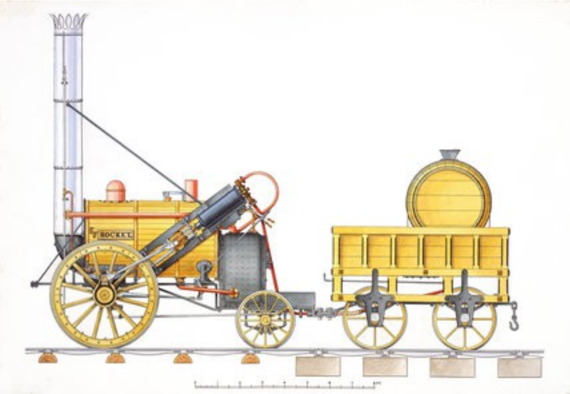
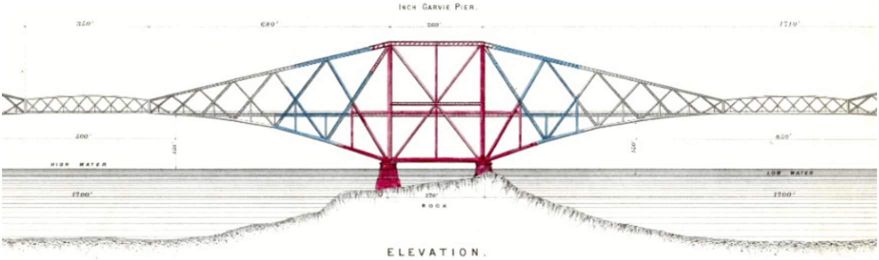


Nineteenth Century
Engineering



Oliver Linton

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Early Canals

Early history

Small canals to supply water for irrigation have been built since prehistoric times and the Chinese were building canals for transport purposes centuries before Christ but the canal which was built during the reign of the emperor Yang Guang in AD 609 – stretching from Beijing to Hangzou – remains the longest canal in the world at over 1000 miles in length. I calculate that its construction required the excavation of 150 million cubic metres of spoil – almost the same, in fact, as that excavated during the construction of the Panama Canal!

The photograph below shows the canal crossed by the famous Gongchen Bridge in Hangzou which was built in 1631.

Great Canal of China (609)

The first great canal to be built in Europe was the Canal du Briare which connects the valleys of the Seine and the Loire. In order to surmount the watershed between the two rivers 36 pound locks (i.e. a short stretch of water with gates at each end used for raising and lowering boats) were used. Pound locks had been used before in harbours and to bypass obstacles on a river but this was the first time such locks had been used to carry a canal over a watershed. It was 35 miles long and was completed in 1642.

The next major canal was the 150 mile long Canal du Midi built in 1681 to connect the Atlantic to the Mediterranean through southern

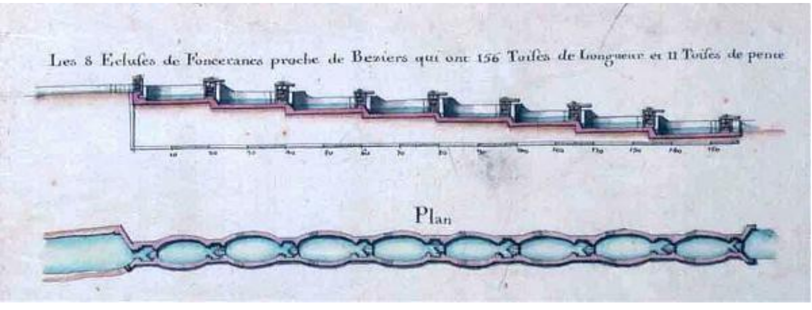
France. This canal involved building an unprecedented number of structures including 63 locks, 126 bridges, 55 aqueducts and a short tunnel the like of which had never been seen before.

The architect was Pierre-Paul Riquet, essentially an amateur who learned the art of canal building by trial and error. This should not be held against him, however, as there were few people who knew any more about canal building than he did at the time.

The first problem to be solved was finding the source of the water that would be fed into the highest section of the canal at 190 m above sea level. A huge earth dam was constructed across the river Laudot in the Montagne Noire 12 miles from the summit at the Bassin de St. Ferréol. This dam, the second largest in the world at the time, was 700 m long and 30 m high.

The second problem was the construction of the locks. From Toulouse the canal had to rise 52 m to the summit and then descend 190 m to the sea. This required 63 locks with an average change in water level of 3.8 m at each lock. The first locks which Riquet built had straight sides and were not strong enough to withstand the pressure exerted by the ground when the lock was empty so Riquet had the brilliant idea of making the locks oval in shape. The side walls acted like arches on their sides and have proved very durable.

At Beziers, a staircase of 8 locks was used. Note the oval shape of the pounds.



Plan of the staircase at Beziers (1681)

Also at Beziers is one of the finest aqueducts on the canal (built much later in 1857) where the canal crosses the river Orb.

The aqueduct over the river Orb (1857)

One of the most serious obstacles which Riquet faced was how to deal with a sandstone ridge near Beziers. The sandstone was very brittle and many people thought that a tunnel was impossible. Riquet persevered, however and the tunnel was built, lined in concrete. The channel was 18 feet wide and the tunnel included a tow path. It may have been only 160 m long but it was an important step forward in the conceptual development of canals.

Inside the Malpas tunnel (1681)

Early canals in England

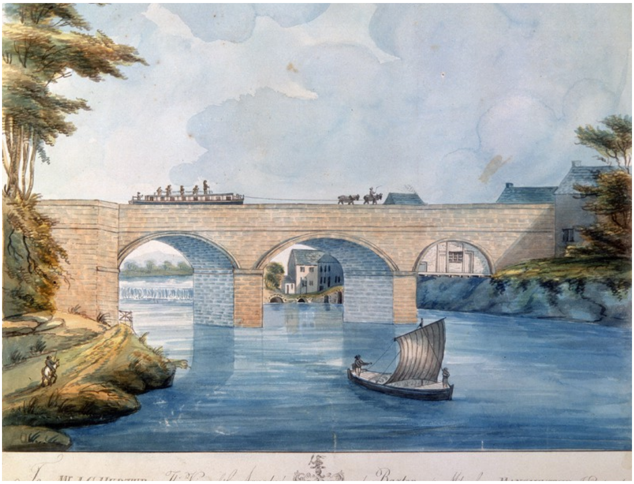
Many rivers in Britain were used for transportation and some of them such as the Aire and the Calder were improved by partial canalisation but the first proper canal to be built in Britain was the so-called Bridgewater canal. In 1759 the 3rd Duke of Bridgewater decided that he needed a better way to transport coal from his mines at Worsley into Manchester. He employed the engineer James Brindley to survey the route.

Now the mines at Worsley were on a hill and for many years, they were drained by a channel (called a sough). The photograph below shows the exit of one of these soughs.

The exit of the Worsley Levels

Brindley had the idea of extending the canal underground into the mine so that the barges or 'starvationers' could be loaded directly, the canal also serving as a drainage channel. An indirect consequence of this decision was that all subsequent canal structures (bridges and locks) were built to accommodate the width of a single starvationer – 7 feet.

No locks were needed between Worsley and Manchester but there was one substantial obstacle in the way – the river Irwell. Brindley crossed the river with a three-arched aqueduct which, at the time, was acclaimed as one of the wonders of the world. The Duke, who had been inspired by a visit to the Canal du Midi, would have surely known better but probably kept quiet as the idea did no harm to his reputation!



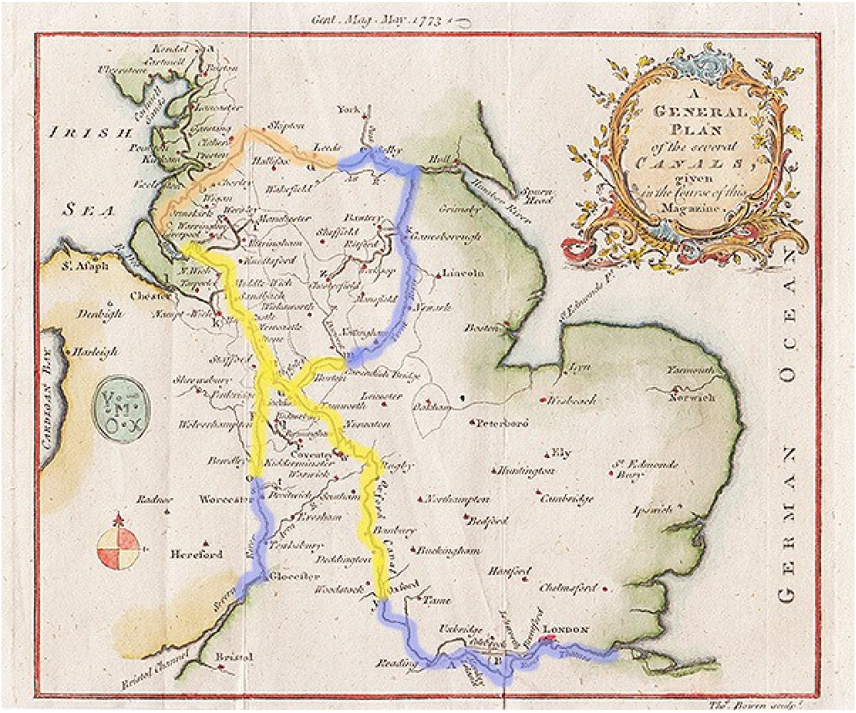
The aqueduct over the river Irwell (1761)

Brindley's aqueduct was demolished in 1891 when this section of the river was itself turned into a canal – the Manchester Ship Canal. The Bridgewater canal is now carried over the ship canal by a swing bridge (see page 20).

Once he realised the potential of a canal network, Brindley began to dream of a complete network of canals linking the four major navigable rivers, the Trent and the Mersey, the Severn and the Thames (highlighted in yellow in the following map; navigable rivers are shown in blue). In the event, this 'Grand Cross' scheme was not completed until 1793 but Brindley was involved in the design and construction of a large part of it over the next 10 years.

The 93 mile long Trent and Mersey canal was completed in 1777. The 46 mile Staffordshire and Worcester canal which connected the former to the river Severn was completed1772 and the Coventry canal and Oxford canals (32 miles and 78 miles respectively) were completed by 1774. Sadly, Brindley died in 1771 and so never saw his vision realized.

Another important canal which Brindley surveyed was the Birmingham canal which connected the Staffordshire and Worcester canal to that city.



Brindley's 'Grand Cross' scheme as published in 1773

The biggest obstacle Brindley faced in the construction of the Trent and Mersey canal was the crossing of the watershed between Stoke-on-Trent and Congleton. Here a 1.6 mile long tunnel was required – the Harecastle tunnel. In order to keep costs down, the tunnel had no tow path and boatmen had to 'leg' their boats through by lying on their backs and walking on the roof.

It soon became apparent that the tunnel was not big enough to carry the volume of traffic and a second parallel tunnel (with a tow path) was built by Thomas Telford in 1827. Brindley's tunnel is now closed.

The next major canal to be completed (in 1789) was the Thames-Severn canal from Stroud in Gloucestershire to Lechlade which included an even longer canal tunnel – the Sapperton tunnel. This 2 mile long tunnel was also built to accommodate narrow boats only and had no tow path so boats were still propelled by 'legging'. It is currently blocked by several roof falls but restoration of the canal is under way and it is hoped that the tunnel itself will be opened again one day.

The 1¾ mile long Dudley tunnel which effectively connected the black country to the Severn by a more direct route was completed in 1791.

The Cromford canal was built in 1794 to connect Arkwright's mills at Cromford to the Erewash canal and thence through to the river Trent. In order to reach the Erewash valley a tunnel 1¾ miles long – the Butterley tunnel, now abandoned – was constructed, the third longest in the world at the time after the Sapperton and Dudley tunnels.

Brindley was also involved in planning the first route across the Pennines from Leeds to Liverpool (highlighted in orange on the map opposite). The obvious route across is to link the Ribble valley at Hellifield with the valley of the Aire at Gargrave, crossing the watershed between Crane Field beck and Otterburn beck at a height of 150m (the route taken by the Leeds-Lancaster railway). But Brindley spotted a narrow twisting valley running south from Gargrave, squeezing between Risebrigg Hill and Risebrigg Hill (sic) to top out at Foulridge Lower Reservoir east of Pendle Hill at a height of 165 m. The planned route would then drop down into the valley of Pendle water and thence via the river Calder (not the Calder east of the Pennines!) into the Ribble valley at Whalley. This route was shorter than the obvious one via Hellifield and was obviously going to be preferred by the merchants and millers of Nelson and Burnley.

After much wrangling and further route changes, it was decided to lower the summit pound by 9 m by building a mile long tunnel at Foulridge. In addition a mile long embankment carrying the canal over the valley of the river Brun was required at Burnley. Both of these huge projects ran into financial difficulties and the route was not completed until 1816 – exactly 50 years after the project was first mooted. By that time, a second route across the Pennines had already been completed – the Rochdale canal.

This canal used the deep meltwater channel between Todmorden and Littleborough. Owing to the height of the summit (183 m) a total of

92 locks were required (but no summit tunnel). The route was opened in 1804 and soon became the main route by which goods crossed the Pennines.

Another major canal opened at this time was the Grand Junction canal (now part of the modern Grand Union canal) which linked London to Birmingham via Northampton and was much shorter than the route through Oxford. It also had the advantage of avoiding the difficult upper reaches of the Thames. The chief engineer was William Jessop. The route required two major tunnels; Braunston tunnel at the northern end of the canal was a little over a mile long and the 1¾ mile Blisworth tunnel. Completion was held up by problems with the latter but the canal finally opened in 1805. Unlike the other ones so far mentioned both of these tunnels were wide enough for two narrow boats top pass each other (but neither had a tow path).

Jessop was also called upon to survey the route of the Huddersfield canal which crosses the Pennines between Huddersfield and Saddleworth. Here the watershed is 388 m above sea level so there was no possibility of building a canal at that height. A massively long tunnel under Standedge would be required, 3¼ miles long at an elevation of 134 m. The tunnel was finally completed in 1811 under the direction of Thomas Telford. Standedge tunnel has no tow path and can only accommodate the width of a single narrow boat. It is the longest canal tunnel in the UK and was reopened after many years of disuse in 2001.

Standedge canal tunnel (1811)

The Worcester and Birmingham canal which completed the 'Birmingham ring' was finally opened in 1815 and included the longest flight of locks in the UK – 30 locks in 2¼ miles. By 1819 the Lancaster canal had reached as far as Kendal, crossing the Lune at Lancaster by means of a fine stone aqueduct designed by John Rennie and completed in 1797.

Lune Aqueduct (1797)

The Kennet and Avon canal linking Bath on the Avon with Newbury on the Thames was opened in 1810 when the flight of 29 locks at Caen Hill near Devizes was finished. The summit pound is 140 m above sea level which is only a few metres below the summit pounds of the canals which crossed the Pennines!

Kennet and Avon canal locks (1810)

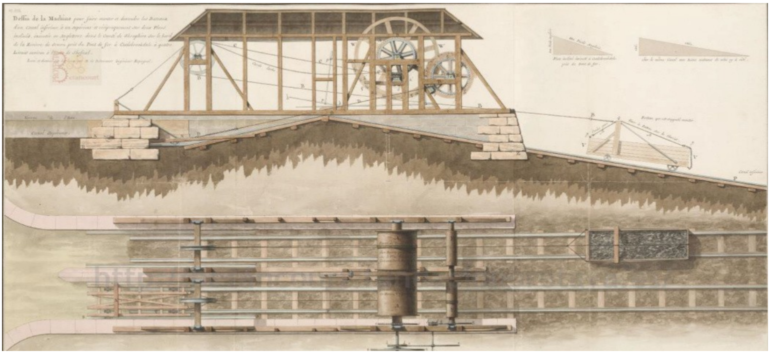
Three other major canal tunnels built before Queen Victoria came to the throne should be mentioned: the1½ mile long Norwood tunnel on the Chesterfield canal, surveyed by Brindley and completed in 1775, the 1½ mile Wast Hills tunnel on the Birmingham Worcester and the 2 mile long Lapal tunnel in the West Midlands completed in 1798. Of these only the Wast Hills tunnel is currently open..

The Shropshire Union canal, the last major canal to be built in England, was built by Thomas Telford and was completed in 1835. It ran from Wolverhampton to the river Mersey linking with the important navigable rivers of the Weaver and the Dee. A branch, now called the Llangollen canal, was built into Wales which crosses the river Dee by means of the famous Pontcysyllte aqueduct, built by Telford in 1805. (see page 106)

Pontcysyllte Aqueduct (1805)

Early canal structures

The great majority of canals use pound locks to cope with differences in elevation but the Shropshire canal, completed in 1798, used an entirely different method – inclined plane. Here the small barges (tub boats) were placed on an iron carriage running on rails. Where possible a full barge running down the incline would pull an empty one up. Alternatively a steam engine would be used to pull the barges up. The Shropshire canal (not to be confused with the Shropshire Union canal to which it was connected much later) used no less than three inclined planes, one of which, the Hay Inclined Plane, has been restored. This was built to connect the Shropshire canal down to the river Severn 63 m below at Coalbrookdale.



Hay Inclined Plane (1798)

Another method which was tried, generally without success, was the boat lift. Two caissons connected by a rope over a big pulley would simultaneously raise one boat and lower another. The idea was that, since a floating boat displaces its own weight of water, the system would always balance even if the full boat was rising and very little power would be needed to operate the lift. Another advantage is that, while pound locks are limited to a height difference of 4 m or so, boat lifts have no such restriction. Several were built on the Grand Western Canal which was to have connected the Bristol Channel with the English Channel at Exeter but the boat lifts, one of which raised the boats by 13 m, were never satisfactory and in the event the canal was never completed.

Canals cannot function without a sufficient supply of water into the summit pound. Wherever possible, streams were diverted into reservoirs and large dams were built to ensure an uninterrupted supply of water. If, however, no streams were available at the appropriate height, the only alternative was to pump water up from below.

This problem was particularly acute on the Kennet and Avon canal and two beam engines were installed for the purpose. The earlier of the two was later replaced but the second, a Boulton and Watt condensing atmospheric engine installed in 1812 is still working and is the oldest steam engine in the world doing the job it was built to do. It was capable of lifting a cubic metre of water a height of 12 m 11 times a minute and could refill a whole lock in 15 minutes.

Crofton pumping station (1812)

A second pumping station was needed at Claverton in Somerset but this one was water-powered using a massive water wheel, 7 m wide and 5 m in diameter. This has also been restored and can be visited.

Many other pumping stations were built during this period but the only other one to survive in working order in the UK is Leawood Pumping Station on the Cromford canal (built in 1849).

Leawood pumping station (1849)

Some pumping station buildings survive, notably Tringford Pumping Station on the Grand Union canal. It is still pumping water but its original 1817 Boulton and Watt engines have long since been replaced.

Early canals in Scotland

The Forth and Clyde canal was the first to be completed in Scotland in 1790. It is 35 miles long and has 30 locks. The Edinburgh and Glasgow Union Canal running from Falkirk to Edinburgh was opened in 1822. Originally it was connected to the Forth and Clyde canal by a flight of locks but it is now connected via the famous Falkirk wheel which raises boats 24 m in a matter of minutes. (Two locks are needed to raise the canal a further 11 m to the Union canal.) Unlike the canals in England, the 32 mile route of the Union canal follows the 73 m contour along its whole length. It therefore has no locks but required several major aqueducts to carry the canal over various valleys. The most notable of these is the Avon Aqueduct which carries the canal over the river of the same name near Linlithgow. It was built by Hugh Baird with advice from Thomas Telford. Like the latter's Pontcysyllte Aqueduct, the canal is contained in iron troughs supported by masonry piers but Baird's design is less daring in that the iron troughs were supported beneath by masonry arches.

Avon Aqueduct (1822)

The 9 mile long Crinan canal which crosses the Kintyre peninsular greatly shortening the route from the firth of Clyde to the Inner Hebrides was completed in 1809. It has 15 locks each 20 feet wide and a number of cast iron swing bridges. Unlike many canals in England which were largely superseded by the railways, the Crinan canal has been in continuous use ever since.

The Caledonian Canal

The Caledonian canal was the first proper ship canal to be built in the world. With locks 35 feet wide and the draught of 18 feet, it was designed to accommodate sea-going vessels who could cross from the Irish Sea to the North Sea without having to brave the treacherous waters round the North of Scotland. The canal follows the fault line of the Great Glen. From Fort William the canal rises Neptune's Staircase, the longest flight of locks in Britain, to Loch Lochy, thence to the summit at Loch Oich. The descent takes the canal through the 23 mile long Loch Ness and terminates at Inverness. Thomas Telford was the presiding engineer and the canal was completed in 1822. It was never really a commercial success but it survived and is now an important tourist attraction.

Neptune's Staircase (1822)

Canal building was not, of course, confined to Britain – though nowhere else were narrow canals built on such an unprecedented scale. In both Europe, Russia and America, the need was to connect the major riverine waterways together.

Canal du Rhône au Rhin

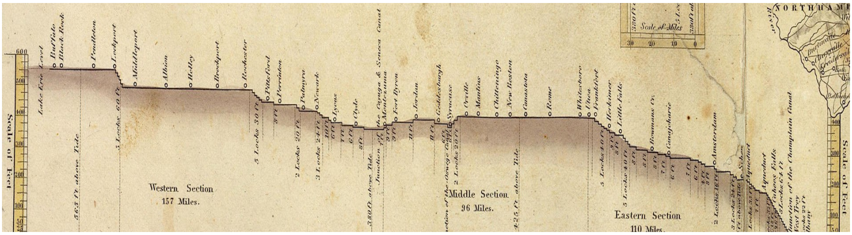
In Europe, the Canal du Rhône au Rhin, built between 1784 and 1833, linked Mulhouse on the Rhine with the river Saône near Dole. In order to climb over the watershed over a hundred locks were needed in its 150 mile length. The canal was upgraded in 1882 to the Freycinet standard which would accommodate boats up to 5 m width, 40 m length 2 m draught. (In 1973 there was a proposal to rebuild the whole canal to take much larger boats but the plan was cancelled in1997.) The canal is now a popular tourist route.

The Ludvig Canal

The Rhine was connected to the Danube in 1846 by the Ludvig canal in southern Germany. Like the Canal du Rhône au Rhin, it was narrow and had numerous locks and was never a commercial success, being soon overtaken by the railways. It was abandoned in 1950 when the modern Rhine-Main-Danube canal was built.

The Erie Canal

In America there was a great need to connect the Eastern seaboard with the Great Lakes. Running due North from New York, the Hudson River carves a huge valley through the Appalachian Mountains right through to the St. Lawrence river at Montreal. By 1823 a canal had been constructed along this valley as far as Lake Champlain but the real need was for a link through to the lakes above Niagara Falls. A smaller valley runs 200 miles west from Albany to the shores of Lake Ontario but Lake Erie is another 160 miles West and another 100 m higher. Construction of this massive undertaking – which many thought sheer madness – began in 1817 and, amazingly, the whole 363 mile canal with 36 locks and numerous aqueducts was completed in under a decade.



Profile of the Eire canal

The impact of the canal was enormous and hugely boosted the growth of the city of New York. It continues to operate to this day, mostly carrying recreational traffic.

The Rideau Canal

With the completion of the Erie canal, Canada too felt the need to improve its access to the Great Lakes. Between Lake Ontario and Montreal the St. Lawrence river has many rapids so it was decided to bypass these obstacles by using the Ottawa river up to the capital Ottawa and thence across to Kingston on the lake. The 126 mile route was completed in 1832.

Plans were also considered to build a canal further up the Ottawa river to connect with Georgian Bay and Lake Huron but although parts of this were constructed during the subsequent decades, the canal (known as the Trent-Severn Waterway) was not completed until 1907

The Mariinsk Canal

In 1709 Peter the Great had built a canal from his capital St. Petersburg through to lake Ladoga and during the next century, the canal system extended all the way to the Volga river at Rybinsk.

Very little of the original eighteenth century canal now exists as the canal system has been continuously upgraded and many of the lakes have since been turned into reservoirs and their levels raised considerably. It now forms part of the Volga-Baltic waterway.

