the lowest tax bracket. The new "light cars" which had engines rated at between 8hp and 12hp would be taxed at 3 Guineas per year and the Ford Model T with a four-cylinder engine of 3.75in bore and 22.5hp would cost 6 Guineas per year (a Guinea is £1 1s or £1.05p). At the top end of the scale there were very few cars with engines over 60hp, but a Rolls-Royce Silver Ghost (officially known as the 40/50hp model)

Table 1 – Scale of horsepower tax, 1909

RAC horsepower rating of engine	**Amount of annual tax**
Below 6½ horsepower	£2 2s
Over 6½, but not over 12 horsepower	£3 3s
Over 12, but not over 16 horsepower	£4 4s
Over 16, but not over 26 horsepower	£6 6s
Over 26, but not over 33 horsepower	£8 8s
Over 33, but not over 40 horsepower	£10 10s
Over 40, but not over 60 horsepower	£21 0s
Over 60 horsepower	£42 0s

which had a six-cylinder engine of 4.5in bore rated at 48.6hp would cost 20 Guineas per year. This Rolls-Royce, incidentally, had a stroke also of 4.5in, while the Ford had a stroke of 4in, and both were therefore typical of the square engines of the pre-1910 period.

Even in this early form, the horsepower tax influenced the engine designs and product plans of British car manufacturers. Among the leading manufacturers, Wolseley until 1910 had made mostly square engines; for instance, their four-cylinder so-called 16hp model of 1906 had bore and stroke both of 4in and was in fact rated at 25.6hp. They now brought out a range of new models with smaller bores and longer strokes, of which the 12/16 model had bore and stroke of 79mm by 114mm – a ratio of 1.44 – was rated at 15.5hp and fitted into the 4 Guinea taxation class. Another new model, the 20/28, kept the 4in (102mm) bore of the old 16, but had a longer stroke of 130mm.[16] Other British manufacturers followed similar policies so that already by 1911, it was calculated that the average stroke/bore ratio of British cars had increased from 1.12 (the 1907 figure) to 1.37, and by 1924 it would reach 1.52.[17]

By that time the next step in developing the horsepower tax had occurred. In 1920, the government introduced the proportional horsepower tax, where the tax would be £1 on each RAC horsepower (or on that part of one hp which exceeded 0.1, i.e. an engine rated at 11.2hp would be taxed on 12hp), with a minimum tax of £6.[18] This was the system which with only slight variation (such as the reduction to

15s per hp in 1935, and the increase to 25s per hp in 1940) would remain in place until the end of 1946.

I have devoted this discussion to the British horsepower tax as it had an important long-term effect on engine design in this country. It has been demonstrated that the stroke/bore ratio of typical car engines changed very quickly even after the introduction of the original broad-band taxation in 1909. From the original pre-1910 square engines, car manufacturers adopted the small-bore long-stroke engines, which remained typical in Britain until well after the horsepower tax was abandoned in 1947-48. It is however correct that at the beginning of the

Table 2 – Development of horsepower tax

Amount of tax per RAC hp	**Effective from**	**Effective to**	**Minimum tax**
£1	1 Jan 1921	31 Dec 1934	£6
15s (£0.75)	1 Jan 1935	31 Dec 1939	£4 10s (£4.50)
£1 5s (£1.25)	1 Jan 1940	31 Dec 1946	£7 10s (£7.50)
Capacity Tax, £1 per 100cc, for new cars only	1 Jan 1947	31 Dec 1947	£7 10s (£7.50)
Flat rate tax for cars first registered on or after 1 Jan 1947	1 Jan 1948		Initially, £10 for all cars

1920s, many car engines, not only in Britain, were of the long-stroke type. One often-cited advantage of a longer stroke was better torque at low engine speeds, an important consideration when most motorists still demanded engines which were flexible enough to allow use of top gear even at very low road speeds. Among the exceptions was the above-mentioned Ford Model T with an engine designed in 1908, and the more recent Rover Eight small car with a two-cylinder engine of 85mm by 88mm.