Victorian canals

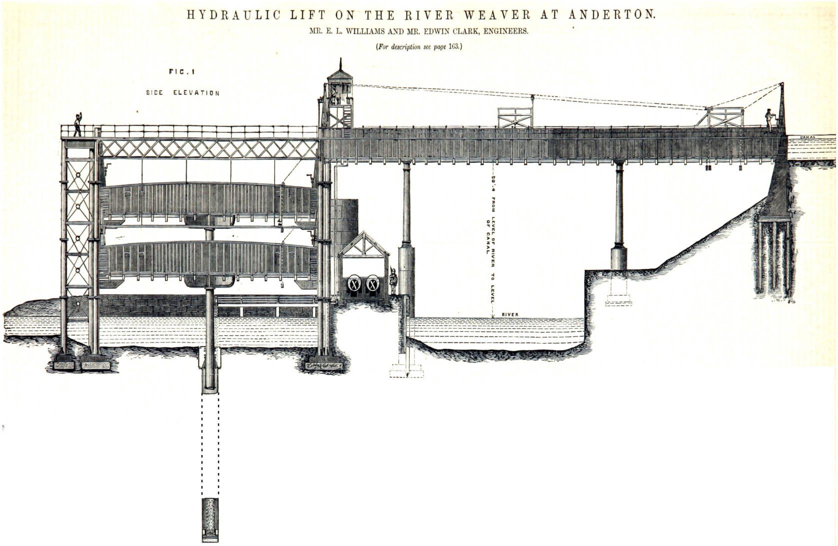
The Netherton tunnel

By the time Queen Victoria came to the throne in 1837, most of the canals in England had not only been built but were facing immense competition from the railways. One major structure on the Birmingham Canal Navigations was, however, completed in 1858, the 1¾ mile long Netherton tunnel. 15 feet wide and with tow paths on both sides, this was a very different kind of canal tunnel from the low, narrow Dudley tunnel which it replaced.

Netherton tunnel (1858)

The Anderton Boat Lift

The river Weaver in Cheshire was an important navigable route from the salt mines of Cheshire to the sea but when the Trent and Mersey canal opened the two waterways were connected by means of an inclined plane like the one at Coalbrookdale. This operated for many decades but it was eventually decided to replace it with a device which would physically lift loaded boats from the Weaver up to the level of the canal 15 m higher. The engineer Edward Leader Williams was called in to suggest a suitable design. Aware of the problems which had beset the chain lifts on the Grand Western canal, Williams proposed a hydraulic design.



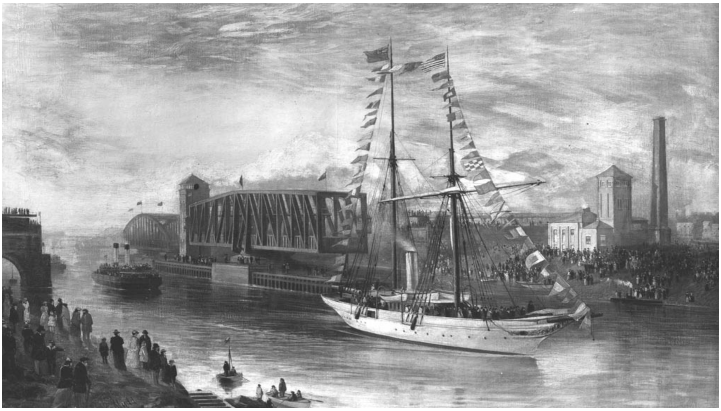
Anderton Boat Lift

Each of the two troughs carrying the barges was mounted on a vertical ram or piston sunk 15 m into the ground below the level of the river. Each trough could be raised and lowered independently by pumping water into the cylinder below the ram or by bleeding water off into the river. A steam engine was used to provide the necessary water pressure of nearly 50 atmospheres. Normally, however, one trough would be raised while the other was being lowered with water simply passing from one cylinder to the other. Essentially the system required no power to operate it but the steam engine was always needed to replace lost water and pump the upper trough up the last few inches.

This amazing piece of Victorian engineering was completed in 1880 and while it worked satisfactorily for many years, the acid canal water corroded the rams and in 1906 the rams were abandoned in favour of an electrically driven pulley system. This involved major reconstruction of the framework which now had to carry the weight of the troughs and it is this Edwardian machine which is largely the one we see today.

The Manchester Ship Canal

The Mersey and the river Irwell were partially canalised up to Manchester in the early 18th century but by 1870 the route was losing custom to the railways and competition from trans-Pennine canals so the manufacturers and merchants of Manchester decided that they wanted their own port and navigable route to the Irish sea. Eventually the finance was obtained and work started in 1887 and was completed six years later under the direction of Sir Edward Leader Williams. At its opening it was the longest ship canal in the world (and at 36 miles is the eighth longest even today). There are 5 locks on the canal, the overall rise in elevation being 18 m. The locks can accommodate ships with a beam of up to 20 m and length 160 m and at its height in the 1950's the canal was handling 18 million tonnes of freight a year. Although the canal was never the commercial success its promoters had hoped, it none the less rejuvenated the city of Manchester which became, for a time, the third largest port in the UK.



The opening of the Manchester Ship canal (1894) showing the Barton Swing Aqueduct

Two swing bridges built in 1894 cross the canal at Barton, both of which are still in use today. One is a road bridge but the other carries the Bridgewater canal and is the only swing bridge aqueduct in the world. Both bridges pivot round their centre points located on an artificial island in the middle of the canal. When the bridges are opened to allow shipping to pass, they are turned so that they lie along the length of the island and ships can pass either side. Naturally, gates must be used on the ends of the aqueduct to contain the water both in the canal and on the aqueduct

Barton Swing Aqueduct (1893)

Just visible in the photograph above is the quadrant gear which allows the gates to be swung out of the way by 90° when the bridge is closed.

Together with its water, the aqueduct weighs 1450 tonnes which was supported on 64 cast iron rollers. Originally, when it was required to rotate the bridge, it was partially lifted hydraulically to relieve the immense pressure on the rollers. Hydraulic power was supplied by a steam engine nearby.

The Suez Canal

Attempts to build a canal between the Mediterranean and the Red Sea go back to the age of Ptolemy but the modern canal was conceived and built by the French in 1859-69. It is 120 miles long and has no locks. It was an immense undertaking and may have involved over a million labourers, a good number of whom were essentially slaves. It is, of course, now one of the most important ship canals in the world.

The Panama Canal

Flushed with the success of the Suez canal, French engineers turned their attention to the problem of crossing the isthmus of Panama. Initially it was hoped to build a sea level canal and building started in 1880 but tropical rains, unstable geology and disease caused the project to founder after only a few years. Eventually, the French equipment was bought by the United States of America and work resumed in 1904, this time using locks to raise the canal 26 m to Gatun lake. The canal finally opened in 1914.

The Corinth Canal

The French were also involved in the construction of the Corinth canal but the company went bankrupt and the canal was completed by the Greek government in 1893. It is 4 miles long, 20 m wide and in places the cutting is over 50 m deep. Owing to its restricted width and the strength of tidal currents through it was never a commercial success.

Allegheny Portage Railroad

Is it a canal? Is it a railway? The Allegheny Portage Railroad is certainly one of the most curious solutions to the problem of getting canal barges from one side of a mountain to the other.

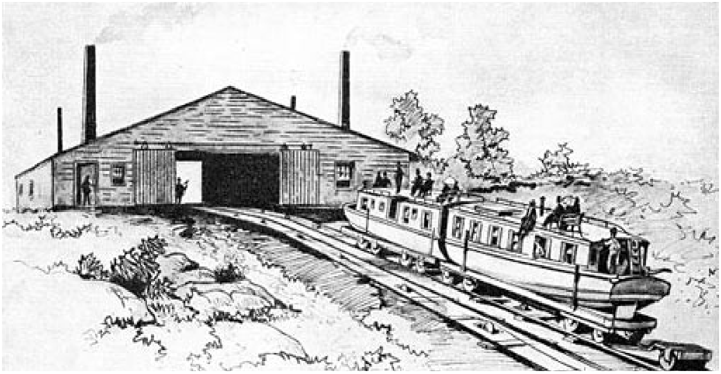
Canal building in Pennsylvania had started in 1797 and by the 1820's there was a large network of canals connecting the industrial cities of Eastern Pennsylvania with the ports on the Eastern seaboard. Likewise, Pittsburgh in the West was connected via river and canal to both the Mississippi and Lake Erie.

But stretching right across the state was a range of mountains, the Allegheny mountains, whose lowest pass at Cresson was at an elevation of 627 m. It was clearly impossible to raise a canal up to this height, nor was it feasible to build a 20 mile long tunnel. The solution? Portage.

Between 1834 and 1854, loaded canal barges were put on flatbed wagons and either dragged along relatively flat sections by horse or winched up steep inclines by a stationary steam engine. The route was 36 miles long and included 10 inclined planes (5 on each side of the divide) a tunnel and several aqueducts. From Holidaysburg on the Eastern side the route climbed 426 m to the summit before descending 357 m to Johnstown. Ingeniously, the canal barges used could be split down the middle so that two flat beds could be used for each barge. The railroad was used by passengers as well as freight and in 1842 Charles Dickens described a journey on the railroad in his 'American Notes'. Curiously, Dicken describes one of the inclined planes as follows:

> *It was amusing, too, when we had dined, and rattled down a steep pass, having no other moving power than the weight of the carriages themselves, to see the engine, released long after us, come buzzing down alone, like a great insect, its back of green and gold so shining in the sun . . . It stopped short of us . . . when we reached the canal, and, before we left the wharf, went panting up this hill again, with the passengers who had waited our arrival for the means of traversing the road by which we had come.*

We can infer from this that by 1842 passengers were conveyed in conventional carriages, pulled by a steam engine but at the inclines, the carriages and the engine were raised and lowered separately.



Allegheny Portage Railroad (1834)

In 1851, railroad technology had developed to the point where it was advantageous to replace the Portage Railroad with a properly graded railway and in 1854, the portage route was abandoned. Sections near Cresson are preserved as a National Park and some of the inclines can be visited.

Steam Locomotives

The steam engine before 1800

The first practical reciprocating steam engine was invented by Thomas Newcomen in 1712 and his engines were widely used for the next 50 years, especially in Cornwall. But, as is well known, in 1769 James Watt invented a much more efficient engine and together with the financier Matthew Boulton he set up a manufacturing company which, by the year 1800, had manufactured nearly 500 stationary steam engines which were used for pumping water, operating bellows and powering machinery. Most, if not all of these engines used steam at atmospheric pressure and produced at most 5-10 horse power. These engines operated on a very different principle from later locomotive engines. Instead of using high pressure steam to force a piston down a cylinder, steam was introduced to the cylinder at atmospheric pressure on the intake stroke; then the steam inside the cylinder was condensed (using Watts ingenious separate condenser for efficiency) creating a partial vacuum on one side of the piston. It was the pressure of the atmosphere on the other side of the piston which provided the motive force which drove the machine.

Watt's condensing beam engines were ideal for the purpose of pumping water from a mine. The technology needed to build them was relatively simple and they were easy to repair and maintain. The boiler could be made of brick and the huge pistons could be sealed with oiled rope and water; the slow speed of operation was perfect for operating simple bucket style lifting devices and although the power output was low, they could lift immense weights.

For example, the typical pumping engine shown in the following illustration has a cylinder of diameter 24 inches and stroke 48 inches. Once the vacuum had been created, the force on the piston would have been more than 2½ tonnes. Assuming that it worked at a rate of 12 strokes per minute, this implies a theoretical maximum power output of 9 horse power.[1]

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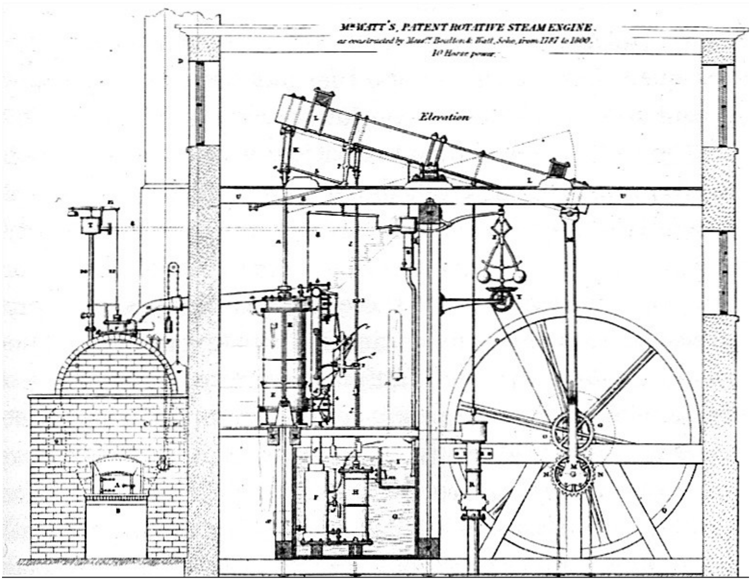
[1] For a formula for calculating the force produced and th power output of a steam engine see the appendix.



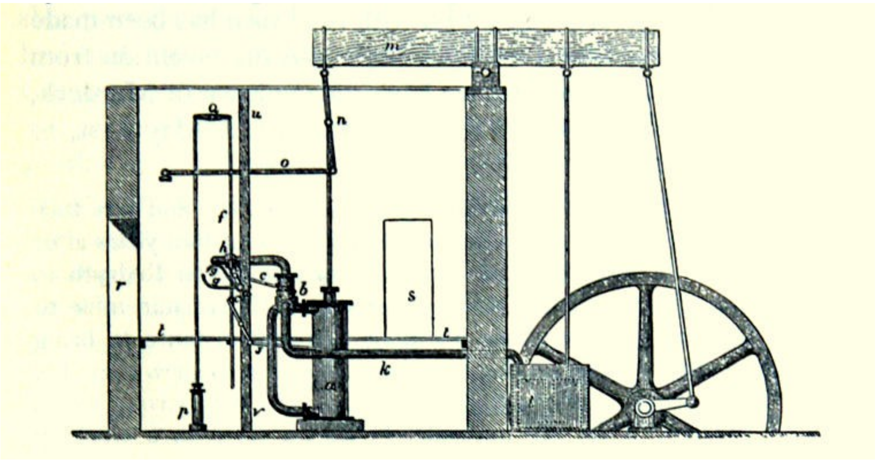
Boulton and Watt engine of 1787

Note the brick boiler which produces steam at atmospheric pressure and the separate condenser below the piston. The rod which operates the actual pump is the thin rod to the right of the central column which supports the bean. Note also Watts patent parallel motion, the centrifugal governor and the 'sun and planet' gear which Watt had to invent in order to circumvent another engineer, James Pickard, who had patented the crank! (In 1780 patent law was still in its infancy. It was more a question of simply buying the right to a monopoly. There was no requirement to prove that your invention was novel – after all the Romans had used cranks. What Pickard patented was a monopoly on using a crank to turn a flywheel. He should have patented the flywheel, not the crank – then Watt would have been in serious trouble!)

With the expiry of Watts patents in 1800, and with the advances made in manufacturing tolerances, other engineers such as Richard Trevithick began to experiment with high pressure steam. Using a steam pressure of between 2 and 4 atmospheres, the pistons could be made much smaller and the bulky condenser could be dispensed with entirely. His first high pressure engine was built for the Cook's Kitchen Mine in

1800 to pump water.

In the following illustration the cylinder is much narrower and the steam inlet pipes can clearly be seen at both the top and the bottom of the cylinder indicating that this is a double acting high pressure engine.

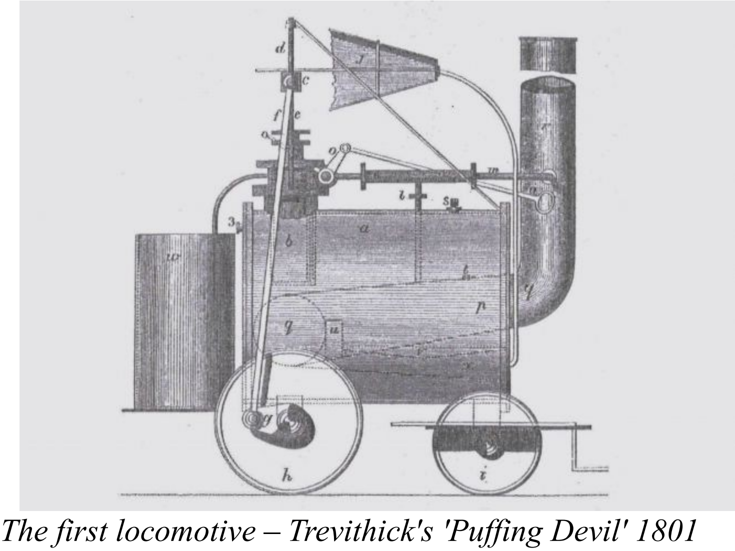


High Pressure engine at Cook's Kitchen Mine – Trevithick c1800

If we make the reasonable estimates that the bore of the cylinder was 8 inches, the stroke was 48 inches and the working pressure 30 psi then at 40 revolutions a minute the engine would have produced about 15 HP – twice the power output of the Boulton and Watt engine from a much smaller and simpler engine.

Having built several high pressure engines for the Cook's Kitchen Mine, Trevithick soon realised that, with careful design, the piston could be incorporated into the boiler and the whole thing put on wheels to create the world's first self-powered vehicle.

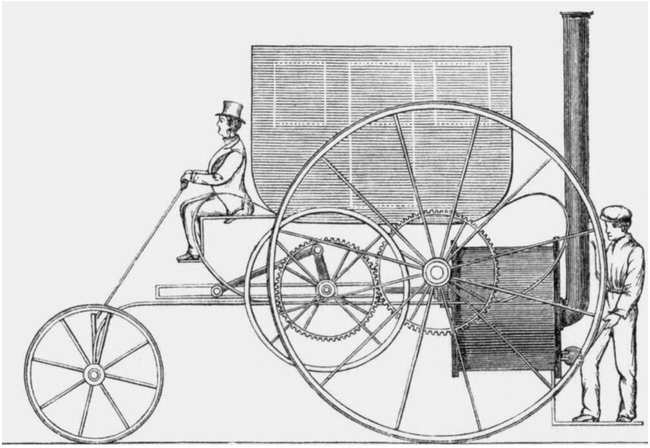
After experimenting with models, Trevithick built a full-sized road vehicle in 1801 which he called *Puffing Devil*. On Christmas Eve of that year he demonstrated its capabilities by transporting several friends up Cambourne hill and on to the village of Beacon. Unfortunately, four days later the engine broke down and the engine was left by the roadside with the fire burning while the men went off for lunch, during which time the water boiled away and the engine was destroyed.



The first locomotive – Trevithick's 'Puffing Devil' 1801

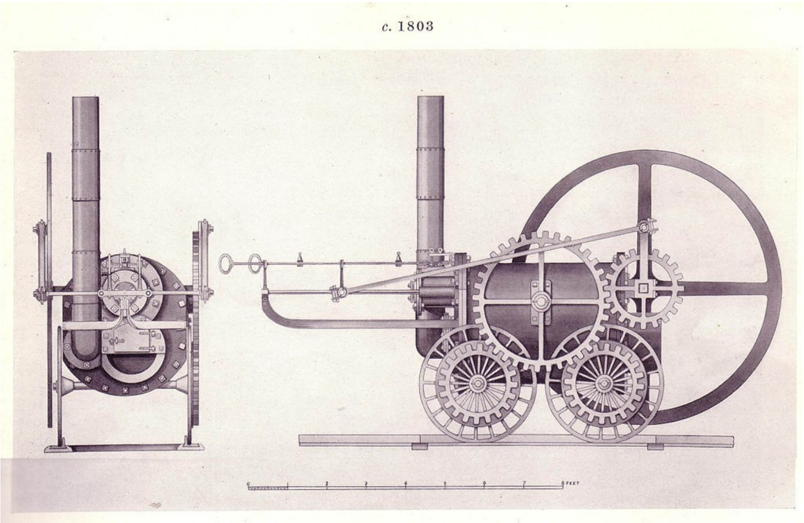
From the above (later) illustration it can be seen that the *Puffing Devil* had a single vertical cylinder incorporated into the boiler with cranks (probably on both sides) driving the wheels. The firebox was situated beside the chimney with a U-shaped flue inside the boiler. The drum at the other end is probably a water tank. As to how it was steered or whether it had any sort of brakes, it is difficult to say. A replica, built by the Trevithick Society in 2011, certainly works though, in spite of the lack of a flywheel to carry it through the top dead centre position. Stopping and starting the machine and making sure that it ran in the desired direction must have been a challenge! One innovation which we may be fairly sure Trevithick incorporated (from the name if nothing else) was the idea of directing the exhaust steam into the chimney, thereby greatly increasing the draw of the chimney and the rate of burning of the fire. This innovation is often attributed, incorrectly, to George Stephenson.

Two years later, Trevithick built a steam carriage (shown below) which he demonstrated to the public in London. This time the piston is horizontal and it drives a crank wheel which is geared to the main carriage wheels.



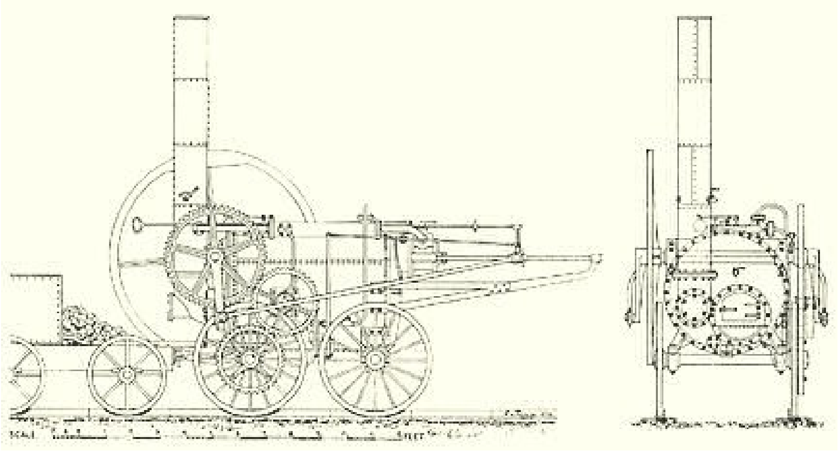
Trevithick's Steam Carriage - 1803

In 1802 Trevithick was in correspondence with the Coalbrookdale Iron foundry over the construction of a locomotive there but it is not known if it was ever finished. The existing drawing, now in the Science Museum, clearly shows the firebox beside the chimney, directly beneath the reciprocation slide bar – an appallingly dangerous arrangement.



Plans for the Coalbrookdale locomotive - 1802

It is often assumed that this was the arrangement used in the famous Pen-y-Darren 'Tram-waggon' but this is unlikely for the reasons stated. It is more probable that Trevithick used the arrangement which he was later to use at Wylam colliery with the piston at the opposite end of the boiler as in the diagram below.



Possible design for the Pen-y-Darren locomotive 1804

The Pen-y-Darren 'Tram waggon' came about as a result of an unlikely bet. The issue at the time was not so much as to whether a steam powered machine could generate enough power, it was whether the friction between the wheels and the rails would be sufficient to produce enough force at the drawbar. The story goes that Samuel Homfray, the owner of the Pen-y-Darren ironworks, bet Richard Crawshay, owner of the nearby Cyfarthfa ironworks, 500 guineas (or was it 1,000 guineas? It hardly matters – it was an enormous sum of money either way) that a steam engine could haul a load of 10 tons of iron from his works along the tramway, to Navigation House, Abercynon. Crawshay accepted the bet and Homfray got Trevithick to convert a stationary engine at the works into a locomotive.

And so it was that the first proper locomotive journey took place on the 21st of February 1804 at the Pen-y-Darren iron works near Merthyr Tydfil. Trevithick described the event a few years later in the following words:

> *"About six years since I turned my thoughts to this subject[2], and made a travelling steam-engine at my own expense, to try the experiment. I chained four waggons to the engine, each loaded with 2½ tons of iron, besides seventy men riding in the waggons, making altogether about 25 tons, and drew it on the road from Merthyr to the Quaker's Yard, in South Wales, a distance of 9¾ miles, at the rate of four miles per hour, without the assistance of either man or beast; and then without the load drove the engine on the road sixteen miles per hour."*

In the event, there was some debate about the outcome of the bet as the locomotive suffered a collision with a bridge on the outward journey and the return journey was done without a load but there was no doubt about the ability of a steam locomotive to pull serious loads along a reasonably level track using friction alone. In spite of this, Homfray had the wheels removed and the engine returned to its former mundane duties. Perhaps this was just a spiteful reaction to the fact that his friend refused to pay the debt!

So what do we know about the locomotive which was used on this

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[2] i.e. the subject of whether a locomotive could pull a useful load along a plateway using friction alone.

historic occasion? The following description of the locomotive from the collieries engine fitter – Rees Jones contains much useful information:

> *"The boiler was made of wrought iron, having a breeches tube also of wrought iron, in which was the fire. The pressure of steam used was about 40 lbs. to the inch. The cylinder was horizontal; it was fixed in the end of the boiler. The diameter of the cylinder was about 4¾ inches. The three-way cock was used as a valve. The engine had four wheels. These wheels were smooth; they were coupled by cog-wheels. There was no rack-work on the road; the engine progressed simply by the adhesion of the wheels. The steam from the cylinder was discharged into the stack."*

We can estimate from the diagram of the Coalbrookdale locomotive that the stroke of the piston was probably about 3 feet and that its driving wheels had a diameter of about 33 inches. From these figures we can deduce that travelling at 4 mph, the maximum power output of the machine would have been about 5 HP and that it would have generated a force at the drawbar of about one quarter of a ton – easily sufficient to pull a 10 ton load along a level plateway and even up a modest grade of 1 in 100.[3]

Trevithick went on to design several more locomotives, including at least one for the Wylam colliery near Newcastle but very little is known about them. As always, the trouble was that they were basically too heavy for the plate and wagon ways then in use.

In 1808, in an effort to raise money, Trevithick put on a 'Steam Show' in Bloomsbury where members of the public could pay a shilling to ride behind his latest creation, a locomotive called *Catch me who can*. The illustration is taken from a contemporary admission ticket so it may be presumed to be a fairly accurate as regards its general appearance. The cylinder has been repositioned so that it is vertical and the complex gearing and flywheel has been deemed unnecessary, the single piston being directly coupled to the rear driving wheels. One supposes that the driver was careful not to stop the locomotive with the piston at 'top dead centre'! Sadly, it too broke its rails and the experiment had to be abandoned after a few weeks.

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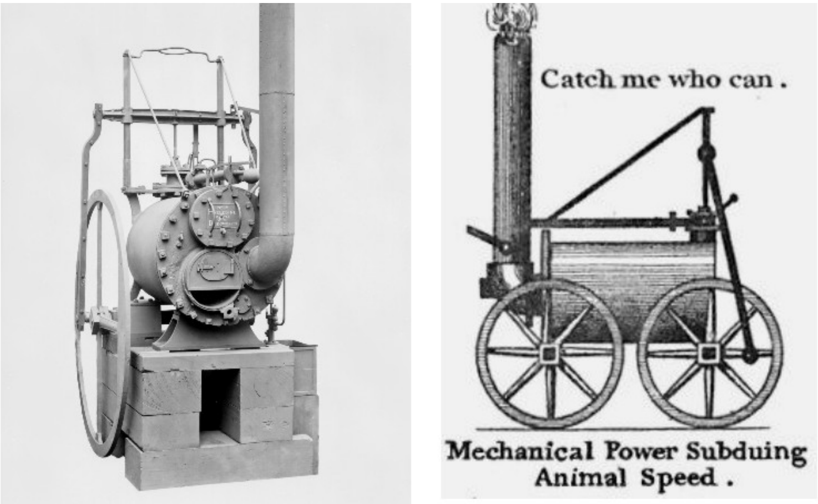
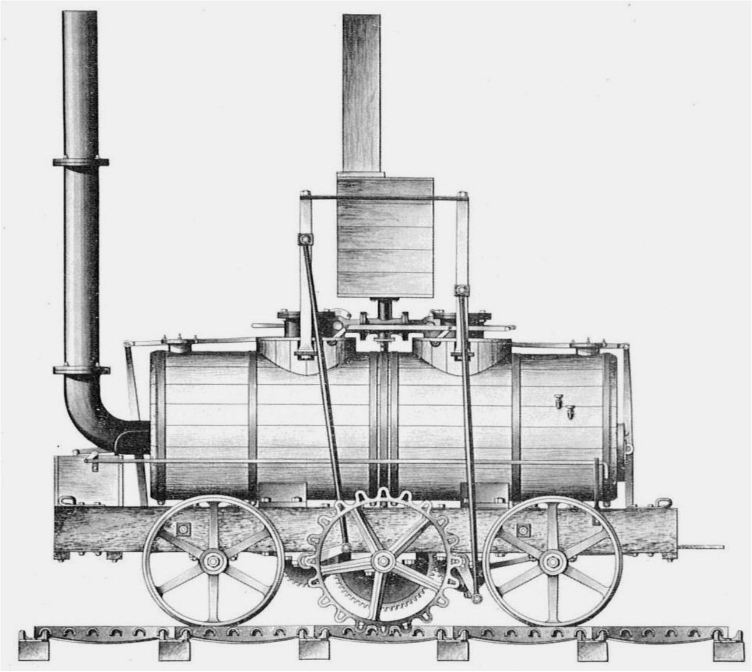
[3] For details of this calculation see the appendix.



Trevithick's 'Catch me who can' - 1808

The photo is of a stationary Trevithick engine originally built in 1806. The fact that it has two angled cranks strongly suggests that at one time there were wheels on both sides of the engine. Could this be the very engine which once powered *Catch me who can*?

It is a little difficult to explain why, after the apparently successful demonstrations at Merthyr Tydfil and Bloomsbury that steam locomotives could indeed pull both coal and paying passengers, other entrepreneurs did not more readily pursue the idea. I suspect that what Trevithick's experiments really demonstrated was that an engine heavy enough to pull a useful load was too heavy to run on existing plateways and that mine owners were reluctant to invest vast sums in new purpose-built tram or railways until the technology had been proved. Eventually, however, the manager of the Middleton colliery, one John Blenkinsop, decided in 1811 that he needed a faster and cheaper way to get his coal to the canal wharfs in Leeds. In order to cope with the steep gradients on the four mile journey, Blenkinsop devised a rack-and-pinion system which he patented. He then employed one Matthew Murray, a partner in the engineering firm of Fenton, Murray and Wood, to design and build a locomotive for him. The result was the world's first commercially successful steam locomotive: the *Salamanca*.



'Salamanca' Matthew Murray 1812

The main innovation here is the use of two pistons whose cranks are set at right angles. This ensures that the engine will start from any position. These cranks are clearly seen in the diagram above, as is the rack and pinion system. Another difference is that the cranks are not attached directly to the driving wheels; instead they communicate with them via a reduction gear which greatly increases the available force at the drawbar. Also the engine is built on a frame. All of Trevithick's designs used the boiler itself as the main structural element, presumably to make the engine as light as possible. Using a purpose-built plateway, Blenkinsop was not so constrained and the wooden frame would have given the locomotive some flexibility. In a slightly retrograde step, however, the flue is single and there does not appear to have been provision for assisting the draught with the exhausted steam.

The first trials of the engine were described in the Leeds Mercury on 27th June 1812

> *"On Wednesday last a highly interesting experiment was made with a Machine, constructed by Messrs. Fenton, Murray and Wood, of this place, under the direction of Mr. — BLENKINSOP, the Patentee, for the purpose of substituting the agency of steam for the use of horses in the conveyance of coals on the Iron-rail-way from the mines of J. C. Brandling, Esq. at Middleton, to Leeds. The machine is, in fact, a steam engine of four horses' power, which, with the assistance of cranks turning a cog-wheel, and iron cogs placed at one side of the rail-way, is capable of moving, when lightly loaded, at the speed of ten miles an hour. At four o'clock in the afternoon, the machine ran from the Coal-staith to the top of Hunslet Moor, where six, afterwards eight waggons of coals, each weighing 3¼ tons, were hooked to the back part. With this immense weight, to which, as it approached the town, was super-added about 50 of the spectators mounted upon the waggons, it set off on its return to the Coal-staith, and performed the journey, a distance of about a mile and a half, principally on the dead level, in 23 minutes, without the slightest accident.*
>
> *The experiment, which was witnessed by thousands of spectators, was crowned with complete success; and when it is considered that this invention is applicable to all rail-roads, and that upon the works of Mr. Brandling alone, the use of 50 horses will be dispensed with, and the corn necessary for the consumption of, at least, 200 men saved, we cannot forbear to hail the invention as of vast public utility, and to rank the inventor amongst the benefactors of his country."*

Four of these machines were built for the colliery and some were still in use 20 years later.

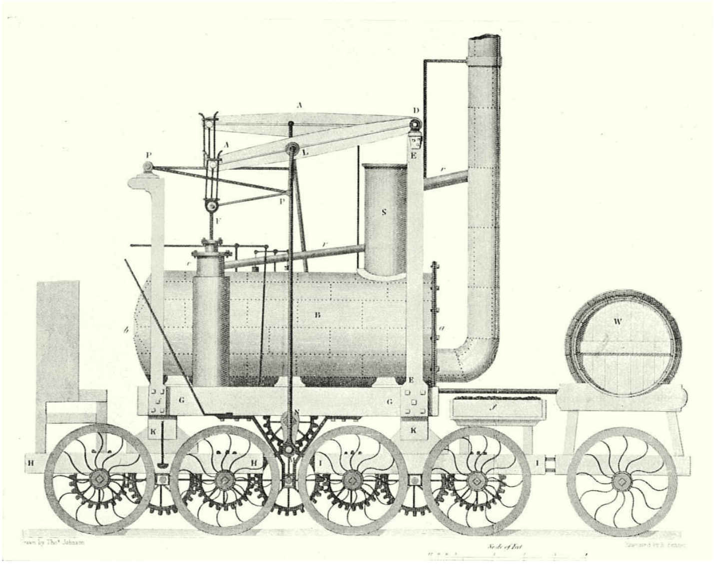
The issue of whether friction was in itself sufficient to provide the necessary force continued to nag, in spite of the experiments at Pen-y-Darren a decade earlier. The manager of Wylam colliery, one William Hedley who had had previous experience with some of Trevithick's early locomotives decided in 1813 to carry out a series of scientific tests described years later as follows:

> *"The experiments were made by men placed upon the carriages, and working the teeth gear by means of handles. The weight of the carriage, and the number of waggons drawn after it varied, but*

> *came to corresponding results, which were decisive of the fact, that the friction of the wheels of an engine carriage upon the rails was sufficient to enable it to draw a train of loaded waggons. So conclusive were the experiments, that an engine was immediately constructed."*

The engine referred to was built by Hedley himself and came to be known as *Puffing Billy.*

Hedley's 'Puffing Billy' 1813



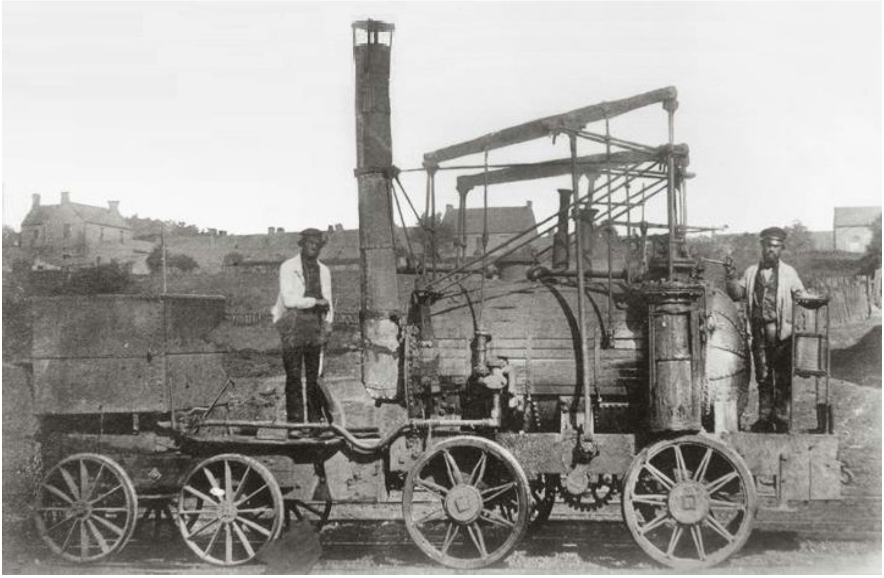
'Puffing Billy' William Hedley 1813

Like *Salamanca* Hedley's engine was built on a timber frame and had two vertical cylinders whose cranks were set at right angles but instead of placing the cylinders inside the boiler where they were difficult to access and maintain, they were placed on either side of the boiler. The reciprocating motion was transferred to the cranks using two beams and thence to eight driving wheels via internal gears. In Trvithick's single piston locomotives and *Salamanca* the central piston was attached to a horizontal crossbar with cranks attached to both ends. This arrangement can be seen in the photo of Trevithick's stationary engine on page 31. Clearly this arrangement could not be used for

Hedley's side-mounted cylinders, hence the need for the 'grasshopper' beams.

The original design had only four flat wheels but these proved too heavy for the cast iron plateway on which it ran, hence the need to spread the load over eight wheels. Eventually, when the plateway was replaced with wrought iron rails, these were replaced with four flanged wheels.

Incredibly, this engine worked until 1862. It is now preserved in the Science Museum in Kensington and there is a working replica at Beamish Museum. The photo below shows it at the end of its working life with its four flanged wheels.

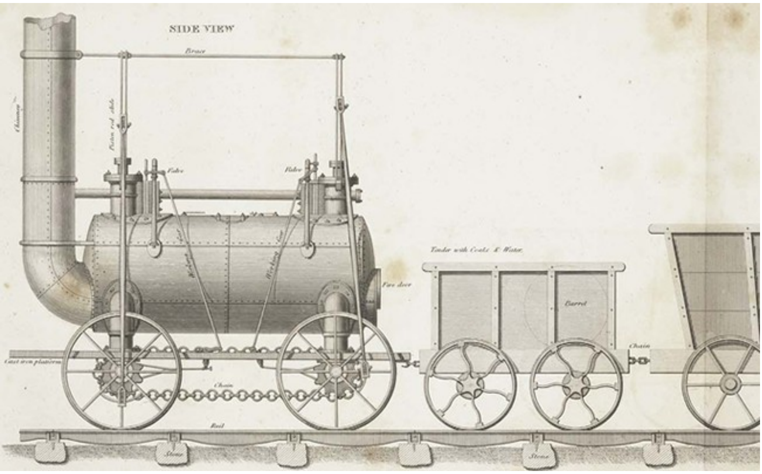


'Puffing Billy' c 1860

Hedley built two more locomotives for the colliery to the same basic design, *Wylam Dilly* and *Lady Mary*. The former is preserved in the National Museum of Scotland.

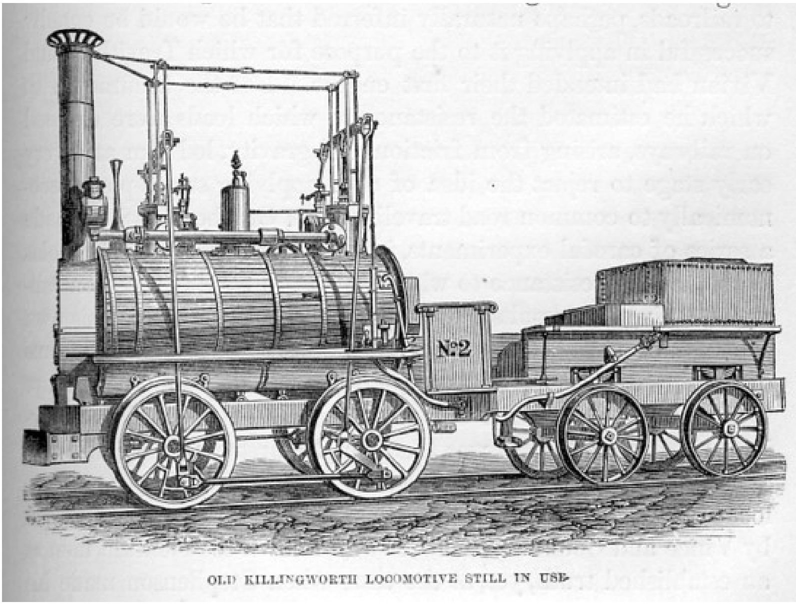
George Stephenson's Killingworth locomotives 1816-20

In the decade after Waterloo, George Stephenson built a number of locomotives for Killington colliery named after Blücher, Wellington etc. These all had the same basic pattern similar to Murray's *Salamanca* with a single flue and twin pistons set into the boiler. The main difference being that the cranks from the pistons were coupled directly to the wheels, one to the front pair, the other to the rear.



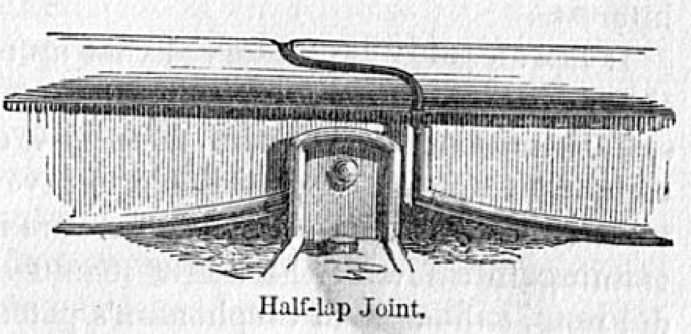
Possibly Stephenson's 'Blucher' with a chain drive connecting the driving wheels

Stephenson tried various ways of preserving the necessary 90 degree phase angle between the two pistons. Initially he used Hedley's gear train but this proved noisy and unreliable. After experimenting with a chain drive he eventually settled on the now ubiquitous coupling rods as shown in this 1816 engine, the *Killingworth Billy* now preserved in the Stephenson Railway Museum in North Shields. It is worth noting that, while the front crank and connecting rod are fastened to the same pin, the rear connecting rod is linked to a fixed arm which rotates with the wheel, thus allowing clearance for the crank to pass behind it each revolution. All of Stephenson's locomotive employed a blast pipe in the chimney but, as we have seen, this device was widely used by Trevithick a decade earlier.



'Killingworth Billy' George Stephenson 1816

In addition to improving the design of locomotives, George Stephenson greatly improved the cast-iron rails on which his locomotives ran by using a lap joint and a special chair to support it.

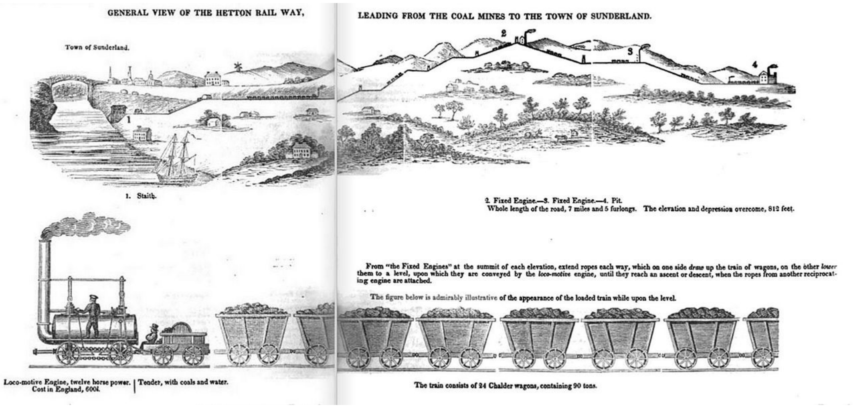


Stephenson's patented rail joint 1816

He also experimented with 'steam' suspension but this was not successful. An effective suspension system had to wait until steel springs of sufficient strength could be made.

Hetton colliery locomotives 1822

In 1819 George and his brother Robert were building a completely new 8 mile long railway for one Thomas Lyon to convey coal from the village of Hetton to the staithes at Sunderland. Barring the way was an 800 foot hill which required two uphill inclines worked by stationary engines and five downhill inclines worked by gravity. For the level sections in between Stephenson supplied a number of new locomotives based on the highly successful *Killingworth Billy* design one of which was called *Lyon*. An engine with that name, now preserved at the Shildon museum, was still working at the colliery in 1912. There is some doubt as to whether any part of this locomotive actually dates back to 1822 – like King Arthur's sword, the blade has been replaced 5 times and the hilt three times – but the fact that Stephenson's design was still in active service for 90 years testifies to its reliability and effectiveness.



Whole length of the road, 7 miles and 5 furlongs. The elevation and depression overcome, 812 feet.

From "the Fixed Engines" at the summit of each elevation, extend ropes each way, which on one side *draw* up the train of wagons, on the other *lower* them to a level, upon which they are conveyed by the *loco-motive* engine, until they reach an ascent or descent, when the ropes from another reciprocating engine are attached.

The figure below is admirably illustrative of the appearance of the loaded train while upon the level.

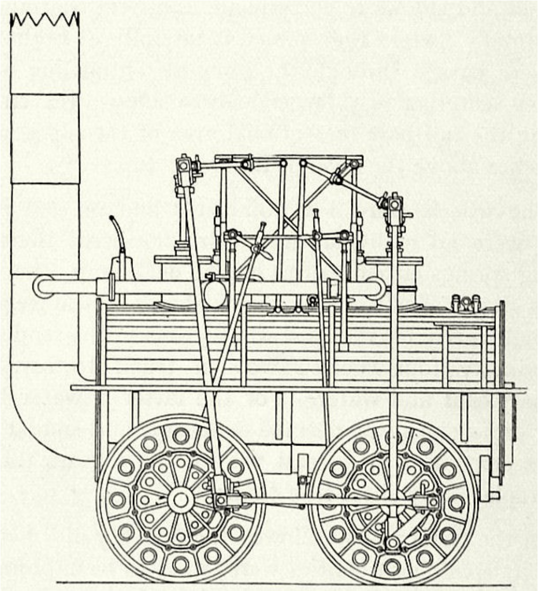
The train consists of 24 Chalder wagons, containing 90 tons.

The Hetton colliery line

At the opening of the railway on 18th of November 1822 crowds of people came to see this new marvel. They witnessed the locomotives pulling seventeen loaded wagons, averaging sixty-four tons, at the rate of four miles an hour.

George Stephenson's 'Locomotion' 1825

For inauguration in 1825 of the first passenger railway, the Stockton and Darlington railway, Stephenson built a locomotive specifically designed for speed – *Locomotion No 1*, now preserved in Darlington. It had large diameter driving wheels and three-point suspension which greatly improved its running capabilities.

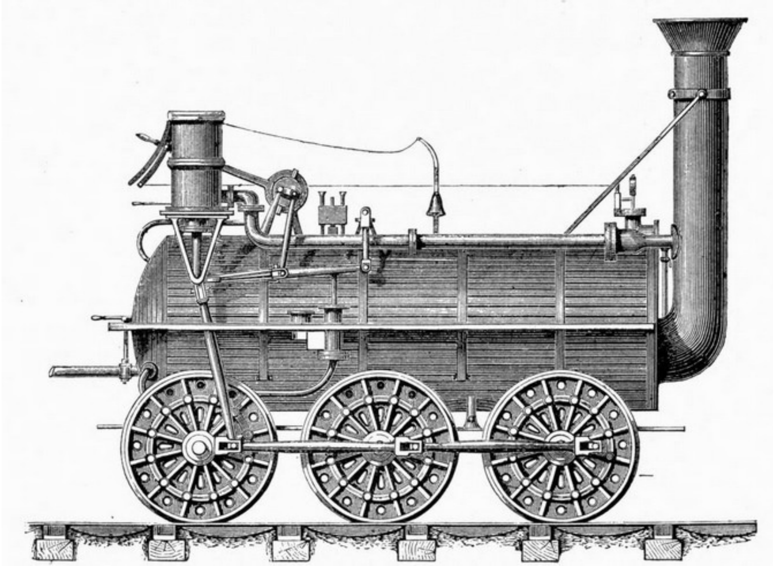


'Locomotion No 1' George Stephenson 1825

This locomotive could be regarded as the end of the road for the *Killingworth Billy* class of locomotive with its complex arrangement of cross bars and cranks. While perfectly serviceable, the single flue design put severe limits on the rate at which steam could be produced and hence on the maximum speed of the engine. In addition, the vertical pistons made it virtually impossible to provide the locomotive with springs making high speed undesirable as well as impractical.

During the first few years of its operation, the Stockton and Darlington Railway had considerable trouble with its Stephenson engines so the resident engineer Timothy Hackworth decided to build a new locomotive to his own design.