Not only did the British taxation system dictate stroke/bore ratios but it also had some influence on the number of cylinders used in engines. Taking as the example an engine of approximately 2000cc which might have four, six or eight cylinders, and using the then prevailing stroke/bore ratio of 1.5, while bearing in mind that the public expected an engine of this size to be rated at no more than 16hp for taxation purposes, we find that the engine can be designed in the following different ways, Table 3.

It will be seen that the horsepower rating increases by 2hp for each additional two cylinders. If we want to design a square engine, with bore and stroke the same, as also indicated in the table, the taxable horsepower ratings become

Table 3 – Variations in engine dimensions

Number of cylinders	Bore	Stroke	Capacity	RAC or tax hp	Stroke/bore ratio
Four	75mm	112mm	1979cc	14hp	1.49
Six	65mm	100mm	1991cc	16hp	1.54
Eight	60mm	90mm	2036cc	18hp	1.50
Four	86mm	86mm	1998cc	18.3hp (19hp)	1.00
Six	75mm	75mm	1988cc	20.9hp (21hp)	1.00
Eight	68mm	68mm	1976cc	22.9hp (23hp)	1.00

quite unacceptably high. Again, the horsepower ratings are higher for the higher number of cylinders.

An engine with a long stroke and a small bore was well suited to the simplicity of the side-valve layout that prevailed between the two world wars. If overhead valves were used on an under-square long stroke engine, the valve sizes were restricted by the small bore, and the engine became taller. This meant that simple thermo-syphon cooling had to be replaced by pump cooling, while overhead valve gear of whichever kind also demanded a full pressure lubrication system.

The quest for efficiency

Major developments occurred between the wars with regard to compression ratios and fuels, a breakthrough that would open the way to more efficient engines. It was acknowledged that one way to improve the efficiency of the petrol engine was to increase the compression ratio, which then was typically around 4:1 or 5:1. Attempts to raise compression ratios were frustrated by contemporary fuels which in engines with higher compression ratios would detonate too early or unevenly, causing engine "knock" (pre-detonation) which could harm the engine. In 1912, Harry Ricardo by experiment determined that benzole, a fuel derived from coal, allowed him to increase the compression ratio from 4:1, to 5:1, which improved the power output of his test engine by about 20 per cent.[19] He subsequently determined that ethyl alcohol had a similarly beneficial effect, and allowed the use of a compression ratio as high as 8:1.[20]

In the USA, Kettering and Midgley, working for the General Motors Research Corporation, discovered in 1922 that addition of a tetraethyl lead compound to petrol would significantly increase its knock resistance. In 1924 the Ethyl Gasoline Corporation was formed for the purpose of marketing this compound, and the first leaded petrol became commercially available. In 1925, Dr Edgar of the Ethyl Corporation devised the octane rating as a measurement of knock resistance of petrol (Ricardo had earlier used a "toluene" rating system). Petrol with a rating of 100 octane was practically knock free. At this time, the best commercially available petrol had an octane rating of 50 to 55, but this limited the compression ratio that could be employed and thus hampered the development of more powerful and efficient engines.[21]

Table 4 – Development of octane rating and compression ratio[22]

Year	**1925**	**1931**	**1935**	**1939**	**1950s**	**1960s**	**2000s**
Octane rating	45-50	63-75	72-78	74-83	85-90	Up to 100	92-98
Compression Ratio	4	5.2	6	6.3	7-8	8-9	9-11

Once higher-octane fuels became available, the compression ratio could be increased, but on the side-valve engines, their lay-out and the design of cylinder head meant that it was impossible to increase the compression ratio much beyond about 6:1.[23] It therefore became desirable to use overhead valves. Overhead-valve engines could be designed more logically and simpler, if the stroke was shorter and the bore bigger. A bigger bore would permit the use of larger valves, advantageous on the overhead-valve engine, which has a better pattern of gas flow than the side-valve engine. Another point to consider was that an engine with a shorter stroke would have a lower average piston speed at a given engine speed, as the piston had to travel a shorter distance up and down in the cylinder. Accordingly, engine life and reliability would be improved. Alternatively, if piston speed was kept the same, the short-stroke engine speed could be higher.