Hackworth's 'Royal George' 1827



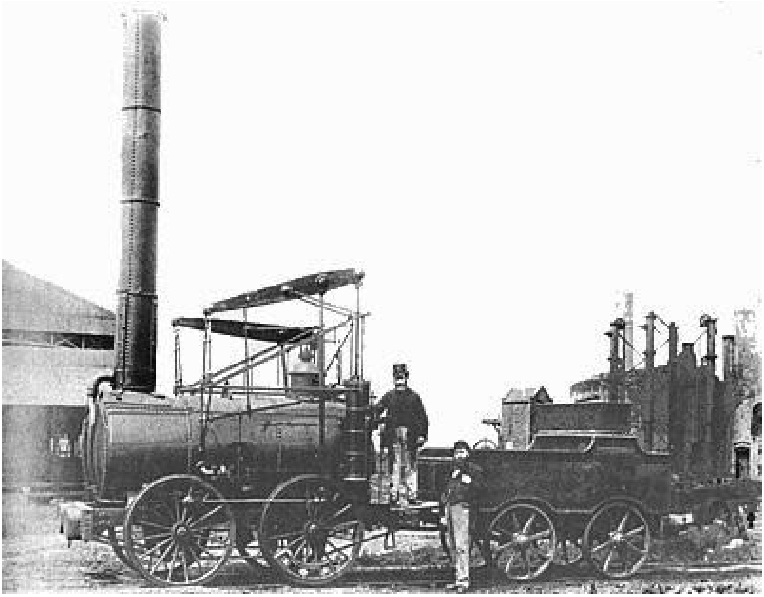
'Royal George' Timothy Hackworth 1827

Hackworth simplified the construction by reverting to the layout of Hedley's *Puffing Billy* with its twin side-mounted cylinders driving the six coupled wheels through a simple link. He also used the double-flue arrangement which greatly increased the efficiency of the boiler. But his greatest improvement was in the design of the blast pipe which assisted the draught up the chimney. Both Stephenson and Trevithick had realised the usefulness of this device but it was Hackworth who perfected it with the use of a carefully positioned nozzle inside the chimney.

Hackworth went on to build many more engines for the S&DR during the next decade, mostly based on the design of the *Royal George* with a return flue. These engines required two tenders – one at the firebox end for the coal and fireman, the other with the water tank and the driver.

Meanwhile, Robert Stephenson (George Stephenson's son) was experimenting with new designs of his own along similar lines.

Rastrick's 'Agenoria' 1829



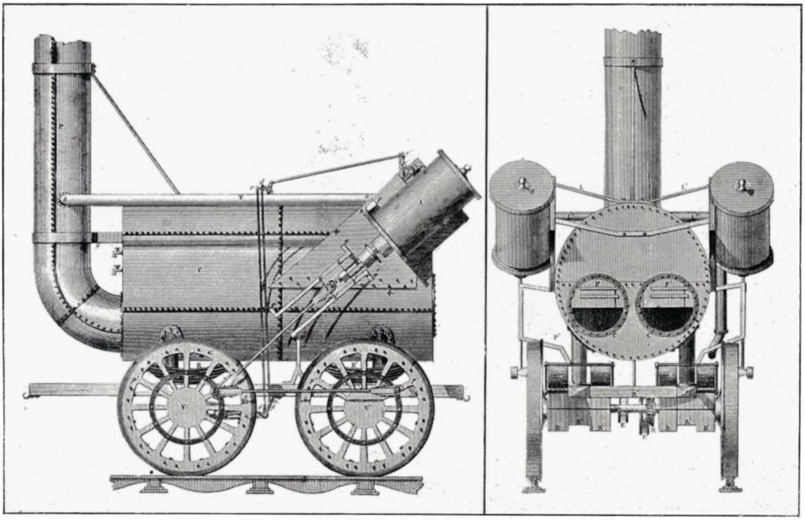
'Agenoria' Rastrick c1860

Not all locomotives at this time were built in Northumberland and Durham. In 1829 a railway was built from the colliery at Shutt End to the canal basin at Ashford on the Staffordshire and Worcestershire canal. It was built in Stourbridge by Foster, Rastrick and Co. and was in use until the 1860's.

It is clear from the photograph that the design of *Agenoria* is a throwback to Hedley's *Puffing Billy* and in no way contributed to the development of the steam locomotive. The two oscillating beams earned it the nickname 'the grasshopper'. Its main claim to fame is that it still survives in the National Railway Museum in York.

Three sister engines including the *Stourbridge Lion* were exported to America, the first in 1828. Almost immediately, American engineers began designing and building locomotives of their own and new railways began to spread over the nation at a prodigious rate.

Robert Stephenson's 'Lancashire Witch' 1828



Locomotive *Lancashire Witch*, de Robert Stephenson (1828).
(Collection Charles Dollfus.)

'Lancashire Witch' Robert Stephenson 1828

The illustration clearly shows that the *Lancashire Witch* (apparently named after the wife of the chairman of the Bolton and Leigh Railway to whom it was delivered) used two flues – presumably with two firegrates as well – instead of the return flue used by Hackworth. In addition the cylinders are angled. This allowed all four coupled wheels have leaf springs and greatly reduced the 'hammering' effect of the engine on the fragile rails. The parallel motion linkage on the *Royal George* has been replaced with a pair of guide rails and the simple valve gear can be seen on top of the cylinder as can the blast pipe leading to the chimney.

A similar locomotive called *America* was shipped to the Delaware and Hudson Canal Company in 1828.

Only one major development remained to be conceived – the multi-flue boiler which was to make its first appearance at the Rainhill trials in the form of the *Rocket*.

The Rainhill Trials

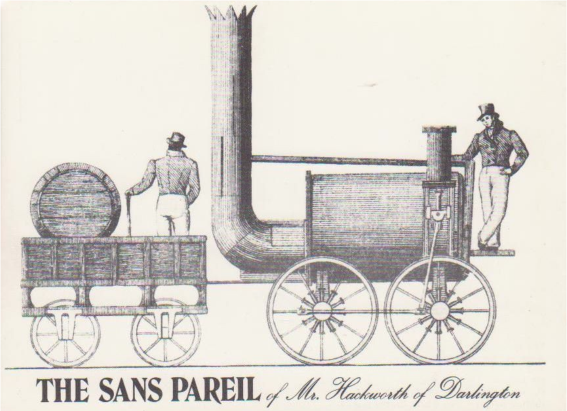
In 1826 George Stephenson was appointed chief engineer on the Liverpool and Manchester Railway. Stephenson argued strongly that it should be steam powered throughout and the directors agreed to organise a competition to find the best locomotive. The rules of the competition were as follows:

> *The weight of the Locomotive Engine, with its full complement of water in the boiler, shall be ascertained at the Weighing Machine, by eight o'clock in the morning, and the load assigned to it shall be three times the weight thereof. The water in the boiler shall be cold, and there shall be no fuel in the fireplace. As much fuel shall be weighed, and as much water shall be measured and delivered into the Tender Carriage, as the owner of the Engine may consider sufficient for the supply of the Engine for a journey of thirty-five miles. The fire in the boiler shall then be lighted, and the quantity of fuel consumed for getting up the steam shall be determined, and the time noted...*
>
> *The Engine, with the carriages attached to it, shall be run by hand up to the Starting Post, and as soon as the steam is got up to fifty pounds per square inch, the engine shall set out upon its journey.*
>
> *The distance the Engine shall perform each trip shall be one mile and three quarters each way, including one-eighth of a mile at each end for getting up the speed and for stopping the train; by this means the Engine, with its load, will travel one and a-half mile each way at full speed.*
>
> *The Engines shall make ten trips, which will be equal to a journey of 35 miles; thirty miles whereof shall be performed at full speed, and the average rate of travelling shall not be less than ten miles per hour.*
>
> *As soon as the Engine has performed this task, (which will be equal to the travelling from Liverpool to Manchester,) there shall be a fresh supply of fuel and water delivered to her; and, as soon as she can be got ready to set out again, she shall go up to the Starting Post, and make ten trips more, which will be equal to the journey from Manchester back again to Liverpool...*
>
> *The gauge of the railway to be 4 ft 8½ in.*

There were five entrants for the trials which took place on a level 1 mile stretch of the line near Rainhill in September 1829: Brandreth's *Cycloped*; Braithwaite's *Novelty*; Birstall's *Perseverance*; Hackworth's *Sans Pareil* and Robert Stephenson's *Rocket*.

The *Cycloped* was simply a horse on a treadmill! It is unclear how this entrant could meet the competition requirement to 'get the steam up to fifty pounds per square inch'. Perhaps the inventor, Braithwaite, bribed the directors to let him compete. In the event the treadmill collapsed and the engine was withdrawn.

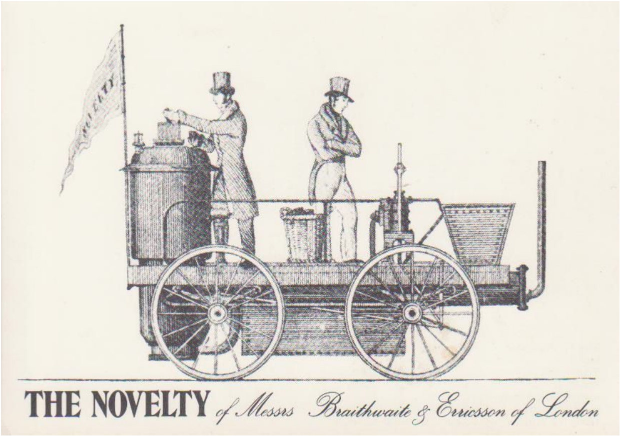
Perseverance suffered an accident on the way to Rainhill and could not be repaired in time. Birstall was, however, given a consolation prize of £25.



'Sans Pareil' Hackworth 1829

Hackworth's *Sans Pareil* was a smaller, lighter version of the *Royal George* and the illustration shows the fireman at one end and the driver at the other. Firing the engine must have been pretty hazardous close to that massive hot chimney!

For a while it looked as if the *Sans Pareil* (meaning 'without equal') showed promise, reaching speeds of 16 mph, but on the penultimate run the cylinder cracked and the engine had to be withdrawn. Despite this, the engine was purchased by the L&MR and ran on the lines for several years.



'Novelty' Braithwaite 1829

The *Novelty* was in many ways the most radical design and it was certainly the most popular entrant, reaching a speed of 28 mph on the first day. However, it too, suffered a burst pipe and was unable to complete the trials. It was probably the first engine ever to use a cranked axle. One cylinder and the wheels are part of a static display in the Manchester Museum of Science and Technology.

The undisputed winner of the competition (and of the £500 prize) was Robert Stephenson's *Rocket*.

For the Rainhill trials, Robert Stephenson realised that simplicity, speed and reliability were much more important than tractive effort. He based his design on the *Lancashire Witch* including the leaf spring suspension (clearly seen in the following illustration at the rear); valve gear mounted parallel and integral with the pistons; exhaust steam pipe leading to the chimney; steam dome and safety vale mounted on top of the boiler but he dispensed with the coupling rods and made the driving wheels larger than the idle wheels.

But the most important innovation (exactly whose idea it was is unclear) was to incorporate not one but 25 straight flues within the boiler.[4] This enormously increased the efficiency of the engine. It also

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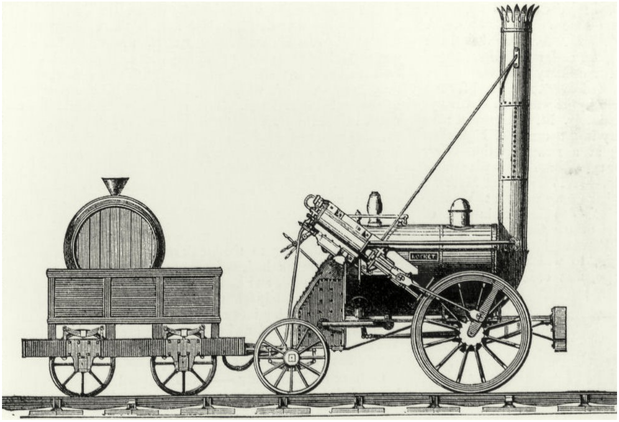
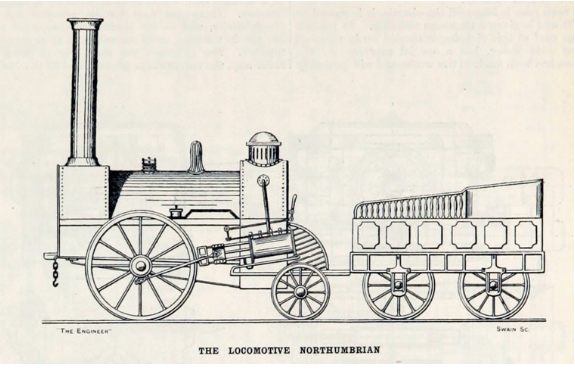
[4] The idea of a multi-flued boiler was not new and the French engineer Marc Seguin built a locomotive with one, probably quite independently, in the very same year.

meant that driver and fireman could share their duties at the rear of the locomotive on a spacious platform with all the tools required ready to hand.



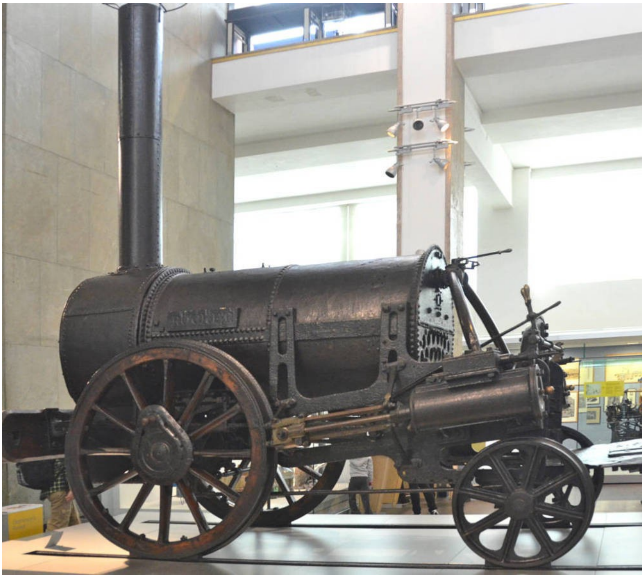
'Rocket' Robert Stephenson 1829 (0-2-0)

After the successful trials of *Rocket* Robert Stephenson built several more locomotives for the L&MR namely *Meteor*. *Comet*, *Arrow*, *Dart*, *Phoenix*, *North Star* and finally *Northumbrian*. This locomotive had a completely redesigned firebox which hung down below the boiler and which was much easier to rake out. It also had a proper smoke box at the base of the chimney where ash, blown through the boiler tubes by the draught, could be collected and easily removed.



'Northumbrian' Robert Stephenson'1830

Many of these improvements were applied to *Rocket* herself and she ran on the line successfully until she was withdrawn in 1862. She now has pride of place in the Science Museum in London alongside a full-sized replica.



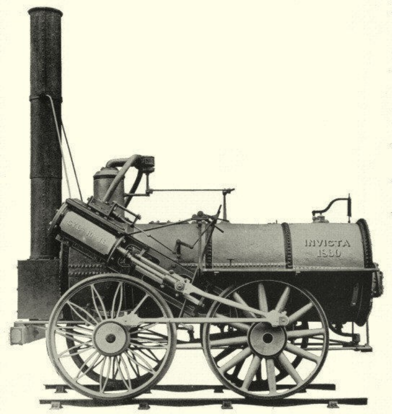
'Rocket' as preserved in the Science Museum

(It was during the celebrations for the opening of the Liverpool and Manchester Railway on the 15th of September 1830 that the MP William Huskisson was knocked down by *Rocket.* George Stephenson raced the injured man to hospital in Eccles using *Northumbrian* covering the 15 miles at an average speed of 36 mph but the doctors were unable to save him.)

Further Developments

Robert Stephenson's 'Invicta' 1829

At the same time as Robert Stephenson was building *Rocket* he was also trying out his ideas on a much heavier locomotive *Invicta*.



Robert Stephenson's 'Invicta' 1829

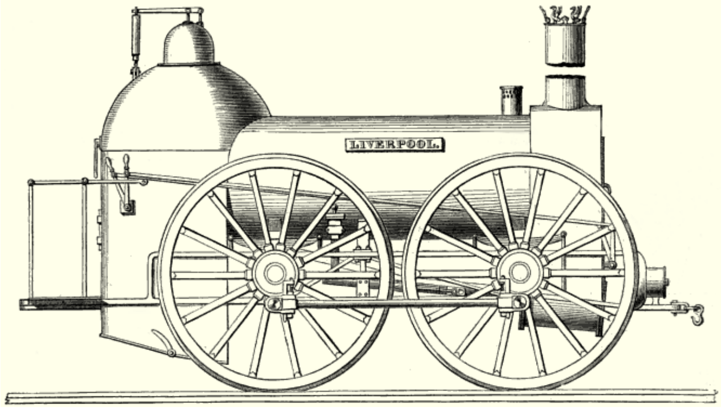
The most conspicuous difference is the greatly elongated boiler and the four coupled driving wheels. In addition and for the first time, the cylinders are placed at the front of the engine. The driver stood on a running board over the real wheels while the fireman stoked the fire from a tender running close behind.

Invicta entered service on the Canterbury and Whitstable railway on 15th April 1830 but soon proved to be very short of steam and underpowered. The reasons for this are unclear but they emphasise the general principle that the difference between a good and a bad steam engine does not lie in the efficiency of its individual parts but the way the fire grate, the boiler, the blast pipe, the chimney, the valve gear, the pistons and the wheels all work in harmony.

Invicta was withdrawn in 1839 and forgotten – which is probably why she is now the most authentic early locomotive still in existence. Currently in store in Canterbury there are plans to move her to a new museum at Whitstable.

Edward Bury's 'Liverpool' 1830

Edward Bury was Robert Stephenson's greatest rival and his first locomotive *Dreadnought* was intended to take part in the Rainhill trials but it was not ready in time. His second engine, *Liverpool* was tried on the L&MR but Stephenson decreed that its 6 foot driving wheels were 'too large for safety'. His motive for saying this can only be guessed at. Nevertheless, Bury went on to supply many locomotives similar to *Liverpool* for the burgeoning railway network, notably the London & Birmingham Railway as well as about 20 locomotives for America.



'Liverpool' Edward Bury 1830

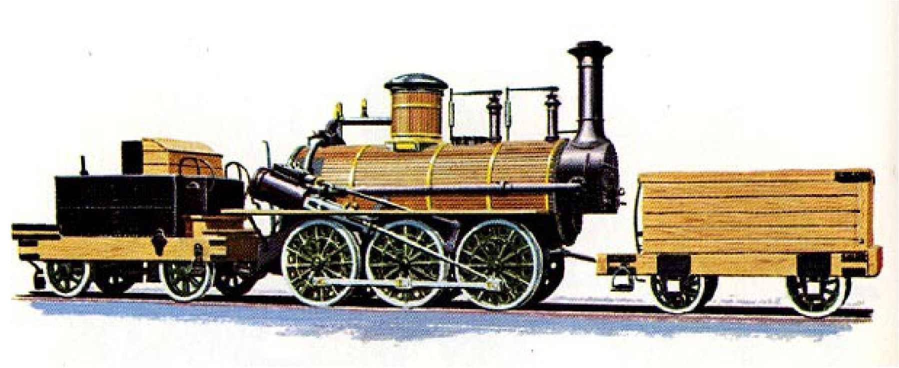
His most notable innovation was to place the two cylinders between the front wheels driving a cranked axle supported by two bearings running in two longitudinal frames called 'bars'. Unfortunately the cast iron cranked axles of the time were not very strong and if an axle broke, the wheels would fall off and the damage would be considerable.

But apart from this defect, Bury's characteristic 'haystack' firebox boiler was very effective and over 100 locomotives were built to this basic 4-wheeled design. They were not very powerful though and the L&BR frequently had to double and triple head its trains

.

Timothy Hackworth's 'Derwent' 1845

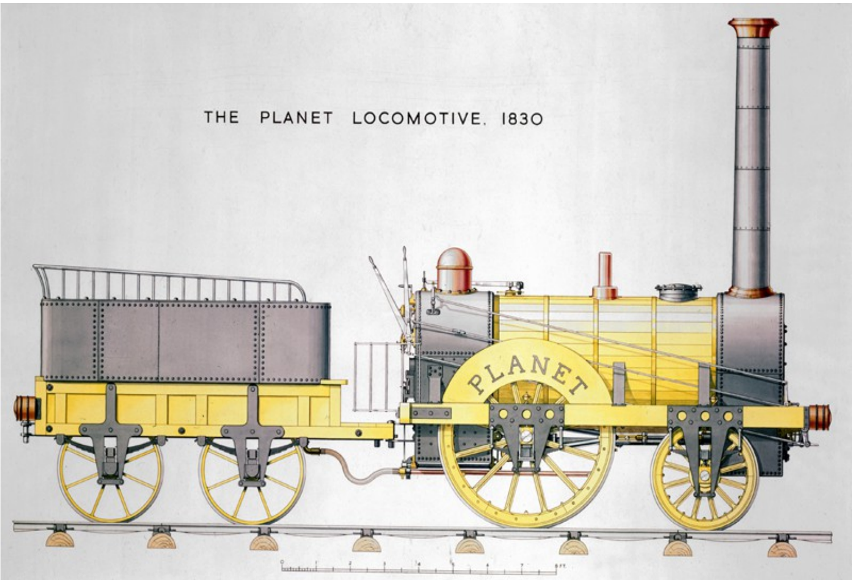
In the years between 1830 and 1848 Timothy Hackworth built several more 0-6-0 locomotive to work on the Stockton and Darlington line but in many respects his locomotives were already obsolete when they were built. He continued to use steeply angled cylinders placed at the rear of the engine and a simple return flue which necessitated tenders at both front and back, the former for the fireman and the latter for the driver. It cannot have been very comfortable for the fireman, shovelling coal into the firebox immediately beneath that huge smokebox which would undoubtedly have got very hot.



'Derwent' Timothy Hackworth 1845

One of the last of this class, *Derwent* is now preserved at the Darlington Railway Centre 'Head of Steam'.

Robert Stephenson's 'Planet' 1830



'Planet' Robert Stephenson 1830 (2-2-0)

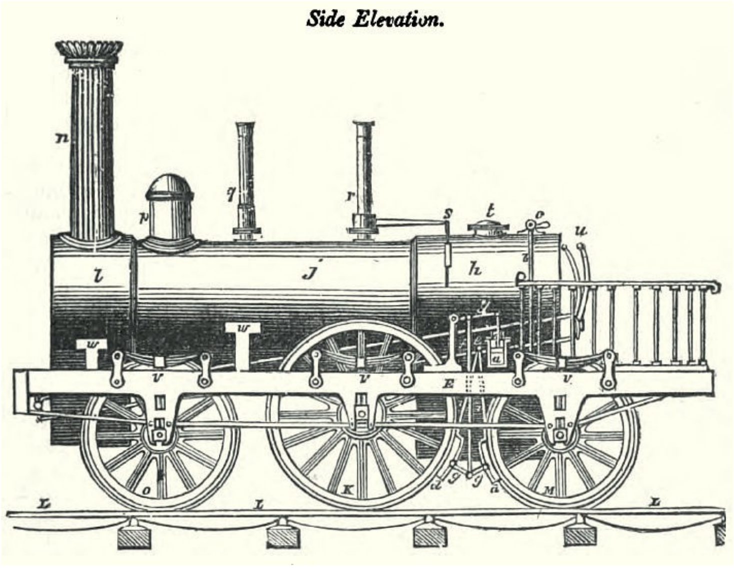
Apparently independently of Bury, Stephenson also had the idea of placing the cylinders inside the wheels beneath the boiler connected to a cranked axle but instead of just using two cast iron bars as a frame on which to build his engine, he used four – two on each side of the driving wheels. In the event of axle failure, therefore, the wheels would survive. In addition, to save weight with no loss of strength, he used wooden beams reinforced with iron plates on each side. This, then, was the first 'plate frame' locomotive and became the standard method of constructing locomotives in Britain.

Another innovation which is clearly seen in the diagram above is the 'horns' which allow free vertical movement of the axle boxes on their respective springs. This allowed the locomotive to sit squarely even on uneven and poorly laid track.

By placing the cylinders at the front and the driving wheels at the back – he was able to direct the exhaust from the cylinders directly up into the smokebox as well as placing most of the weight of the engine on the driving wheels. The result is what we might call the first 'modern' steam locomotive, the only essential difference between this machine and the last steam locomotive ever built for BR 'being a lot more wheels!

Indeed the need for more wheels soon became apparent as the short wheelbase of *Planet* lead to a rough ride and a rather excessive axle loading. These problems were solved by Stephenson's *Patentee* design which had a 2-2-2 or 0-4-2 configuration which also allowed for a longer boiler and therefore more power.