One remarkable design using overhead valves, operated by pushrods, and a very high compression ratio was the Talbot engine developed by George Roesch in the 1920s and early 1930s, which despite a stroke of 100mm (later 112mm) ran happily at up to 5000rpm with a compression ratio of 10:1 in racing form, using high-octane fuel, producing up to 138bhp from a capacity of just under 3 litres. Part of the secret was the lightness of its reciprocating parts. The Talbot engines also showed remarkable reliability and quietness of running.[24]

Engines with shorter strokes began to appear both in the USA and in Europe. In the USA, Chevrolet for 1929 introduced a new overhead-valve six-cylinder engine of 84mm by 96mm. In Europe, an example of similar development was seen in the case of the Italian Fiat. Their 509 model of 1925 had cylinder dimensions of 57mm by 97mm, but their 508 model of 1932 had dimensions of 65mm by 75mm. In 1934, this engine was converted from side valves to overhead valves, and the overhead-valve engine of the 1937 Fiat 1100 was of 68mm by 75mm.[25] In Germany in the latter part of the 1930s the trend was similarly back towards the original pre-1914 type of engine with more square bore and stroke dimensions, even in some cases towards the over-square engine with a bore larger than its stroke. Of popular German cars, the 1938 Opel Olympia had an engine of 80mm by 74mm (1488cc), and the original Volkswagen of 70mm by 64mm (985cc).[26] Both basic designs incidentally continued in production into the 1960s.

Because of the restricting horsepower tax, over-square engines were not acceptable to the British public between the wars. A survey of thirteen British small car engines below 1300cc capacity of 1938-39 shows that stroke/bore ratios varied from 1.4 to 1.67, with an average of 1.56. At the same time, sixteen European small car engines of similar size (but including the 1488cc Opel engine) had stroke/bore ratios varying from 0.92 to 1.64, but with an average of 1.19.[27] This group included four German engines which were over-square: the Opel and the Volkswagen which both had overhead valves, and two DKW two-stroke engines.

General developments from 1919 to 1939

The typical engine of around 1920 was not very different from the Model T: an in-line four-cylinder unit with side-by-side valves, a monobloc casting for a combined block and crankcase but with a detachable cylinder head, a crankshaft with three main bearings, but often only two on smaller engines. Lubrication was still often by splash, cooling by thermo-syphon, and ignition by magneto. American manufacturers had been quicker to adopt coil ignition and despite some resistance, this also eventually triumphed in Europe. The electric self-starter soon became universal. Similarly, pressure lubrication systems and cooling systems with pump and thermostat had become the norm by the 1930s.

The continuing trend towards more cylinders was understandable, as six or eight cylinders offered smoother running and greater flexibility. One of the first successful straight-eight engines was offered by Bugatti in 1920 and became associated with the sports and racing cars of this make, while in Britain there was the Leyland Eight of 1921. This engine type was popular in the USA where thanks to higher production figures it could be made at reasonable cost, several makers eventually offered such engines in cars costing less than $1000, and from 1931 onwards Buick made only straight-eights with overhead valves. In Europe the straight-eight was mostly found in the luxury class although Hillman and Wolseley brought out more modestly-priced versions. It may have been invented for the sole purpose of “making a larger car longer”,[28] and finally disappeared in the 1950s when it was replaced in the USA by V8 engines.

Small six-cylinder engines had been introduced from 1919 onwards, with the two-litre AC being an early example, followed by a Talbot of 1.5 litres in 1924. The popularity of the six grew during the next decade and by 1930, they outnumbered all other types. The “pint-sized six” – actually typically of 1200-1400cc or over two pints – enjoyed a vogue in early 1930s, especially in Britain where the 1930 Wolseley Hornet began this trend. They were effectively made redundant within a few years, as rubber engine mountings were introduced on four-cylinder engines, and synchromesh made gear changing much easier. In later years there were very few six-cylinder engines smaller than 2 litres.

Many European engines of the early 1920s featured single overhead camshafts, often inspired by wartime aero engine practice, but such engines were mostly confined to the more expensive type of quality or sporting car. In Britain, there were AC, Bentley, Lanchester, Leyland, Napier, and Wolseley: only the latter was in the popular class, as were the later Singer and Morris, and the Italian Fiat 509. In Europe, Ballot, Bugatti and Hispano-Suiza adopted this system. Overhead camshafts were at this time often driven by shaft or by eccentrics, more rarely by gear trains, but chain drive was a rarity as it was considered noisy and was some times unreliable; the AC was an exception, and was interesting as it adopted a spring tensioner for the camshaft drive chain. A pioneer of twin overhead camshafts outside the sports or racing car class was the German Horch from 1926 and in the light car class, the French Salmson from 1931. Some manufacturers rejected the overhead camshaft on grounds of noise, notably Rolls-Royce, but despite its advantages on high-performance engines, it was still a more expensive and complicated solution.

Pushrod-operated overhead valves had a vogue on American cars in the early 1920s although many manufacturers here later went back to side valves, often using the more efficient "turbulent" head devised by Ricardo. Two important American manufacturers using overhead valves were Buick and Chevrolet. Gradually, however, they gained ground on European cars, although even by 1939, of the important British mass-producers only Morris and Vauxhall had introduced them; they were more widely used elsewhere in Europe. Some manufacturers endeavoured to combine the best of both worlds, by adopting systems which permitted a near-hemispherical shape for the combustion chamber with the simpler pushrod-operated valves. Here Riley was a pioneer with the Nine engine of 1926, with its twin chain-driven camshafts high in the cylinder block, and a similar layout was adopted by the French Talbot company in the 1930s. In 1936, BMW in Germany came up with a cross-pushrod system for the 328 sports car engine. Georges Roesch of Talbot had patented a layout for pushrods operating overhead valves in V-formation in 1924 but this was not used on his production cars.[29] Instead the same idea appeared on the Peugeot 203 in 1948, and later on the Armstrong-Siddeley Sapphire.

One of the most unusual production engines of the early 1920s was the compact V4 engine of the Lancia Lambda. The company had made V-type aero engines during the war and experimented with a prototype narrow-angle V12 car engine, before introducing the Lambda in 1922, with a 2119cc engine that had four cylinders angled at 13 degrees and 6 minutes. The engine was also notable for having a single overhead camshaft that was driven by chain. It began a tradition for the company that until 1961 made only narrow-angle V-engines, but otherwise the V4 remained a very unusual power unit.

Another unusual engine was found on the Czech Tatra light car. This was a horizontally opposed twin with air-cooling. While the horizontally opposed engine offered excellent balance and vibration characteristics as demonstrated by the early Lanchesters, it had other complications. It was used successfully by Jowett and by the Rover Eight, and other light cars and cycle cars. Air cooling likewise was by then unusual, having been largely abandoned on car engines in the early years of the twentieth century, but remained common on motorcycles, and in consequence on cycle cars, as well as on aero engines. Air cooling was particularly suited to engines with spread cylinders, whether radial, horizontally opposed, or V-engines, although the American Franklin company successfully used air cooling on large in-line engines and even on a V12. Tatra was the foremost exponent of air-cooling on cars, with either horizontally opposed or V-engines, until the introduction of the Volkswagen.

The rise of the two-stroke engine was a phenomenon of the inter-war period. There had been some early two-stroke engines, and the British Trojan was designed around 1910, but they only became popular in cars from the 1920s onwards, thanks to the crankcase compression invented by Joseph Day and Frederick Cock in Britain in about 1892-94[30] which avoided the need for valves or for separate charging or pumping cylinders, and which was improved by the loop scavenging invented by the German engineer Adolf Schürle in 1926.[31]

The attraction of the two-stroke engine was the reduction in the number of moving parts, and the fact that there was a power impulse in each cylinder for every revolution. The main protagonist was DKW in Germany, which used them at first for motorcycles but from 1928 also in small cars. DKW began with a single-cylinder engine for motorcycles, then a twin for their cars, as well as a V4, and finally a three-cylinder engine which continued in production until the 1960s. Many other manufacturers in Germany and elsewhere copied DKW engines. The disadvantages of two-stroke engines were their often higher fuel consumption and that for many years they had to be lubricated by adding oil to the petrol. They were also noisy, although some two-stroke engines had remarkably high specific power outputs. They were finally discontinued due to emissions problems but survived in East Germany until the 1980s.