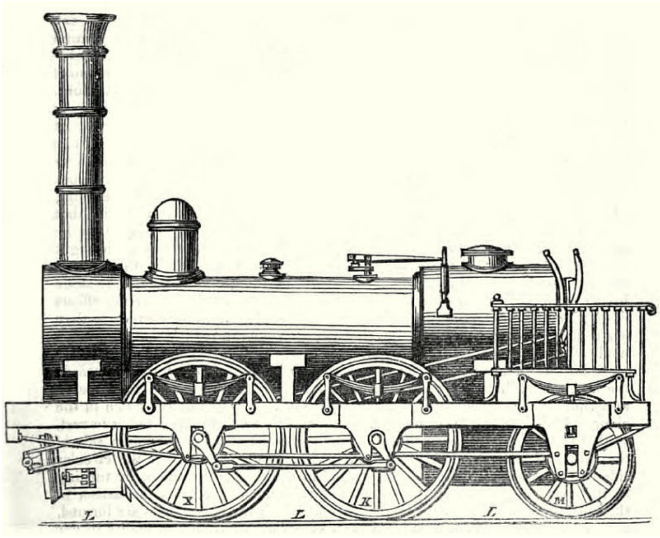
Stephenson's 'Patentee' 1835



'Patentee' Robert Stephenson 1835

The addition of a third axle behind the driving wheels allowed for the use of a longer boiler (and hence improved thermal efficiency) and a much larger firebox. It also greatly improved the stability of the engine, particularly at speed but it came with a problem. Any locomotive with three pairs of wheels set in a straight line will have problems turning a corner. Stephenson solved this problem by the simple expedient of omitting the flanges on the central pair of wheels.

This was the first truly successful locomotive class and many hundreds were built by several firms for use in Britain and abroad in both 2-2-2 and 0-4-2 configurations.



A 'Patentee' in a 0-4-2 configuration

L&MR 'Lion' 1838

One of the most famous locomotives of all time called *Lion* was built by Todd, Kitson and Laird in 1838 for the L&MR. She worked on the line until 1859 when she was sold to the Mersey Docks and Harbour Board and for many years she worked as a stationary pumping engine. In 1927 she was rescued by the Liverpool Engineering Society and restored to working condition. Her moment of glory came in 1952 when she starred in the film 'The Titfield Thunderbolt' and she was still able to take part in the 150th anniversary celebrations of the L&MR in 1980. Since then she has retired and is now on static display in the Great Port Gallery of Liverpool Museum. She must, surely, have had the longest working life of any steam locomotive – an incredible 122 years![5]

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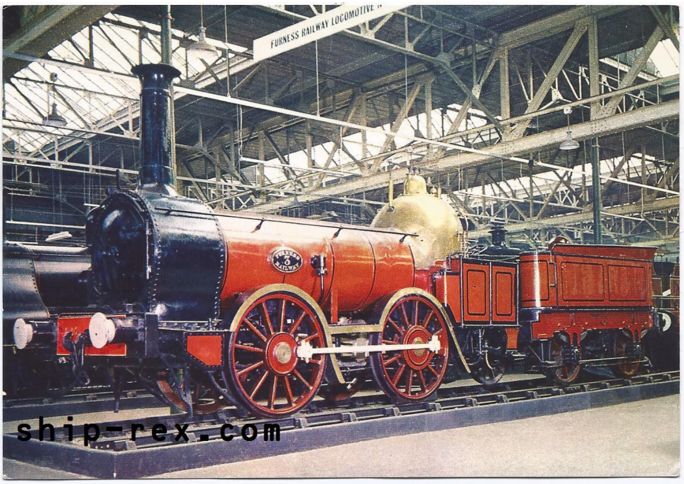
[5] There are plans to build a replica of her sister locomotive '*Tiger*'.

'Lion' 1838 (The 'Titfield Thunderbolt')

As can be seen from the photograph, she combines many elements of Stephenson's 'Patentee' and Bury's *Liverpool* with an 0-4-2 configuration, outside plate frames and a 'haystack' boiler.

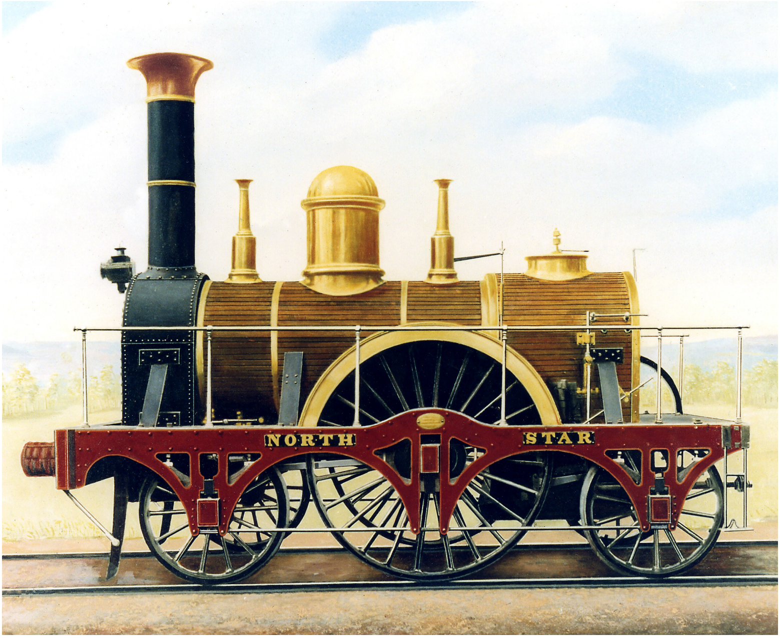
Another variation on Bury's *Liverpool* design was delivered to the Furness Railway in 1844 and the third member of its class has been preserved and is in the National Railway Museum. It is affectionately known as ' Old Coppernob' for obvious reasons.



'Old Coppernob' 1846 (Furness Railway)

Broad Gauge

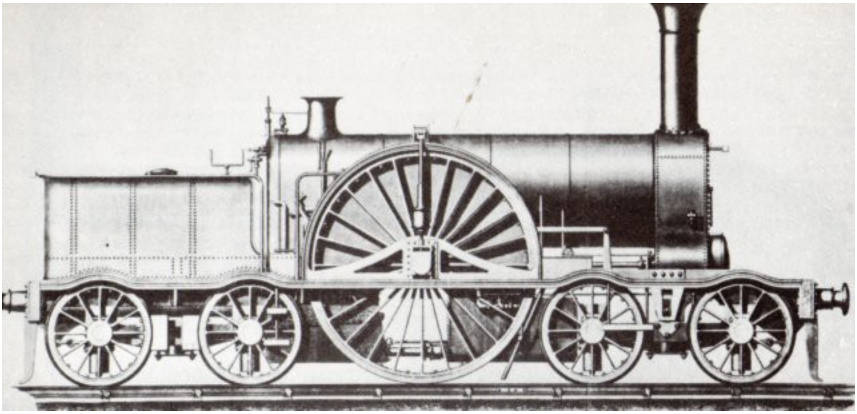
Isambard Kingdom Brunel wanted nothing but the best for his new railway and he started by converting a couple of large 'Patentee' class engines which had been returned unsold from the New Orleans Railway to his broad 7' gauge. To do this he employed a young engineer called Daniel Gooch and the result was the gorgeous *North Star* which regularly ran at 40 mph between London and Maidstone.



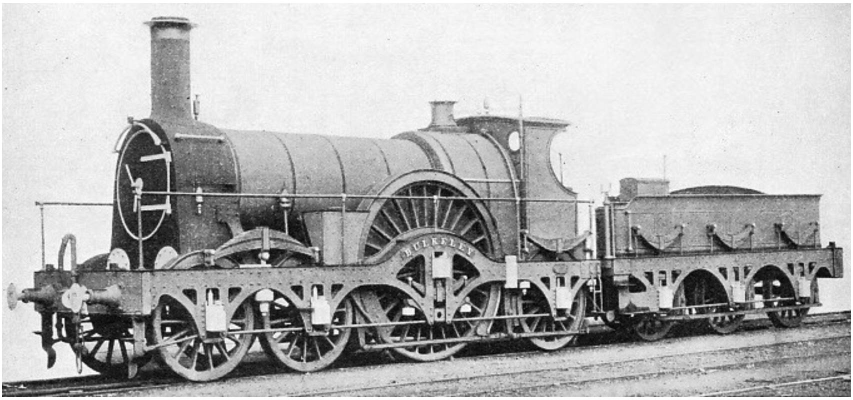
'North Star' Daniel Gooch 1837

A replica of this locomotive is in the GWR museum in Swindon.

Gooch continued to enlarge and refine the design producing in 1846 a series of engines of unrivalled speed and power, the *Iron Duke* class, and the GWR continued to build and run a variety of 'singles' (i.e. engines with a single pair of driving wheels) until the end of broad gauge in 1892.



'Iron Duke' class Daniel Gooch 1846



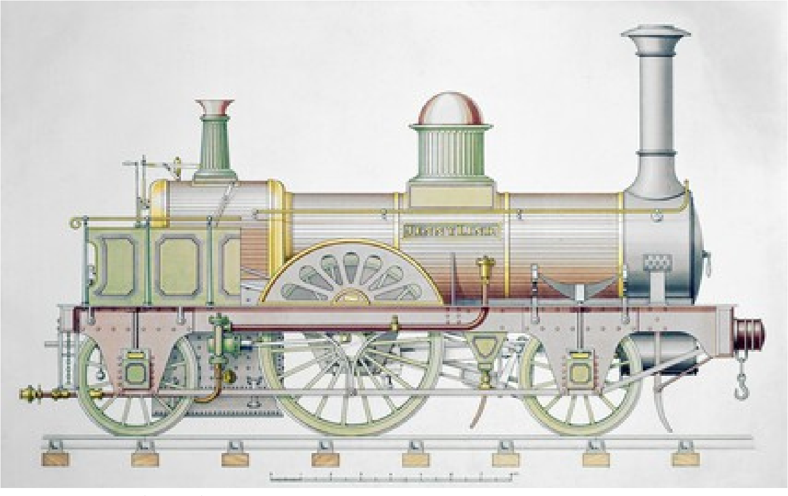
'Iron Duke ' class 1880

Broad gauge locomotives invariably had outside frames and inside cylinders.

Standard Gauge

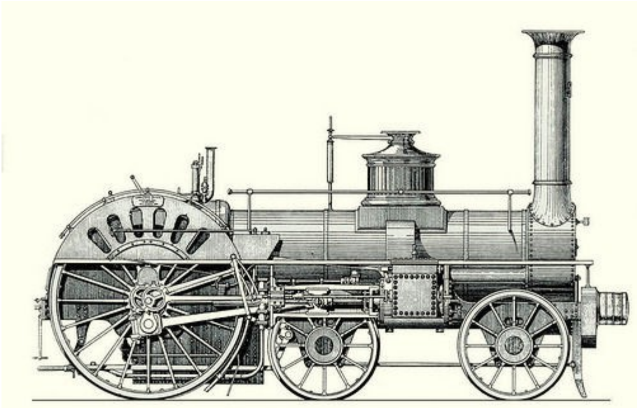
In 1842, concerned that the smoke boxes at the front of his 'Patentee' class locomotives were getting far too hot, Stephenson took out a patent for a 'Long Boiler' locomotive which retained the 2-2-2 wheel arrangement but placed the firebox behind the rear wheels. This did not prove very successful and did not handle well at speed but the design eventually morphed into the hugely successful and ubiquitous 0-6-0 freight locomotive.

A much more successful variant of the 'Patentee' design was the *Jenny Lind*, built for the London, Brighton and South Coast Railway in 1847 by E.B.Wilson & Co. Leeds. It had the unusual feature of outside frames for the leading and trailing wheel but inside frames for the driving wheels.



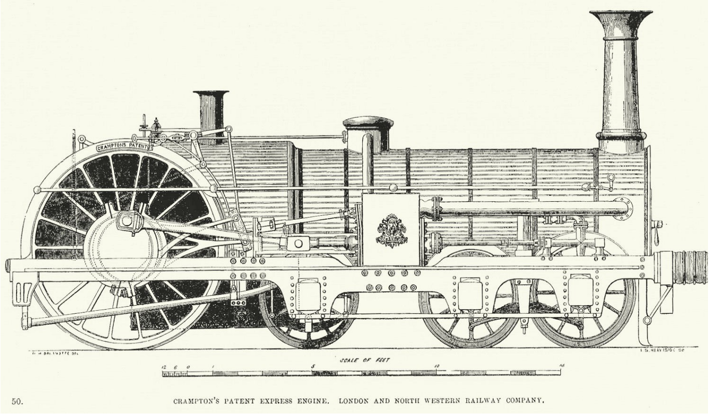
'Jenny Lind' Wilson 1847

Another idea was tried by Thomas Crampton for the London and North Western Railway. This involved placing the huge driving wheels behind the firebox and placing the outside cylinders between the two front wheels. This gave the locomotive a very unbalanced appearance.



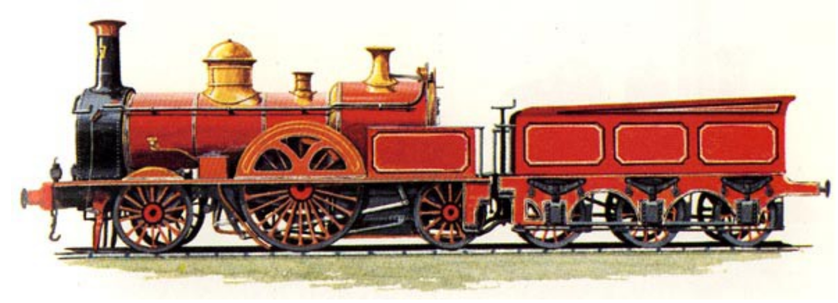
Crampton locomotive 1847

Another variant, the 'Patent Express', had a lengthened boiler and a 6-2-0 wheel configuration. Although very successful, this arrangement was not popular in Great Britain but it was widely used on the continent and in America.

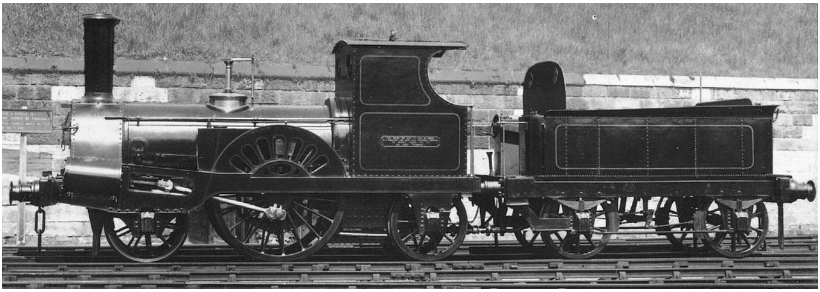


'Patent Express 'Folkestone' Crampton 1851

Of more conventional appearance were the 'Bloomer' class produced for the L&NWR at Wolverton by J.E.McConnell which had the classic 2-2-2 wheel arrangement with inside frames and inside cylinders.


'Bloomer' class McConnell 1851

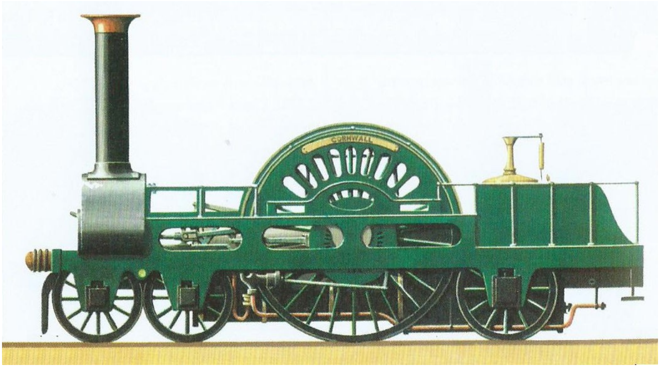
Meanwhile, at the L&NWR works in Crewe Alexander Allan was building a series of smaller engines with outside cylinders which were eventually to become the standard pattern for all British locomotives. First was *Columbine.* built in 1845 but here depicted as she was in 1880 with a cab.


'Columbine' Alexander Allan 1845

And then a class of coupled goods locomotives such as this one.

2-4-0 Goods engine Allan 1845

In 1847 Francis Trevithick (Robert Trevithick's son) tried an unusual solution to the problem of combining large driving wheels (for speed) with a low centre of gravity (for stability) by placing the boiler effectively *underneath* the main axle! The result was the *Cornwall* and she proved to be very fast and stable achieving a speed of 79 mph on a trial run. Unfortunately, though, the complications introduced by the design forced Trevithick to rebuild her with a conventional boiler. *Cornwall* is preserved at the Buckinghamshire Railway Centre.



'Cornwall' Francis Trevithick 1847

'Cornwall' as rebuilt 1858

From now on it becomes very difficult to trace developments in a single chronological sequence because the many different railway companies both in Britain and abroad, under the influence of many different designers, began to build locomotives designed for particular tasks and particular circumstances. It is easier to follow the development of certain features of locomotive design and to mention some classic locomotives in which those features were incorporated.

Valve gear

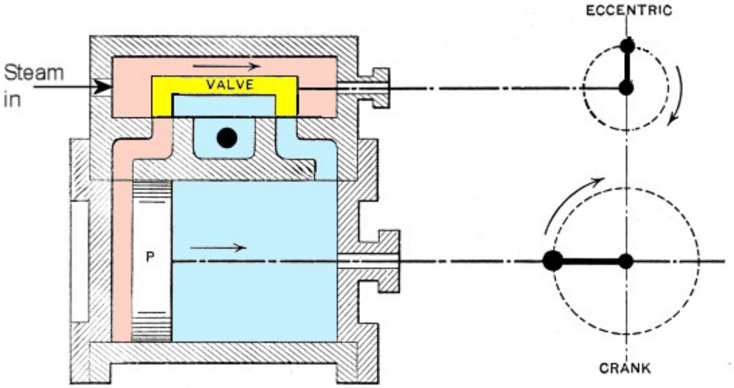
Very little has been said so far about the actual way a steam engine works apart from the obvious fact that high pressure steam is used to drive a piston down a cylinder and hence to turn the driving wheels.

The first point to make is that, right from the start, pistons were double-acting. That is to say, steam was admitted to both ends of the piston alternately. Together with the fact that the two cylinders were operated 90° out of phase, the exhaust blast gave every early steam engine the familiar and characteristic 'CHUFF-chuff-chuff-chuff CHUFF-chuff-cuff-chuff' beat with four 'chuffs' per revolution.

It is obvious that the design of the valve gear which controls the flow of steam in and out of the cylinders is of crucial importance to the efficient working of the engine.

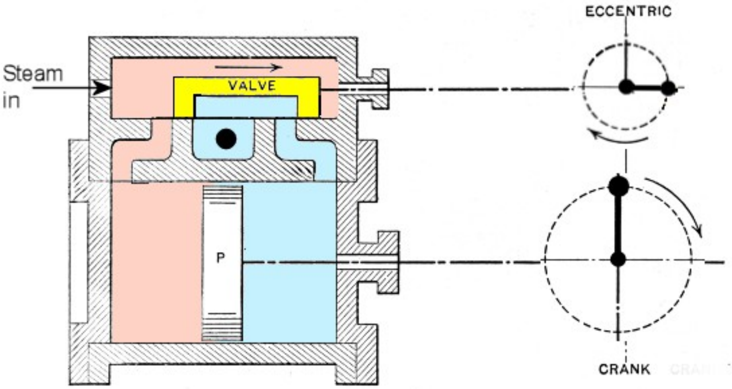
Stationary engines and early locomotives such as Trevithick's 'Coalbrookdale' locomotive had simple clack valves (so named because of the noise they made) which were simply knocked over at the end of the pistons' travel, opening the exhaust port and admitting new steam to the other end of the cylinder.

Later engines up to the period of the 'Patentee' had simple but effective slide valves which worked on the following principle.



Slide valve with piston at TDC

Mounted beside the piston is a slide valve (yellow) which is designed to exactly cover the steam ports when the piston is in the top dead centre position shown. The slide valve is connected to an eccentric (or crank) which rotates 90° ahead of the piston so it is currently moving rapidly to the right and is about to admit live steam to the left hand side of the piston. At the same time, the exhaust port is about to open. One quarter of a revolution later, the slide valve has reached the end and the piston is in the middle. Both ports are now fully open.



Slide valve with piston central

When the piston reaches the far end, the slide valve has moved back to the middle and the the exhaust port becomes the entry port and the entry port the exhaust. Ingenious, don't you think?

It soon became apparent that it was not necessary to open the entry port for the whole of the the cycle. By just opening the steam port for as little as 50% of the time, huge savings of steam could be achieved with little loss of power. This was very simply achieved by increasing the size of the steam side of the valve (the 'lap') and adjusting the phase angle of the eccentric to about 120° (i.e. an advance of 30°)[6] so that steam was still admitted at Top Dead Centre (TDC).

To make the engine go in reverse, all you have to do is to alter the eccentric so that the slide valve oscillates *behind* the piston instead of ahead.

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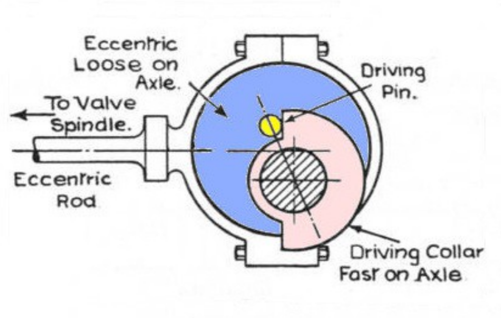
[6] For a more detailed explanation of 'lap' and 'lead' see the appendix.

In very early locomotives there were two eccentrics and the slide valve had to be manually disconnected from one eccentric rod and connected to the other. In order to make this process simpler, in engines like 'Rocket' one eccentric was used which was loose on the drive shaft. A pin on the eccentric (shown in yellow below) engaged with a collar fixed to the axle. In this way, when the axle was rotating one way the eccentric would lead but when the axle was rotating in the opposite direction it would automatically lag.



Loose eccentric valve gear

This system is simple and effective but it has one serious drawback. Basically it ensures that, once the engine is rolling forwards or backwards, it will continue to move in that direction but there is no simple way to change from forward gear to reverse without manually resetting the eccentric; nor is there any way of controlling the phase angle while the engine is in motion.

These defects were overcome by two of Stephenson's fitters, William Williams and William Howe, who in 1842[7] devised a linkage (since called Stephenson's link motion because it was first used by Robert Stephenson, not because he invented it) which combined the oscillations of two eccentrics which enabled the driver to control exactly when and how much steam was admitted to the cylinders. With the gear in the forward position, the motion of the valve would be maximum and would be in advance of the wheels; when the lever was moved to the

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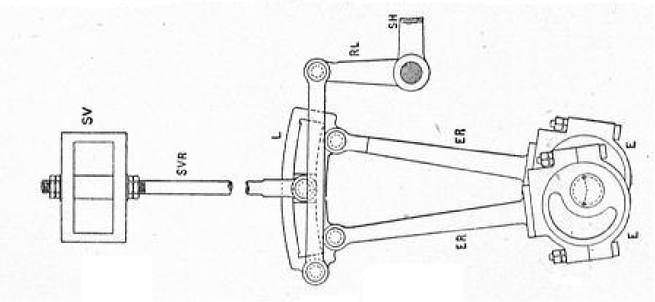
[7] Unknown to them an American William T. James had devised an almost identical system 10 years earlier for use on the Baltimore and Ohio Railway but the boiler on his experimental locomotive exploded and his invention was forgotten.

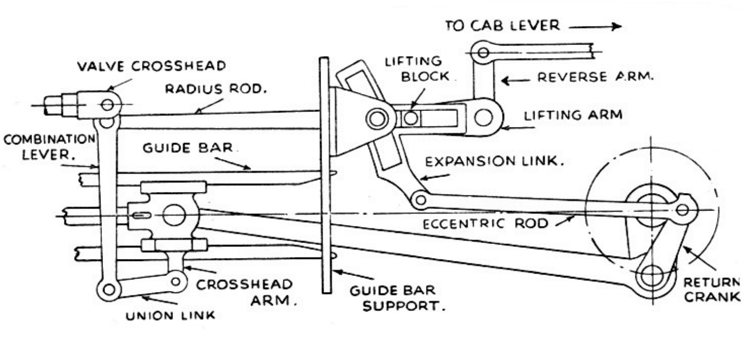
other extreme, the motion of the valve would be retarded and the locomotive would move in reverse.



Stephenson's Link Motion

With the gear in the middle (as illustrated above), the slide valve would oscillate in anti-phase (i.e. at 180°) to the piston with a relatively small oscillation allowing the locomotive to 'coast' with minimal wastage of steam.

In 1844 a slightly different arrangement was invented by a Belgian engineer Egide Walschaerts. Its main advantage was that it only required one eccentric and could be easily mounted on the outside of the locomotive. This also made it easier to mainmtain. For most of the 19th century, however, inside cylinders and Stephenson's link motion was preferred.



Walschaert's Link Motion

Bogies

All the locomotives illustrated so far had their wheels set between rigid frames. In order for locomotives with six or more wheels to be able to negotiate sharp corners, the central wheels did not have flanges. This solution was fine but it limited the length of the boiler and hence the power output of the engine.

In America the problem was particularly acute because owing to the pressing need for railways, the scarcity of iron and the hilly terrain, the early tracks were of poor quality, uneven and with tight curves and steep gradients. Rigid 6-wheeled locomotives of the 'Patentee' design were prone to frequent derailments and broke the rails but 4-wheeled locomotives like Bury's were simply not powerful enough.

Who actually invented the bogie (or 'truck' as it is called in America) is unclear. A patent for a swivelling bogie was granted to William and Edward Chapman in 1812 and the 8-wheeled version of 'Puffing Billy' (illustrated on page 34) was mounted on two 4-wheeled bogies but these early examples hardly qualify.

The first proper bogie was designed and built by John B. Jervis, the chief engineer of the Mohawk and Hudson Railway Co. in 1832. It is clearly seen in the following illustration.

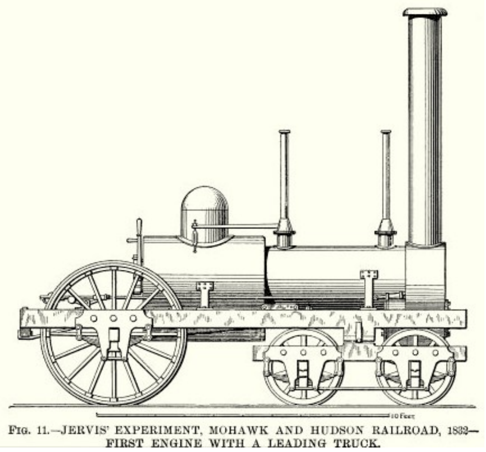


FIG. 11.—JERVIS' EXPERIMENT, MOHAWK AND HUDSON RAILROAD, 1832—FIRST ENGINE WITH A LEADING TRUCK.

'Experiment' John Jervis 1832

The advantage of this arrangement is that the locomotive is effectively resting on just three points and therefore, like a milking stool, it will sit happily on any surface however uneven.

When it became apparent that a single pair of driving wheels was insufficient, Henry Campbell of the Germantown Railroad added a second pair of driving wheels creating the first of a huge line of classic American 4-4-0's. Unfortunately he completely nullified the advantages of the swivelling bogie by preventing it from turning!

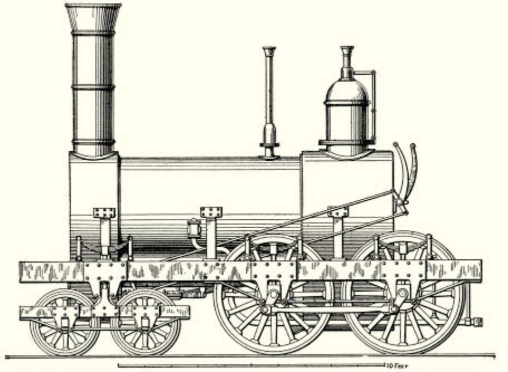


FIG. 12.—CAMPBELL'S FIRST AMERICAN EIGHT WHEEL ENGINE, 1836—PHILADELPHIA, GERMANTOWN, AND NORRISTOWN RAILROAD.

Unnamed locomotive, Campbell 1837

So the honour of creating the first true articulated 4-4-0 locomotive must go to Joseph Harrison who designed and built *Hercules* in 1838.

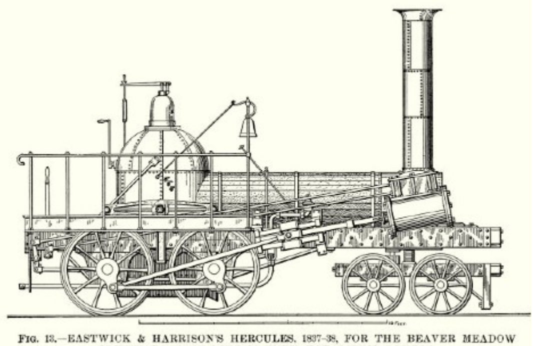
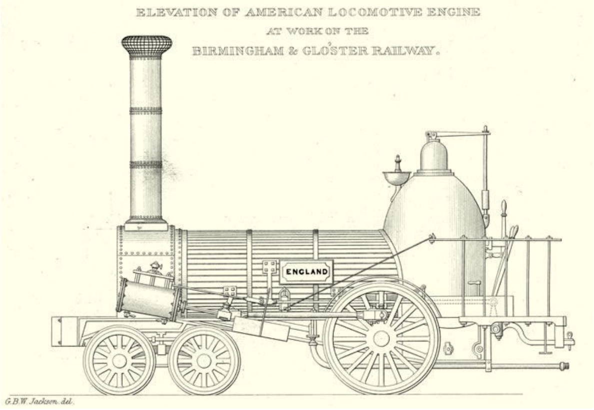


FIG. 13.—EASTWICK & HARRISON'S HERCULES, 1837–38, FOR THE BEAVER MEADOW RAILROAD—FIRST ENGINE WITH EQUALIZING LEVERS.

'Hercules' Joseph Harrison 1838

This remarkable engine is noteworthy for two further innovations the most important of which was its system of suspension. Gone are the 'horns' which are characteristic of the independent suspension favoured by British designers. Instead the driving wheels 'share' their leaf springs by means of an 'equalizing beam'. In this way, if one of the wheels is suddenly forced upwards by hitting bump in the track, its partner is forced downwards thus sharing the shock. The other innovation was a simple method of exchanging the inlet and exhaust ports so that the engine could easily be moved into reverse.

In 1838 the Birmingham and Gloucester Railway company was looking for a range of powerful engines to work the famous 'Lickey Incline', a 2 mile stretch of line at a gradient of 1 in 37.7, the steepest line in the United Kingdom. The directors quickly decided that the Bury locomotives used on the London & Birmingham Railway were not up to the job and turned to an American company founded by William Norris of Pennsylvania to supply nine 4-4-0 locomotives similar to *Hercules*. These were the first locomotives with bogies to run in the UK.



William Norris 'England' 1838

Over the next two decades the American locomotive acquired its distinctive profile and by 1850 the Rogers Locomotive Works in Paterson, New Jersey was churning out great numbers of classic American 4-4-0's complete with spark-arresting funnel, cow-catcher, panelled cab, bell and lamp.

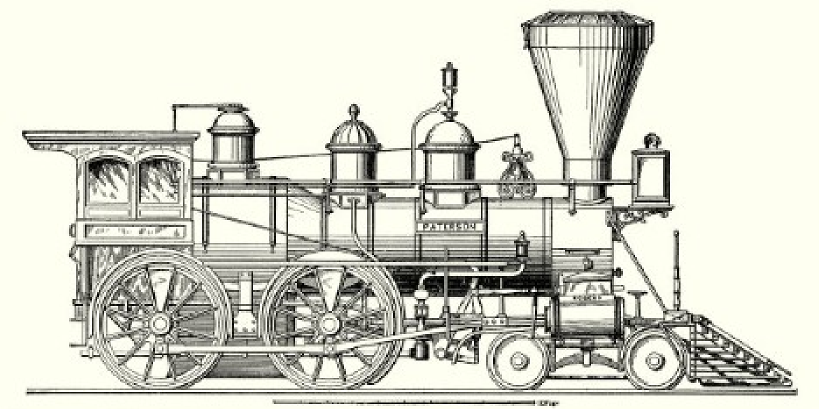
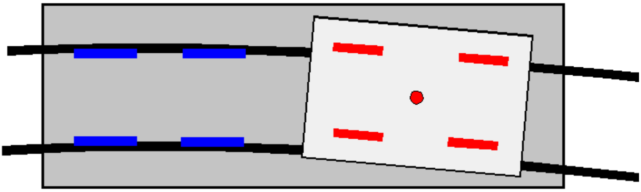


FIG. 18.—ROGERS' STANDARD PASSENGER LOCOMOTIVE, 1850, HAVING ALL THE ESSENTIAL FEATURES OF A MODERN AMERICAN ENGINE.

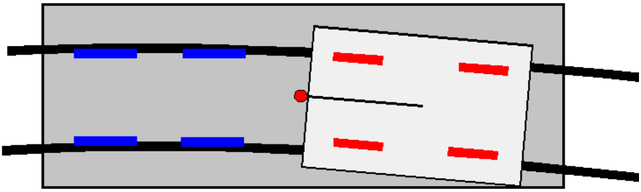
Rogers Standard locomotive 1850

There is one last twist (literally) to the story of the bogie. All bogies up to now were pivoted in the middle and the central pivot also carried the weight of the locomotive. While this is a huge advance over a rigid 8-wheeler, it does not quite solve the problem of turning a corner as the following diagram shows.



4-4-0 locomotive with a swivel bogie

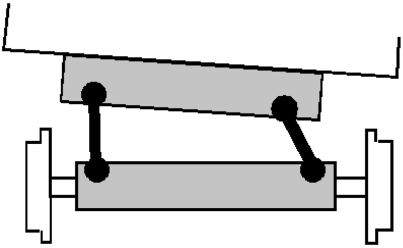
If the driving wheels are to remain aligned correctly with the track, the bogie must not only swivel, it must slide sideways too. This problem was solved by Levi Bissell in 1857. Instead of pivoting the bogie in the centre, the pivot is moved to a point midway between the bogie and the driving wheels. The front of the locomotive rests on a sliding surface which allows for the sideways movement but also carries the weight of the locomotive.



4-4-0 locomotive with a Bissell bogie

In more modern designs, a pair of slings is used instead of a sliding surface. In addition to allowing for the desired sideways movement, the design can cause the locomotive to tilt in the direction of the turn.

In the following diagram the locomotive is entering a right hand curve. Owing to the fact that the two links are wider at the bottom than at the top, as the locomotive swings out towards the outside of the curve the right hand link pushes the body of the locomotive up causing it to tilt slightly.



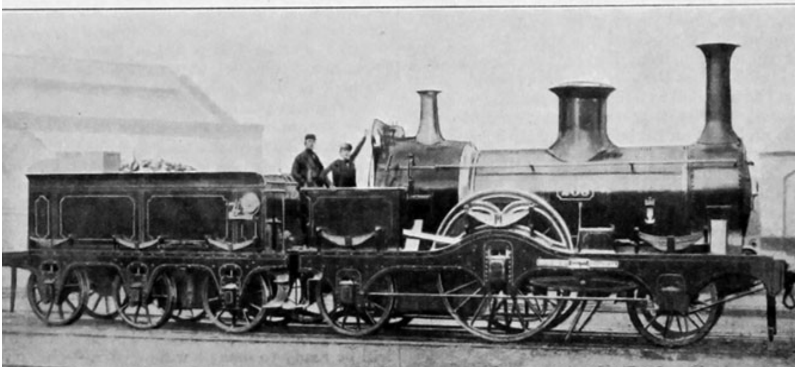
Bogie linkage

Victorian heyday

From 1840 on steam locomotives were being built in their hundreds, if not thousands in workshops all over the UK and abroad. We are fortunate that many of these fine locomotives have been preserved and Britain's oldest steam locomotive still in regular use is the delightful 0-4-0 locomotive built by Bury, Curtis and Kennnedy in 1846 for the Furness Railway.

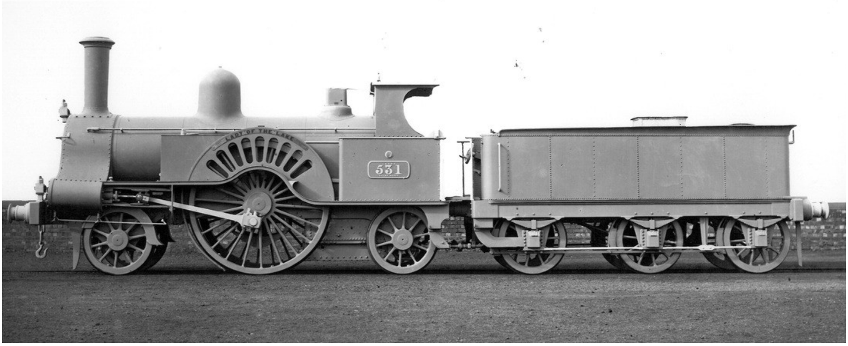
Furness Railway No 20 1846

Throughout the second half of the nineteenth century, passenger locomotives were usually 2-2-2 with large driving wheels for speed. Typical of the class were the locomotives built for the Great Northern Railway by R & W Hawthorn & Co.



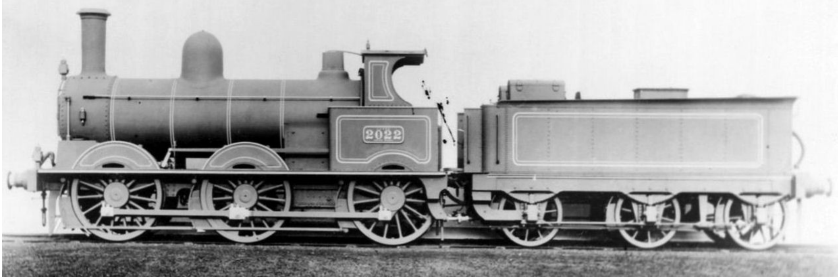
'Hawthorn' class locomotive 1852 (GNR)

Another 2-2-2 was the 'Problem' class of locomotive, built for the London and North Western Railway by John Ramsbottom who succeeded Francis Trvithick as chief engineer in 1857.



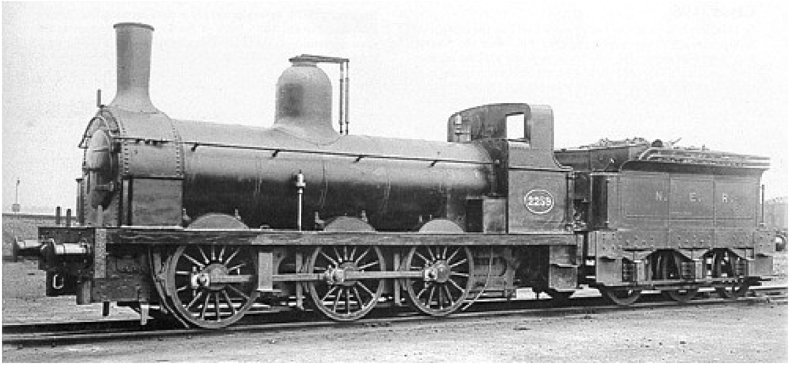
'Problem' class John Ramsbottom 1859 (LNWR)

Freight locos were often 0-6-0, their smaller wheels giving much greater traction at the expense of speed.



'DX-goods' class: John Ramsbottom 1859 (LNWR)

William Bouch was chief engineer on the Stockton and Darlington Railway at this time and he designed a number of locomotives for the railway, among them being a 0-6-0 in 1852 known as a class 1001. A member of this class, built in 1875, is preserved in the National Railway Museum.



Class 1001 Freight loco: William Bouch 1852

Bouch was also the first designer to use the 4-4-0 wheel arrangement which had become so popular in America,

Meanwhile Matthew Kirtley was designing a new express locomotive for the Midland Railway. He chose outside frames, inside cylinders and a 2-4-0 wheel arrangement of which there is a fine example in the National Railway Museum.

'156 class': Matthew Kirtley 1866 (MR)

These locomotives proved to be both fast and reliable, the last being withdrawn from service in 1936. Later versions – the famous 'Midland Compounds' – had 3 cylinders and a 4-4-0 wheel arrangement.[8]

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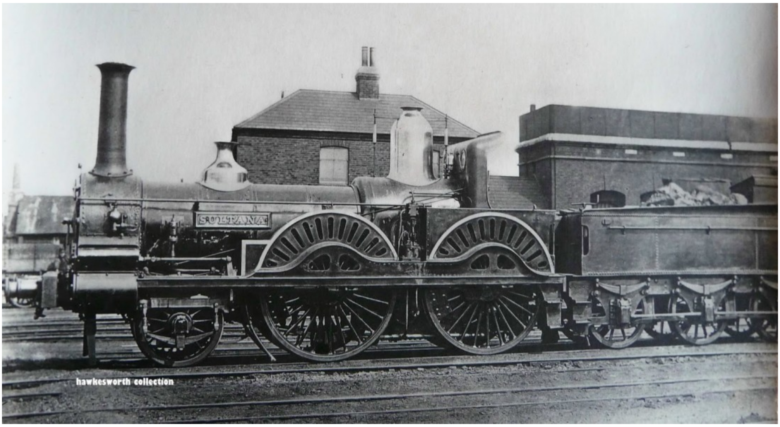
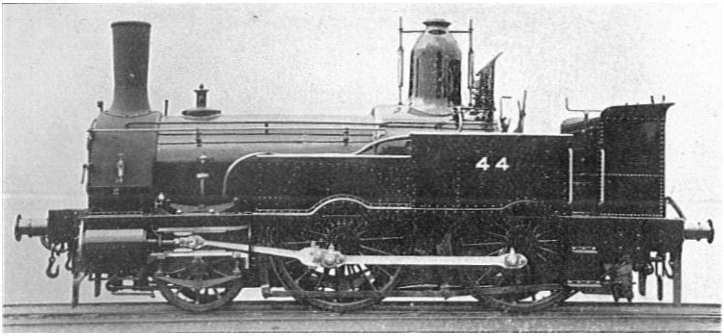
[8] A 'compound' locomotive is one which has both high pressure and low pressure cylinders, the latter using the exhaust steam from the former. Compound locomotives usually had three or four cylinders and were very efficient.

Another engineer who favoured the 2-4-0 wheel arrangement was Joseph Hamilton Beattie, locomotive superintendent on the London and South Western Railway.



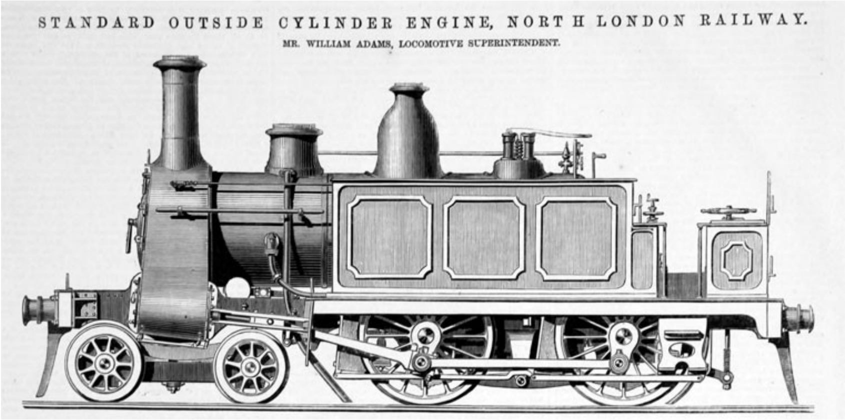
'Sultana': J.H.Beattie c1859 (LSWR)

It was Beattie who designed the incredibly successful 'Well Tank' class of locomotive , the forerunner of the ubiquitous 'tank' locomotive which has no need of a tender.



'Well Tank' locomotive: J.H.Beattie c1860 (LSWR)

The first engineer to experiment seriously with bogie designs was William Adams who designed a 4-4-0 locomotive for the North London Railway in 1868.



4-4-0 Express locomotive: W. Adams 1868 (NLR)

Adams moved to the London & South Western Railway in 1878 where he designed and built a huge number of 4-4-0's of which this is one.

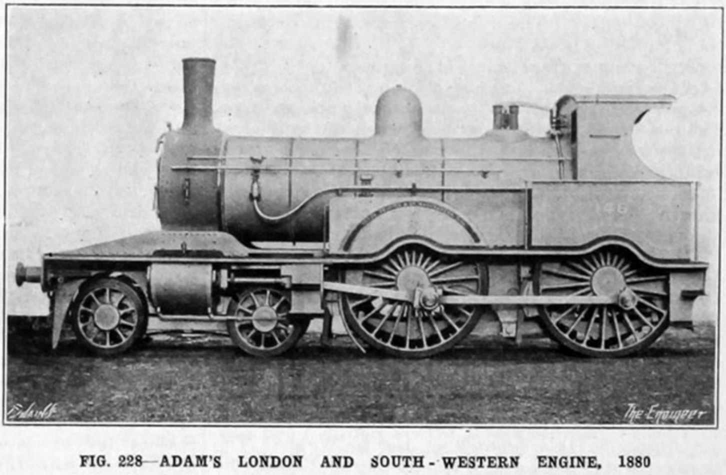


FIG. 228—ADAM'S LONDON AND SOUTH - WESTERN ENGINE, 1880

4-4-0 Express locomotive: W.Adams 1880 (LSWR)

One of the most successful class of locomotives ever built were the 'Stirling singles' designed by Patrick Stirling' in 1870 for the Great Northern Railway. With outside cylinders, a 4-2-2 wheel arrangement, cab and close-coupled tender, they really look the part.

'Stirling single' Patrick Stirling 1870 (GNR)

This fine locomotive is preserved in the National Railway Museum in York.

Also preserved in the NMR is the rather reactionary 0-4-2 *Gladstone*, designed for the London, Brighton and South Coast Railway by William Stroudley.

'Gladstone' William Stroudley 1882 (LB&SCR)

Yet another express locomotive from this era which is preserved in the NRM is *Hardwicke* one of the 'Precedent' class built by Francis Webb in 1874 for the LNWR.

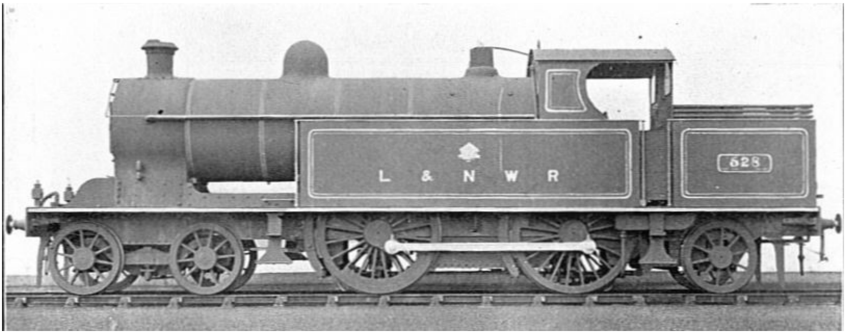
'Hardwicke': Francis Webb 1874 (LNWR)

Matthew Kirtley was succeeded by Samuel Johnson at the Midland Railway in 1874 and in 1887 he came up with a new design for a 'single driver' engine which became known as the 'Johnson spinner' because of its tendency to spin its wheels on starting.

'Spinner': Samuel Johnson 1887

Number 673, built in 1897, is preserved at the NRM.

Meanwhile, William Adams was developing a series of highly efficient 4-4-2 tank locomotives for suburban routes on the LNWR.

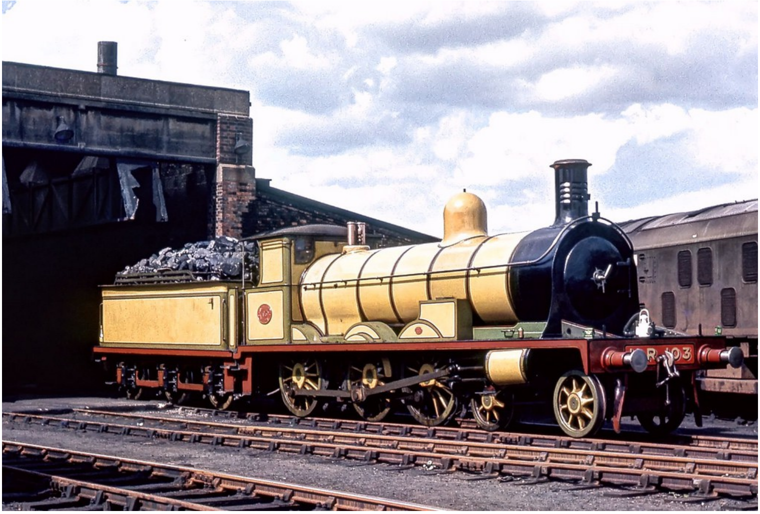


'Precursor' class: William Adams 1880 (LNWR)

By this time, the need for a new breed of more powerful engines became apparent. One way of achieving this was to employ three or more cylinders. Typically two of the cylinders would use steam at high pressure and the exhaust from these cylinders would be used again in a pair of low pressure cylinders. This technique is called 'compounding'. Apart from some early experiments it was first used by the Swiss engineer Anatole Mallett. In the UK, the idea was taken up by F. W. Webb of the LNWR who designed a class of 4 cylinder compound 2-4-0's in 1882. (Interestingly, the driving wheels are not coupled. The high pressure cylinders (visible) drive the rear wheels while the low pressure cylinders inside drive the front wheels.)