Apart from the two-stroke engines mentioned, two-cylinder car engines became increasingly uncommon between the wars (they would make a comeback after the Second World War), as four-cylinder engines were successfully miniaturised and came to dominate the small car class. Notable examples included the 747cc Austin Seven of 1922 and the 570cc Fiat 500 of 1936 which was one of the smallest four-cylinder car engines in mass production. Otherwise both of these engines were conventional.

At the other end of the scale, we have seen how the straight-six and straight-eight engine enjoyed a vogue between the wars. In the luxury class, there were several examples of V12 engines, and the American manufacturers Auburn and Lincoln even brought out V12s costing around $1200-1400. Also in the USA, Marmon and Cadillac offered V16 production cars. Most successful of the multi-cylinder V-engines was however the Ford V8 introduced in 1932, featuring the first single-casting V8 cylinder block, which set the pattern for most American car engines through the 1960s and beyond.

Aluminium cylinder heads became relatively common in the 1930s, but all-aluminium engines were much rarer. Aluminium blocks typically required the use of cylinder lines, of the dry or wet type. The latter were used on the 1934 Citroën although this engine did not have an aluminium block. In fact the first engine designed for large-scale production that made extensive use of light alloys was probably the Volkswagen engine of 1938, with a split crankcase of magnesium alloy and aluminium cylinder heads. The VW engine was generally of unorthodox design, as it was a horizontally-opposed four with air cooling, being in some respects similar to Tatra engines. Since the 1960s, all-aluminium engines have increasingly become the norm.

Many high-performance and racing engines of the interwar period used superchargers of various types. Apart from a few early examples (such as Chadwick in the USA, around 1908-10), they were originally introduced soon after the First World War, having been used on some wartime aero engines to improve performance at high altitude. They were at first found on racing engines such as the 1924 Fiat and soon became universal on Grand Prix cars, but by the mid- to late 1920s were also gradually introduced on road cars. A supercharger was adopted by Mercedes in 1924 but was not permanently engaged, being instead used to provide the occasional spurt of high performance, and Mercedes-Benz remained the main exponent of using superchargers on touring cars until 1939. With changes to the racing formulae, superchargers disappeared after the Second World War but were eventually rediscovered.

A final inter-war development to be mentioned is the adoption of Diesel engines for passenger cars. The Diesel type of compression-ignition engine had originally established itself as a stationary or marine engine, but after the First World War it began to be used in commercial vehicles, particularly in Germany. As could be expected, it was also in Germany that it was brought into use on cars in the 1930s, by Mercedes-Benz and Hanomag, but also briefly by Citroën. Still considerably more expensive than petrol engines, Diesel engines were also heavier as their construction had to withstand much higher compression pressures, but they offered better economy.

Early post-war developments

Most engines of the period 1945-50 were not surprisingly developed from the best and most advanced pre-war designs. One general trend was that virtually all new engines had overhead valves, a rare exception being the new 1476cc Morris Oxford engine of 1948, but naturally many earlier side-valve designs remained in production for a long time. It also took a long time for many of the earlier long-stroke designs to be replaced, and indeed several new post-war engines were of the under-square type. In the popular price class, a benchmark was set by Ford in Britain in 1950 with over-square ohv engines of four and six cylinders, both of 79.37mm by 76.2mm, and near-identical dimensions were adopted for new Vauxhall engines a couple of years later. BMC by contrast stuck with under-square engines throughout the 1950s and beyond.