'Experiment' compound locomotive: F. W. Webb 1882 (LNWR)

To handle this extra power, more wheels were needed and the first 4-6-0 locomotive to be built in Britain was the 'Jones Goods' loco, built for the Highland Railway by David Jones in 1892.



'Jones Goods': David Jones 1892 (HR)

This locomotive was the most powerful engine of its day and was used for both freight and passenger duties. It was only superseded in the 1920's by compound engines with superheated steam and as such represents the epitome of Victorian engineering. One of these fine locomotives (photographed above) is preserved in the Glasgow Museum of Transport.

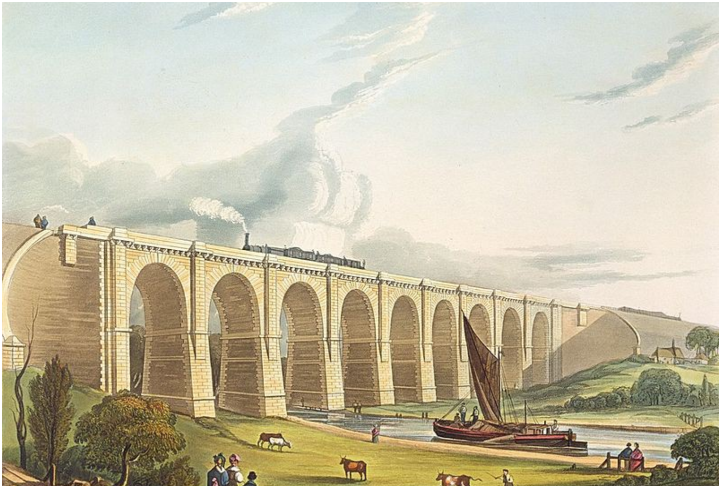
Victorian Railways

The Liverpool and Manchester Railway

As is well known, the first intercity railway, the Liverpool and Manchester Railway, opened on 15th September 1830. and sparked off two decades of 'railway mania' at least equal to the 'canal mania' of the 1770's and 80's.

The main obstacle facing the George Stephenson and his assistant Joseph Locke in building the Liverpool and Manchester Railway was the crossing of the notorious region of bog called Chat Moss which appeared to be able to swallow any amount of rubble without trace. Stephenson's solution was to 'float' the railway of a raft of empty tar barrels and criss crossed timber beams.

Another obstacle was the valley of the Sankey Brook which Stephenson crossed by means of a fine nine-arched stone viaduct sufficiently high above level of the Sankey canal so that sail-rigged canal barges could pass beneath without lowering their masts.



The Sankey Viaduct in 1830

The Sankey viaduct is still in use today and is a Grade I Listed structure described in the listing as 'the earliest major railway viaduct in the world'.

Another first for the Liverpool and Manchester railway was the 1¼ mile Wapping tunnel built right under the city carrying the line down to the docks on the Mersey at a gradient of 1 in 48. This was too steep for the locomotives of the day and wagons were initially winched down on cables.

The upper entrance to the Wapping tunnel (1830)

The tunnel is not currently used but it is still in good condition and it may yet have a further lease of life.

The Leicester and Swannington Railway

In 1832 George Stephenson was called in to build a mile long tunnel to connect the coal fields round Swannington with the city of Leicester. Billed by the good people of Leicester as 'the longest steam railway tunnel in the world at the time' its status is arguable but there is no arguing with the challenges that Stephenson faced and overcame in its construction. The Glenfield tunnel only ever accommodated a single track and when the tunnel was pressed into service to carry passenger trains (up to 1928 that is), special carriages had to be built with barred windows to prevent foolish passengers who stuck their heads out of the windows from being decapitated. It is currently abandoned.

The Great Western Railway

In building a railway from London to Bristol, Brunel faced three major challenges.

First was the crossing of the river Thames at Maidenhead. Brunel had recently completed the elegant Wharncliffe viaduct over the river Brent near Ealing which incorporated several unique features. Firstly it was made of brick, not stone; secondly the structure was hollow so it was very light and thirdly, the eight arches were semi elliptical each with a span of 21 m and a rise of only 5.7 m – a span to rise ratio of 4.1. To bridge the 90 m wide Thames while keeping the railway as level as possible, Brunel decided to use two elliptical spans each with a width of 39 m but a rise of little over 7 m (a span to rise ratio of 5.3). Such a flat arch had never been built before and many people thought it would fall down as soon as a locomotive passed over it – but stand it did and, indeed, it stands to this day, carrying the weight of modern trains travelling at speeds Brunel could only have dreamed of.

Maidenhead Bridge (1838)

The bridge was completed in 1838 and doubled in width in 1890 without altering its classic appearance in any way.

Travelling west the next obstacle was Sonning Hill. Local objections from the land owners forced Brunel to take the line through a cutting over a mile long and 60 feet deep. The cutting was was widened in 1890.

Between Chippenham and Bath, the line had to cross Box Hill at the Southern end of the Cotswolds which at this point stand at an elevation of 146 m. Rather than have his railway climb a hill, slowing his trains down, Brunel opted for a 1¾ mile long tunnel, the longest railway tunnel in the world at that time. The tunnel was not easy to build and it was completed two years behind schedule in 1841 but it carries high speed trains to this day.

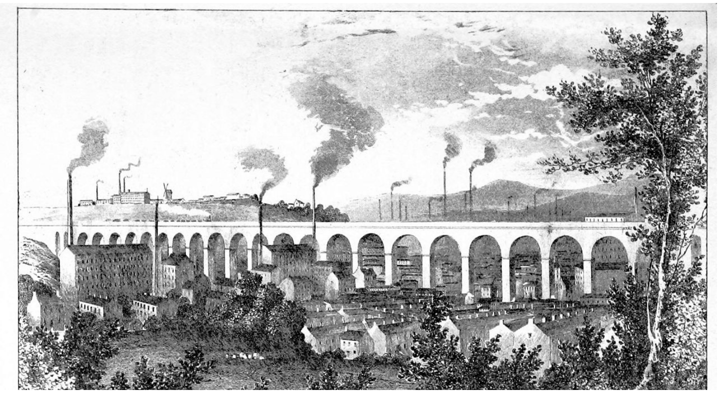
The London and Birmingham Railway

In finding a route for a railway between London and Birmingham Robert Stephenson faced a similar ridge of high ground between Daventry and Rugby. His solution called for a horseshoe shaped tunnel 8.5 m high and over a mile long under the village of Kilsby. Mainly to overcome passengers fear of suffocation, he turned the excavation shafts into two huge ventilation shafts which can be clearly seen from the A5 today. The tunnel was completed at great cost in 1838 and was by far the longest railway tunnel in the world (until the completion of Brunel's Box tunnel three years later). It remains a crucial part of the West Coast Main Line today.

Box tunnel (1841)

Kilsby tunnel (1838)

Further North the West Coast Main Line divides at Crewe; one branch has no difficulty crossing the Mersey near Warrington but the branch which goes to Manchester crosses it at Stockport 6 miles south of the city. Here it flows in a valley half a mile wide 30 m below the height of the surrounding plain. In order to cross this barrier, a viaduct was needed, bigger by far than anything which had been constructed to date. At 500 m in length with 22 spans each 19 m wide, and up to 33 m in height, it required 11 *million* bricks. Originally built with a double track it was widened to 4 tracks in the 1880's. It opened in 1840



Stockport or Edgeley Vvaduct (1840)

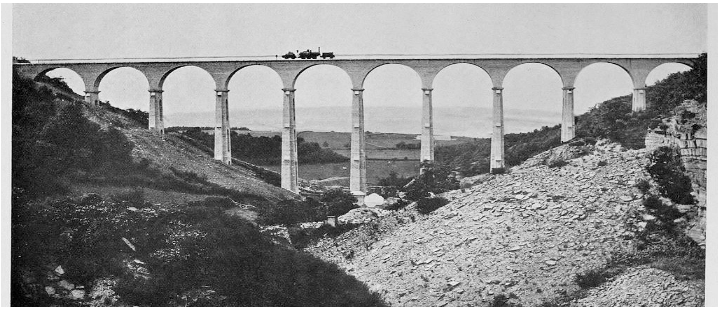
The Edgeley viaduct did not hold its record for long. In 1851 the astonishing Göltzsch viaduct was opened carrying trains from Leipzig to Nuremberg. About the same length as the Edgeley viaduct, the Göltzsch viaduct is over twice as high. Uncertain whether brick columns could be built that high, the designer decided to use the Roman technique of 'building a 'bridge on a bridge'. In the original design, all the arches were of equal width but technical problems with the foundations required the central arch to be wider than the others making the comparison with the Pont du Gard even more stricking. (The Pont du Gard is 50 m high and 275 m long; the Göltzsch viaduct is 78 m high and 570 m long). It is estimated that the Göltzsch viaduct required 26 million bricks and remains the largest brick built viaduct in the world.

Göltzsch viaduct (1851)

The Stockton and Darlington Railway

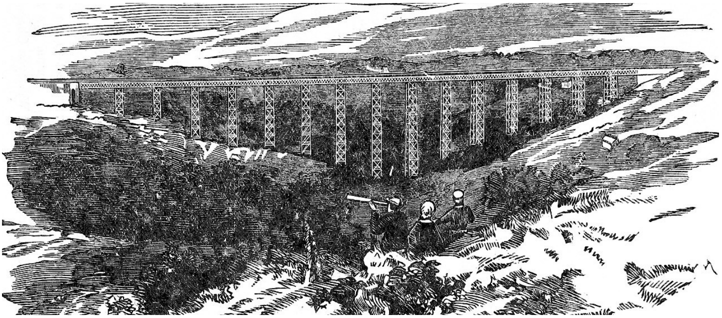
The Stockton and Darlington Railway which opened in 1825 is famous for being the first public railway to use steam locomotives albeit initially for freight trains only. Over the years the railway expanded, eventually becoming part of the Great North of England Railway (GNER) whose rails extended North to York and East across the Pennines to Tebay.

The most notable structures on the line were the Shildon tunnel (⅔ mile long, completed in 1842 and still in use) , the Hownes Gill viaduct (designed by Thomas Bouch, 210 m long, 46 m high, completed in 1858, currently used as a cycleway),



Hownes Gill viaduct in 1858

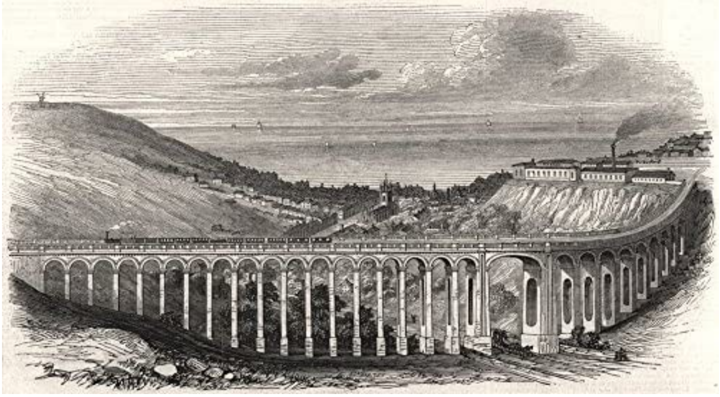
and the Belah viaduct on the Stainmore line, the largest trestle bridge built in the UK (also designed by Thomas Bouch, 315 m long, 60 m high, completed in 1860 and demolished in 1963)



Belah viaduct (1860)

The London and Brighton Railway

In 1842 John Rastrick completed a fine viaduct for the L&BR over the valley of the Ouse in Sussex. It was an amazing construction ¾ of a mile long with 37 elegant double brick arches. 4 years later he completed a second, curved viaduct in Brighton itself just outside their terminus at London Road. The illustration below is rather fanciful but it does show its 27 arches, one of which is wider than the others, and its beautiful decoration with string courses and balustrades, all of which can be seen today as both viaducts are still in constant use.



London Road viaduct (1842)

The Great Northern Railway

Linking London with the North East, the Great Northern Railway was completed in 1850 with the construction of the Digswell viaduct bear Welwyn Garden City. Its 40 arches carry the current East Coast Main Line 30 m high over the river Mimram.

Digswell viaduct (1850)

Another viaduct worth mentioning is the Bennerley viaduct, built by the GNR over the Erewash valley on their Derbyshire extension. Although constructed much later in 1877, it remains one of the last surviving wrought iron trestle bridges in the UK.

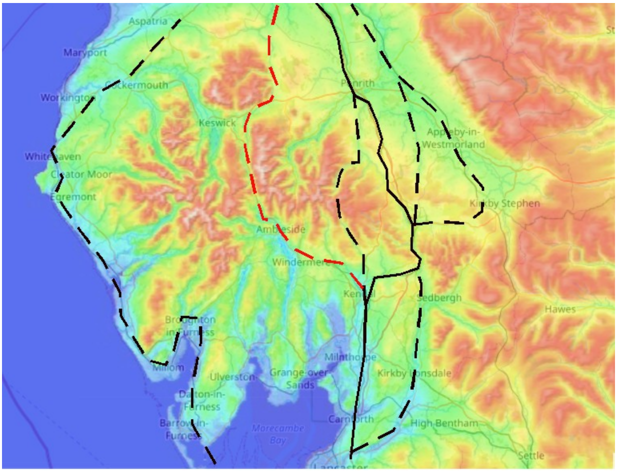
Bennerley viaduct (1877)

Railways to Scotland

In 1829 Joseph Locke was given the job of surveying a route from Birmingham to Glasgow. By 1840 the railway had reached Lancaster but the route north was now blocked by the formidable mountains of the Lake District and the high moors of the Pennines. One school of thought championed by Brunel was that main lines should be as straight and as level as possible so as to permit fast running of trains even if this involved lengthy tunnels and viaducts. Locke was of the 'up and over' school, arguing that shorter steeper routes were more cost effective. Locke therefore favoured a route straight up the Lune valley and over Shap fell. George Stephenson, however, was in favour of a route round the west coast involving a long viaduct across Morecambe Bay. Other routes involving tunnels were also considered. One went north from Kendal up Long Sleddale and under Gatescarth Pass into Mardale (now drowned by the Hwesewater Reservoir). Another took a more eastern route passing under Orton Scar.

One route which was apparently never considered was the route (shown in red on the following map) through Windermere, Ambleside and Grasmere, over Dunmail Raise and down to the Glenderamackin valley. If it had been built this would have been one of the most scenic railways in the world. Perhaps we should be thankful that it never was built but I can't help feeling a frisson of disappointment. Of course, Wordsworth would have fought the proposal tooth and nail but the railway that Wordsworth objected to was only a branch line which, largely owing to his objections, only ever got as far as Windermere. If Locke had favoured this route and persuaded the shareholders to back him, I doubt if Wordsworth's voice would have been heard.

In the event the route chosen was a bit of a compromise. In order to satisfy the burghers of Kendal, the railway climbed up the side of the Helm to a station at Oxenholme before crossing over to the Lune gorge at Greyrigg. Locke was dead against a tunnel of any sort but this meant a gruelling climb from Tebay to the summit of Shap – 4 miles at a gradient of 1 in 75. Throughout the days of steam, this involved using banking engines stationed at Tebay to help the expresses over the hump.



Routes to Scotland

The route from Carlisle to Glasgow was not without its problems either. Here again, Locke chose the direct 'up and over' route from Moffat over Beatock summit – a climb which was no less steep but over twice as long. Again, I am baffled as to why he chose this route. A much gentler alternative passes through Annan, Dumfries and Sanquhar to Kilmarnock. This route is longer but it passes through a much more populated area and with the summit at an elevation of less than 200 m, the gradients would have been very modest. Perhaps the directors of the Caledonian Railway wanted to ensure that they had a short route to Edinburgh as well as Glasgow, an objective easily realised by splitting the line in two at Carstairs.

The Caledonian line was finished in 1848. The east coast route via Berwick upon Tweed to Edinburgh was finished at about the same time. The 'Waverley' route from Carlisle to Edinburgh through Hawick and Melrose was not completed until 1862.

The Midland Railway

The Midland Railway was established in 1844 by the merger of a number of smaller railways centred on Derby. Immediately it began an ambitious program of expansion running trains on rented lines through to London, Birmingham, Manchester, and York. But relying on other companies to allow them access to these desirable destinations was not a long term solution so wherever possible,the MR simply bought up rivals and when that course was frustrated, the MR simply built their own railways.

The routes to London and the North East were relatively easy but to get to Manchester, the high country of the Peak District had to be crossed. By 1863 the MR had reached Bakewell and Buxton but by that time, a railway line had already been built from Buxton to Manchester by another company. Running trains over someone else's lines was not acceptable so the MR drove a railway up Great Rocks Dale to Chapel-en-le-Frith and thence into Manchester. This gave the MR a complete main line route from London to Manchester. The most substantial structure along this route was the viaduct at Chapel Milton. Its fifteen graceful arches span the Black Brook valley at a height of 31 m.

Chapel Milton viaduct (1867)

At about this time, the MR was looking to improve its connections to Scotland. In an effort to force the London and North Western Railway to give it unfettered access to the North, the MR decided to survey their own route to Carlisle via Settle and even got a bill through parliament to give them authorisation to build it. But their bluff was called and they were forced to build it anyway which was not what the directors really wanted. Still, it gave us the most spectacular mountain railway in the British Isles. Unlike the Scottish railways which were always built in wide glaciated valleys, the Settle-Carlisle railway climbed to a height of

1000 feet and then contoured for 15 miles through wild untamed moorland, flying over dales and burrowing through fells along a succession of viaducts and tunnels – Ribblehead viaduct, Blea Moor tunnel, Ais Gill viaduct, Dent head viaduct, Rise Hill tunnel, Dandry Moor viaduct and many more.

Tunnels under the Pennines

The first trans-Pennine railway route was opened by the Manchester and Leeds Railway Co. in 1841. For most of the route it ran beside the Rochdale canal through Hebden Bridge, Todmorden and Littleborough, but at the summit of the line the chief engineer Thomas Gooch (brother of the more famous designer of locomotives, Daniel Gooch) decided to build a little-known tunnel over 1½ miles long. Why he chose to do this is a mystery to me. The watershed at this point lies at a height of 190 m and one would have thought that, if a canal could surmount this obstacle without a tunnel, so could a railway. Instead, Gooch chose to build the longest railway tunnel in the world at the time, all 2885 yards of it containing a double track line to boot. Not only that, he built it so well, it remains in use today.

I suppose that, being the first railway in the world to cross a proper mountain range, it was only right that the tunnel at the top should be simply be called 'Summit Tunnel' but with a name like that, and with longer and more spectacular tunnels under the Pennines following hard on its heels, it is not surprising that Gooch's achievements have largely been forgotten. It only held the accolade of 'the longest tunnel in the world' for three months as it was soon overtaken by Brunel's tunnel at Box Hill.

In 1845 Joseph Locke engineered the first proper tunnel under the Pennines between Penistone North of Sheffield to Glossop at a place called Woodhead. At 3 miles in length it was by far the longest railway tunnel in the world at the time. It only had a single track and a second single track bore was completed beside the first in 1852. The narrow tunnels were not popular with engine drivers but remained in use until the completion of a third double track tunnel suitable for electrification in 1953. (Even this tunnel is now closed.)

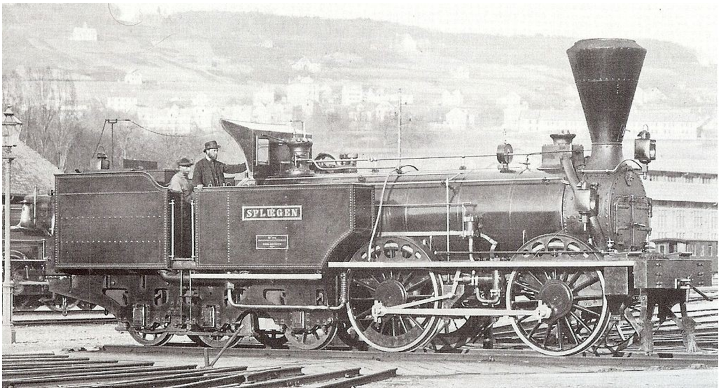
Woodhead tunnels 1 & 2 (1845 & 1852)

Once again, the prize for the longest tunnel in the world was soon to change hands again because in 1848 the London and North Western Railway completed a line between between Huddersfield and Manchester. It ran parallel to the Standedge canal tunnel to which it was connected by a series of passages. The use of the canal to remove spoil greatly speeded up the construction of the tunnel. By the end of the century a second single track tunnel had been bored and then a double track tunnel – the one that is in use today.

The line which is now used as the main link between Sheffield and Manchester is the Hope valley line built by the Midland Railway and completed in 1894. Two major tunnels were required: the 2 mile long Cowburn tunnel and the Totley tunnel 3½ miles long, now the longest railway tunnel in the UK not counting the tunnels of the London Underground or the Severn and Channel tunnels.

Tunnels under the Alps

The first tunnel to be built in the Alps was the mile long tunnel at the summit of the Semmering Pass in Austria. The line, which opened in 1854, also featured thirteen more tunnels and almost as many viaducts, climbing 400 m to the summit at an elevation of 900 m with some gradients in excess of 2.5%. A special fleet of locomotives had to be designed to cope with the steep gradients and sharp curves.



Engerth Locomotive as used on the Semmering Railway

The line was superbly built and has been in continuous use ever since.

It was not until 1871 that a railway tunnel was built which actually crossed the alpine watershed. This was the Fréjus tunnel under Mont Cenis between France and Italy. At over 8 miles in length it was more than twice as long as anything built so far.

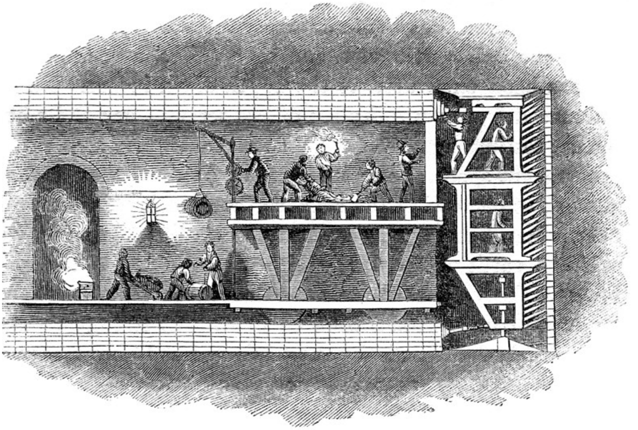
Tunnels under the Thames

In the early 19th century there was an urgent need to convey goods from the wharves in Rotherhithe on the south side of the Thames to the road network leading to the rest of England on the north bank. A bridge would have prevented sailing ships from reaching the Pool of London just below London Bridge and so the idea of a tunnel under the Thames was considered and several attempts were made to construct one but it was not until Marc Brunel (Isambard's father) devised a tunnelling shield that the idea became at all feasible. Even so work, which started in 1825, was beset with both technical and financial challenges and the tunnel was only completed by father and son in 1843.

Unfortunately, the graded approach roads which would have allowed horses and carts to pass through the tunnel were never built so the tunnel never served its purpose, remaining little more that a tourist attraction, catering for pedestrians only.

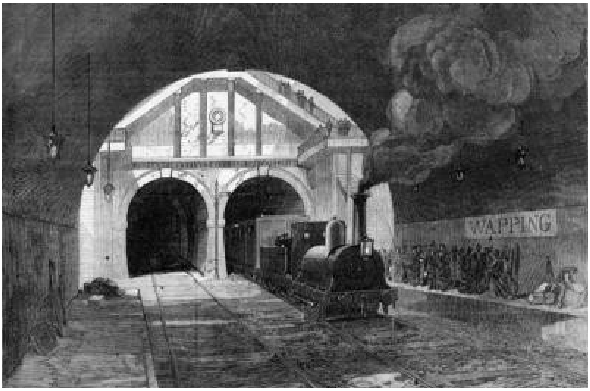
The Thames tunnel in 1850

On the other hand, the techniques which the Brunels pioneered, in particular the use of a tunnelling 'shield', were invaluable in the construction of the further tunnels which followed.