One of the most remarkable new post-war engines was the Jaguar XK launched at the 1948 London Motor Show. This was arguably the first engine intended for mass-production that had two overhead camshafts, driven by chain, and valves angled at 35 degrees from the vertical in hemispherical combustion chambers. As the engine had been developed during the war before the horsepower tax was finally abolished, dimensions were conservative at 83mm by 106mm, for 3442cc. The brief had been to design an engine which would give a full-sized saloon car a top speed of 100mph, and it was calculated that this required 160bhp (gross). This figure was certainly achieved with a compression ratio of 8:1. The XK engine had a very high specific output for a production engine at the time of 47bhp per litre, when 25-30bhp was still the norm. Unlike some earlier twin-cam engines, it was also noted for its reliability and lack of temperament, and went on to power a remarkably diverse range of vehicles, from racing and sports cars to limousines, even some armoured fighting vehicles.[32] In 1950, Alfa Romeo in Italy similarly brought out a mass-production twin-cam engine, in the four-cylinder 1900 model.

Also in 1948, Cadillac introduced an all-new short-stroke ohv V8 engine, of 96.84mm by 92.07mm and 5422cc which, like the Jaguar engine, developed 160bhp (gross) and gave the car a top speed of nearly 100mph. The Cadillac V8 was intended to take full advantage of the development of high-octane fuels and was designed for a compression ratio of up to 12:1, although production engines were at first limited to 7.5:1, for fuel of 84-88 octane rating. The specific output of just under 30bhp per litre did not compare with the Jaguar engine, but the Cadillac V8 was designed with durability in mind, and the maximum power was developed at only 3800rpm, compared with 5000rpm for the Jaguar.[33] This Cadillac engine began the “horsepower race” which within little more than ten years saw the universal adoption of high-performance V8 engines in the USA, of up to 7 litres and with claimed power outputs of anything up to 400bhp.

The third trend-setting engine of the early post-war period was introduced in the Lancia Aurelia in 1950. It will be remembered that Lancia had a long tradition for making narrow-angle V-engines, with four or eight cylinders, but the Aurelia engine was their first V6, and furthermore this was the first example of this configuration to see series production. V6 engines had been tried before, Marmon in the USA made a V6 with an angle of 90 degrees as early as 1904, and soon after Frederick Simms in Britain proposed a V6 aero engine with a cylinder angle of the supposedly ideal 120 degrees (110mm by 110mm, 6272cc).[34] The difficulty with most V6 layouts was poor balance so that vibration was unacceptable. The design of the Lancia engine was worked out by Francesco De Virgilio as a theoretical exercise. He established that a crankshaft with six crankpins at 60 degree intervals for equally spaced firing and an angle between cylinders of 60 degrees would give an almost perfectly balanced V6 engine; indeed he found that eight different V6 engines were possible, four with 60 degree angles, four with 120 degree angles, all with different crankshafts, all perfectly balanced.[35]

While the Lancia engine was highly successful in the Aurelia and its descendants, it took a long time for other manufacturers to adopt the V6. Buick introduced a V6 engine of 90 degrees (less satisfactory for balancing) in 1961, and Ford of Europe a 60 degree V6 in 1964. The advantages of the compact V6 engine in terms of packaging only became fully exploited when it was fitted transversely in front-wheel drive cars. Now it is the dominant type of engine in the 2.5-3.5 litre class.

Thus by 1950 several of the prerequisites for engines even today had been realised in mass-production: two overhead camshafts, high compression, and the V6 layout, often combined with a return to the near square dimensions of bore and stroke which prevailed before 1910.

Some later developments

History of course does not stop at a particular moment in time, and there have been many developments in engine design over the past sixty years. Among the more important has been the introduction of fuel injection, originally used on Diesel engines and introduced on petrol engines in fighter aircraft during the Second World War. Fuel injection was first used on a petrol car engine by Mercedes-Benz on the 300SL in the early 1950s, and it has now virtually superseded the carburettor.

One and later two overhead camshafts gradually became commonplace, and the question of how to drive them was finally resolved in favour of the toothed belt, first introduced by the German Glas company in 1961. Ten years later the first engine with four valves per cylinder in mass production appeared in the Triumph Dolomite Sprint. Diesel engines became more popular for passenger cars, at first in Continental Europe, and the breakthrough to the modern small, lightweight, efficient Diesel engine for cars came with the Volkswagen Golf in 1976. Meanwhile the exhaust-driven turbocharger had migrated from Diesel to petrol engines and was first used on some General Motors products in the USA in the early 1960s.

In the last forty years, many developments have been driven by changes in legislation. The first emissions restrictions were introduced in California in the 1960s, and were adopted generally in the USA in 1968, as well as subsequently in other countries. Concerns over pollution eventually led to the disappearance of leaded petrol, in tandem with the introduction of catalytic converters. The first oil crisis of 1973-74 high-lighted the increasing importance of fuel economy, and ever since enormous effort has been put into developing ever more economical and efficient engines, which has been assisted by sophisticated electronic systems for engine management.

It is astonishing to contemplate that a large saloon car weighing over 1.5 tonnes with a 3-litre Diesel engine developing in excess of 200bhp and a top speed around 150mph is now nearly as economical as a Mini was fifty years ago, with its engine of 848cc and 34bhp, a weight of 650kg, and a top speed of barely over 70mph.

Appendix: Some early engines

With regard to motor vehicles, the most important other early pioneers predating Daimler and Benz were as follows: Niepce in France patented an internal combustion engine fuelled by the dust from moss spores in 1807, and used it in a boat. Isaac de Rivaz in Switzerland built an internal combustion piston engine fuelled by a mixture of oxygen and hydrogen and fitted this in a four-wheeled cart around 1808. Samuel Brown of London patented a "gas vacuum" engine in 1823 and fitted one in a carriage in 1826. Carnot in France founded the theory of thermodynamics with his 1824 book about heat engines and recognized the importance of compression. Morey in the USA patented a compression-less gas engine in 1826 and fitted one in a cart. Barnett in Britain applied for a patent for a compression engine in 1838. The Italians Barsanti and Mateucci patented an internal combustion engine in 1854. Etienne Lenoir in France invented an atmospheric gas engine in 1858, had it patented in 1860, and demonstrated two apparently different vehicles in 1860-63. Christian Reithmann in Austria patented an engine in 1860 and is credited with inventing the four-stroke cycle. Siegfried Marcus in Austria built a four-stroke engine and is believed to have fitted this in a vehicle between 1870 and 1875. George Selden in the USA infamously first applied for a patent for a gas-engined road vehicle with a two-stroke engine in 1879. Edouard Delamare-Deboutteville in France built a four-stroke engine in 1883, which he fitted in two different vehicles in 1883-84, and was granted a patent in 1884.[36]

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Notes on Contributor

Anders Ditlev Clausager, b. 1949 in Denmark. Education, in Denmark, then the Royal College of Art 1974-76, MDes(RCA) in automotive design, and the

University of Warwick 1998-2000, MA by research in history, with the dissertation "In Search of a British People's Car". Career, worked as a designer in the car industry 1977-79, then archivist to the British Motor Industry Heritage Trust 1979-2000, since 2000 Chief Archivist to Jaguar Heritage. Publications, co-author of Britain's Motor Industry – The First Hundred Years (1995); more than fifteen titles on single makes or models including Austin, Austin-Healey, Jaguar, MG, Mini, Porsche, Sunbeam-Talbot and Volvo; various conference papers and articles. Honorary posts: member of the dating panel of the VCC of GB 1998-2008, currently secretary of the Society of Automotive Historians in Britain, and trustee of the Michael Sedgwick Memorial Trust.

Addresses:
Home: 20 Mapperley Gardens, Moseley, Birmingham B13 8RN
Tel. 0121 449 0666, e-mail anders.clausager@virgin.net
Office: Jaguar Heritage, Browns Lane, Allesley, Coventry CV5 9DR
Tel. 024 7640 1286, fax 024 7640 1052, e-mail aclausag@jaguarlandrover.com