Brunel's tunnelling shield

In 1869, the tunnel was purchased by the East London Railway Co and became part of London's underground railway system. Since 2007 it has been part of the East London extension of the overground network.



The Thames tunnel in 1870

In that same year (1869) a second tunnel under the Thames was opened next to the Tower of London – the Tower Subway.

Passengers travelling on the Tower Subway

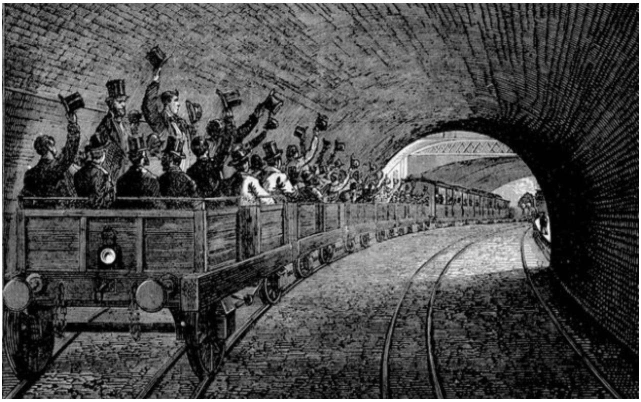
This tunnel was built using an entirely different kind of 'shield' developed by the South African engineer James Henry Greathead. This was circular, not rectangular; made of cast iron, not wood and propelled forward by hydraulic jacks, not muscle power. As the shield advanced, cast iron sections lined the tunnel behind the shield and compressed air was used to prevent the ingress of water. In effect, his shield was the first TBM (Tunnel Boring Machine). It was ideally suited to boring through the relatively soft chalks and clays on which London is built.

Initially passengers were hauled through the 7 foot diameter tunnel in a carriage running on rails. Later, this was removed and the tunnel was converted to pedestrian use. It closed in 1898 and is now used as a service tunnel for water pipes.

It wasn't until 1897 with the completion of the Blackwall tunnel between Blackwall and the Greenwich peninsular that London got its first vehicular crossing of the Thames below Tower Bridge (itself only completed in 1894).

The London Underground

The world's first underground urban railway was opened on January 10th 1863. It ran 3¾ miles from Paddington to Farringdon Street. It must have been a pretty hellish ride. Interestingly, the illustration below shows that initially it was laid with dual gauge tracks.



The inaugural train on the Underground Railway

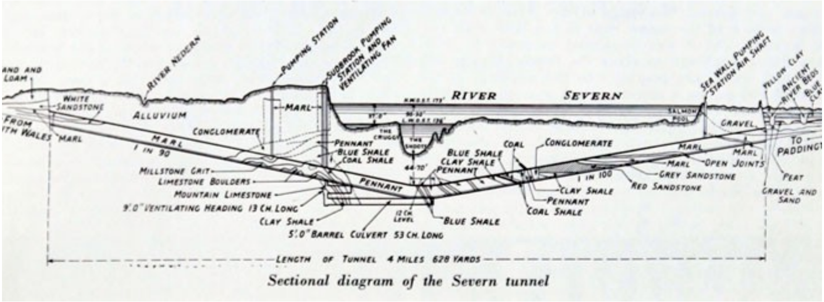
It was built largely using the 'cut and cover' method. This caused immense disruption in the city and it was soon realised that new lines would have to be constructed at a much deeper level. This became a practical possibility by virtue of two technological advances: the first was Greathead's tunnelling shield and the second was the development of electric trains. The first 'tube' line was started in 1886 by Greathead and ran from King William street (on the north side of the Thames) to Stockwell on the south using a tunnelling shield 10 feet in diameter.

This was followed by the Waterloo and City railway in 1898 and the Central London Railway in 1900.

The Severn Tunnel

The first railway tunnel to be built under the sea was the Severn tunnel. It was built by Sir John Hawkshaw, the chief engineer of the Great Western Railway. It enabled the GWR was able to run through trains from London and Bristol to Swansea and Cardiff.

As far as I can tell, it was built using conventional tunnelling techniques – that is to say, without using a shield. It took over 10 years to build and at one point the tunnel flooded (with fresh water from a spring, not the Severn) and enormous pumps had to be brought in to pump the water out. The tunnel was, however, completed and opened on September 5th 1885. At 4⅓ miles in length, it was the longest under water tunnel in the world, a record which it held for over 100 years. A staggering 76 million bricks were used in its construction.



The Severn Tunnel

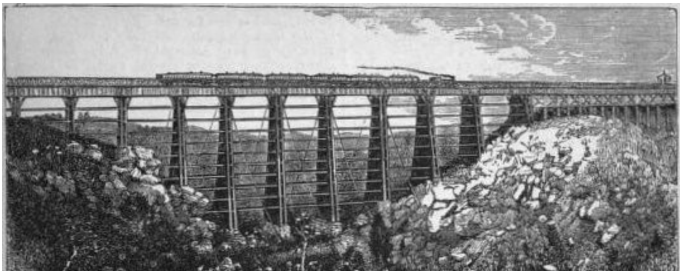
Just 4 months later, a second under water rail tunnel was opened – the relatively short Mersey tunnel.

The ceremony at Promontory Summit

The famous photograph of the Central Pacific locomotive *Jupiter* (on the left) face to face with the Union Pacific locomotive No 119 was taken on the 10th May at Promontory Summit in Utah at the northern end of the Great Salt Lake and marked the moment when the American continent was first crossed from East to West by rail. (Promontory Summit is no longer on the line having been bypassed in 1904 by the completion of a 12 mile long trestle bridge and subsequent causeway over the Great Salt Lake.)

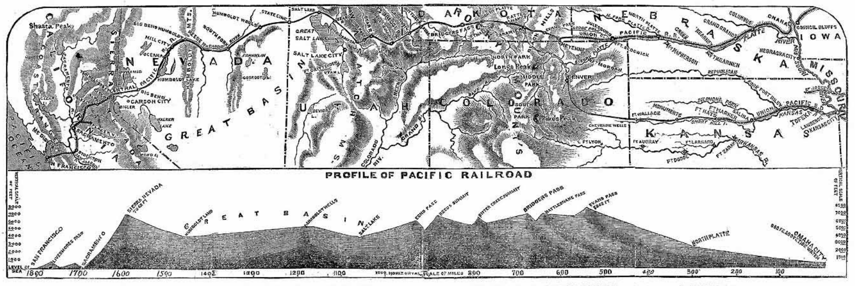
In spite of its name, however, Promontory Summit is by no means the highest point of the transcontinental line. That distinction goes to Sherman Summit which is 20 miles south east of Laramie in Wyoming and stands at an elevation of 8000 feet.. A few miles to the west, the line crossed Dale Creek on an enormous, 200 m long trestle bridge 46 m above the valley floor. The structure was barely strong enough to carry the weight of the heavy trains and it was replaced with a spindly iron bridge a few years later. In 1901 both Sherman Summit and Dale Creek Crossing were bypassed by a loop in the line to the south.

The original summit of the line is marked by a large pyramid called the Ames monument which now stands in the middle of nowhere.



Dale Creek Crossing (1868)

The other major summit on the line is the Donner Pass just north of Lake Tahoe in California at the summit of the Sierra Nevada. Here, at a height of over 7000 feet, mainly Chinese labourers had to construct 11 tunnels through solid granite in appalling conditions. (The single track line which they built was in continuous use for 125 years until a 2 mile long double track tunnel was built under the mountain as late as 1993.)



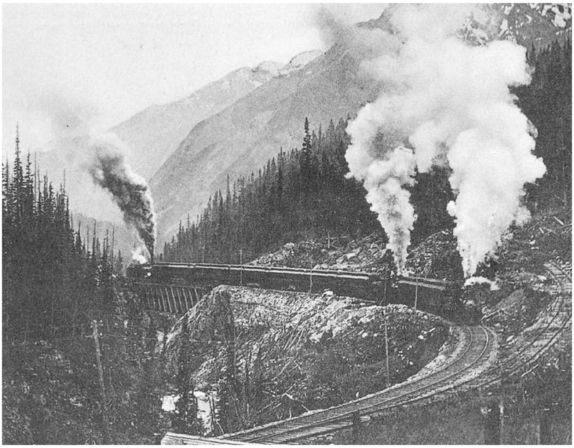
CENTRAL PACIFIC RAILROAD—MAP AND PROFILE MAP OF THE LINE FROM OMAHA TO SAN FRANCISCO.—[DRAWN BY C. H. WELLS.]

Profile of the Central Pacific Railway through the Rockies

Engineers and workmen faced with the granite summits of the Sierra Nevada and the deserts of Nevada may have thought that they faced an impossible task but their troubles were as nothing compared to the challenges which faced the builders of the Canadian Pacific Railway in the 1880's. Four stretches of the line looked, on the face of it, impossible to build. The first was the 500 mile stretch between Lake Nipissing and Fort William on the northern shore of Lake Superior across the totally barren and inhospitable wastes of the Canadian Shield. In between the great quartzite ridges which crossed the route and which had to be blasted away with dynamite there were bottomless bogs which could swallow any amount of ballast and even the odd train without trace.

The second was the building of a route through the steep sided Fraser Canyon. No-one knows how many Chinese labourers lost their lives falling from the cliffs or being blasted to bits by a premature explosion.

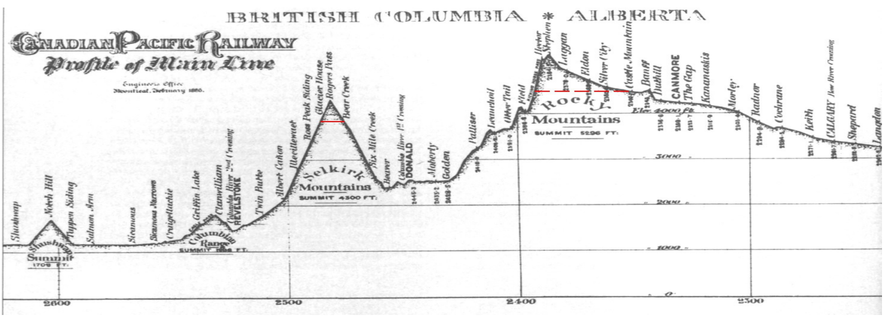
Lastly, there were not one but two mountain ranges that had to be crossed in the Rockies. The route chosen seems bizarre. There is a perfectly good pass through the Canadian Rockies just west of Edmonton and Jasper called the Yellowhead Pass (later used by the Grand Trunk Pacific Railway). The approach gradients are not severe and at maximum height of under 4000 feet, the route is entirely feasible. But for a variety of reasons, some political but mainly financial, a more southerly route over the plains was decided upon which meant looking for a more southerly pass over the mountains. The one eventually decided upon was Kicking Horse Pass just west of Calgary. This pass is 1650 feet higher than the Yellowhead and the descent down into the valley of the Columbia river on the west side was so steep (with grades of up to 4%) that trains virtually slid down the mountain. (Later, in 1909, the famous 'spiral tunnels' were built to ease the grade.)



Eastbound train climbing the 'Big Hill'

(In the foreground of the above picture can be seen one of the many 'run off' rails designed to stop a runaway train. These were frequently required in the days before trains were fitted with continuous vacuum brakes.)

Having descended nearly 3000 feet to the river , the railway next had to climb 1800 feet back up again to the summit of the Rogers Pass. The following profile illustrates just how ridiculous this route is.



Profile of the Canadian Pacific Railway through the Rockies

(A route avoiding the mountains altogether by following the Columbia River round the 'Big Bend' was considered but the extra mileage made the route no cheaper and, it was thought, more expensive to run.)

One of the unforeseen benefits of the chosen route was the tourist trade which was generated by the spectacular scenery through which the line passed. While not as high as the Kicking Horse Pass, the Rogers Pass was particularly impressive with huge glaciers on the upper slopes of the mountains which towered over the visitor. On the other hand, these very slopes were a constant source of avalanches which seriously hampered both the construction and operation of the railway line. Eventually (in 1916) the line over the pass was abandoned when the 5 mile long Connaught tunnel was built (indicated on the profile by a red line) and much of the tourist attraction of the Rogers Pass was lost. The attractions of Yoho and Lake Louise remained, however. (Although there are currently no actual plans to build one, an obvious development would be a 20 mile base tunnel under the Kicking Horse Pass shown as a dotted red line on the profile.)

The 'Last Spike' was driven home at a place called Craigellachie 20 miles west of Revelstoke on 7th November 1885.

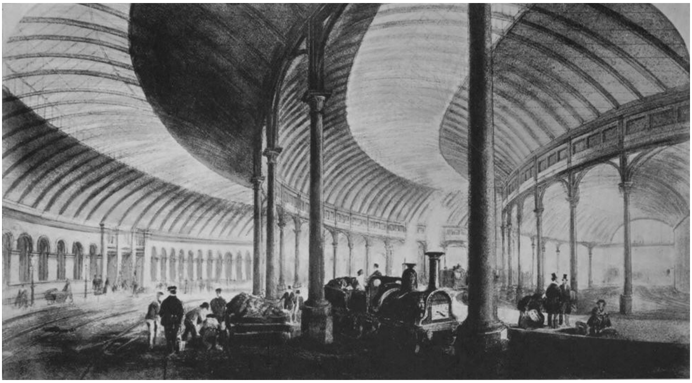
Station shed canopies

From the very start of the development of the railways it was realised that the stations – and particularly the major termini – had to impress. On the one hand that meant building grand hotels and adding distinctive decorative touches to all railway buildings but from an engineering stand point, the challenge was to build a roof big enough to cover several trains.

Euston station was one of the first to have such a roof but its dimensions were relatively modest. It did, however, have nice cast iron arches supported by classical columns.

Euston station in 1837

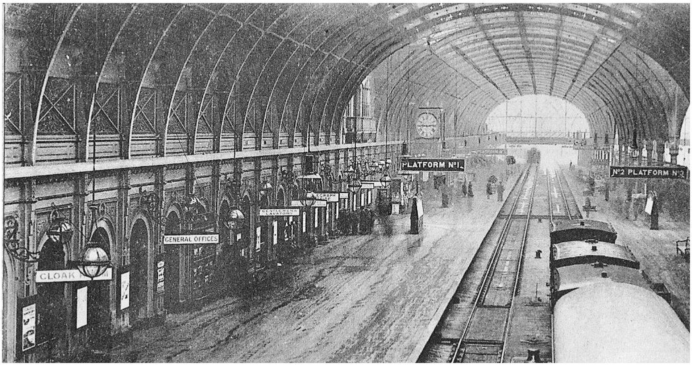
The 1850's saw station building on a grand scale. Newcastle Central station was the first to be completed and was opened by the queen on 29th August 1850. It had three curved canopies, each 18 m wide and averaging 160 m in length. Like the station at Euston, the roofs were supported by nicely decorated columns a cast iron arches but the roof itself floated above the platforms without any internal bracing.



Newcastle Central station (1850)

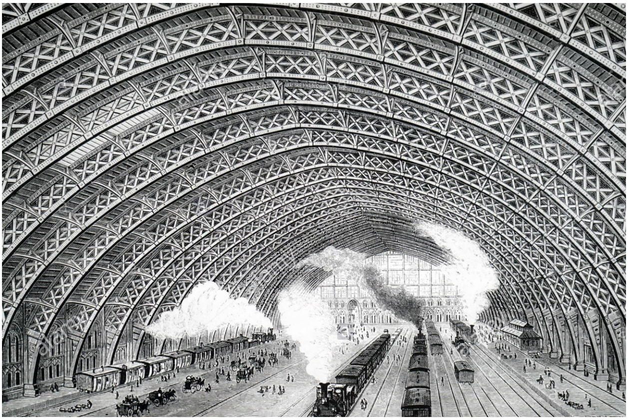
In 1852 the Great Northern Railway opened their terminus at Kings Cross. Its two distinctive brick arches fronted two massive but uninspired sheds each 30 m wide and 240 m long – a total area of 14,400 square metres.

When Brunel got the chance to build a new terminus at Paddington, he decided to build the largest roof the world had ever seen. It had three wrought iron spans of width 21 m, 31 m and 21 m and a length of 200 m. It was completed in 1854. With its cathedral-like nave, double transepts and painted arches it was said to have been inspired by Paxton's Crystal Palace.



Paddington station in 1888

In 1868 it the the turn of the Midland Railway to open a structure the like of which had never been seen before. This was an enormous single span arched roof 70 m wide and 210 m long.



St Pancras station (1868)

After a period of decline in the 1980's the station was completely restored and refurbished in 2007 and is now the the terminus of the Eurostar High Speed Train. Together with the magnificent hotel next door, the train shed at St Pancras must be one of the most outstanding monuments to Victorian engineering in the UK.

The Parisian terminus of the Eurostar train is the Gard du Nord – completed at around the same time as St Pancras. This huge tent-like structure was even wider that the arch at St Pancras but it was partially supported inside by two rows of slender iron columns (incidentally cast in Glasgow).

Gard du Nord (1867)

Iron Bridges

Men have been building bridges since pre-historical times. The simplest bridge is a log or stone slab placed across a stream but ancient peoples of mountainous regions such as the Himalayas have long used rope bridges to cross prodigious ravines[9].

By the time of the Romans, bridge building in wood, brick and stone was a highly developed art and many Roman bridges survive to this day, as do many bridge built by the Chinese[10]. By mediaeval times, the technique of building an impossibly slender arch in stone had been perfected in Europe and there was little need to develop the art of bridge building any further until new materials (notably iron) became available and new modes of transport (notably the railways) arose.

And so it came about that by far the most innovative bridge to be built for a thousand years was designed by Thomas Pritchard and built at Coalbrookdale in Shropshire by Abraham Darby III (the grandson of the famous ironmaster).

Iron Bridge, Coalbrookdale (Thomas Pritchard 1780) – 31m

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[9] One of these, the Chushul Chakzam near Lhasa, was built in 1403 and was actually made of iron link chains.

[10] For example the amazing masonry arch Anji Bridge in the province of Hebei which was completed in 605.

It was constructed of cast iron – a material which is notoriously brittle in tension. The design of the bridge ensures that, like a stone or timber bridge, all the structural members are in compression. The decision to build in iron rather than timber or masonry was not made on economic, practical or aesthetic grounds; it was built in iron so that Darby could advertise his product. In effect the bridge (which proudly bears the inscription 'THIS BRIDGE WAS CAST AT COALBROOKDALE AND ERECTED IN THE YEAR MDCCLXXIX'.) is saying to the world – Look what I can do; you want a bridge – I can build it!

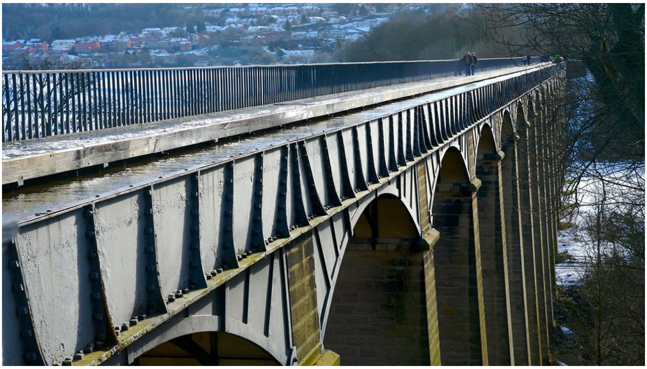
The success of the bridge at Coalbrookdale prompted the building of a number of other cast iron bridges. The next being at Wearmouth in Sunderland. As may be seen from the following illustration, its design owes much to its predecessor but it is a radical improvement being both twice as wide and only three quarters of the weight.

The bridge at Wearmouth (Thomas Wilson 1796) – 51m

Another cast iron bridge was built not far from Ironbridge in the same year (1796) at Buildwas by Thomas Telford. The two original cast iron arches can be clearly seen but I suspect that the panels are later additions. (This bridge suffered several cracks due to movements of the abutments and was replaced completely in 1905.)

Buildwas bridge (Telford 1796) - 40m

Cast iron was also the material which Thomas Telford chose to use in the construction of the 300m long Pontcysyllte aqueduct over the river Dee near Llangollen. Essentially it consists of a water trough constructed of cast iron plates bolted together supported by massive cast iron arches resting on masonry piers. The ironwork was supplied by William Hazledean and took 10 years to complete.



Pontcysyllte aqueduct (Thomas Telford 1796) - 18×17m

In 1799 a competition was opened to design a replacement for London Bridge. Fired with enthusiasm for this new material, Telford designed a truly staggering cast iron bridge with a colossal span of 180 m. Although the design was accepted as practical, it was probably a step too far and the council opted for a more traditional design with five stone arches.

Telford's design for London Bridge (1799) - 180m

In 1800 Thomas Wilson was asked to design a bridge over the river Cobre in Jamaica. Of a similar design to the bridge at Wearmouth, it was cast by Walkers of Rotherham and transported in sections to Jamaica.

Bridge over the Rio Cobre (Wilson 1800) - 28m

Another bridge which owes much to Wilson's designs is at Tickford near Newport Pagnell. It still carries modern traffic. (Wilson also built a smaller bridge which still survives in the park at Stratford Saye near Reading.)

Tickford Bridge (Henry Provis 1810) - 18m

In 1813 Thomas Telford designed a small bridge at Cantlop in Shropshire with an innovative design. Instead of an arch with a separate road deck supported by spandrels, Telford simply used two massive castings for each rib with the deck laid on top.

Cantlop Bridge (Telford 1813) - 10m

A similar design was used to build the famous pedestrian bridge in Dublin known as the Ha'penny Bridge which was cast at Coalbrookdale in 1816 and shipped across to Ireland.

Ha'penny Bridge, Dublin (1816) - 43m

A particularly fine bridge which survives to this day crosses the River Spey at Craigellachie, near to the village of Aberlour in Moray, Scotland. Designed by Thomas Telford it carried modern road traffic until 1972.

Craigellachie Bridge (Telford 1814) - 46m

Telford was at it again the very next year with the Waterloo Bridge over the river Conway in Betws-y-coed. Although it has been greatly strengthened over the years, this bridge still carries the heavy traffic of the A5 to Holyhead.

Waterloo Bridge, Betws-y-coed (Telford 1816) - 32m

One of the loveliest cast iron bridges ever to be built was designed by John Rastrick and constructed in the same year at Chepstow. It has five spans which increase in length towards the middle in pleasing proportion and still carries traffic today.

Chepstow Bridge (Rastrick 1816) – 10-20-34-20-10 m

Just before Prirchard built his iron bridge over the Severn, a bridge with iron ribs and a wooden deck had been constructed over the river at Coalport. It had two spans with a central pier but it was never satisfactory and in 1818 it was decided to rebuild the bridge with a single iron span.

Coalport Bridge (1818) – 32 m

The cast iron bridge with the longest span ever built was the Iron Bridge at Southwark completed in 1821 which had three 73 m spans. It was replaced by the present structure exactly 100 years later.

Southwark Iron Bridge (1821) – 3 × 73 m

In 1824 Charles Hollis designed a bridge to link the town of Windsor and Eton further up Thames. It has three arches of unequal span, the centre on being 17m in length.

Windsor Bridge (Hollis 1824) – 13-17-13 m

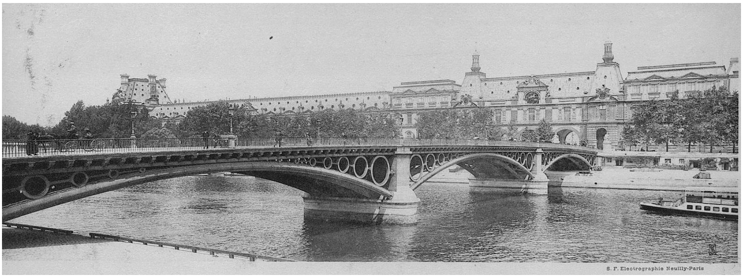
That same year Telford designed a lovely bridge for the 1st Marquis of Westminster to link his mansion with the village of Aldford in Cheshire. Essentially the same design as the Craigellachie bridge, it was decorated with lovely trefoils and quatrefoils in the spandrels.

Aldford Bridge (Telford 1824) - 50m

Many more cast iron bridges were built in Britain and an amazing number of them still survive. The list includes:

Mythe Bridge, Tewksbury (1826)
Bigsweir Bridge over the river Wye (1827)
Fleet Bridge, Holt (1828)
Galton Bridge, Smethwick (1829)
Powick Iron Bridge (1837)
Gauxholme Viaduct, Todmorden (1840)
Frodsham Viaduct (1850)
Old Spey Bridge, Fochabers (1854)
Albert Edward Bridge, Coalbrookdale (1864)

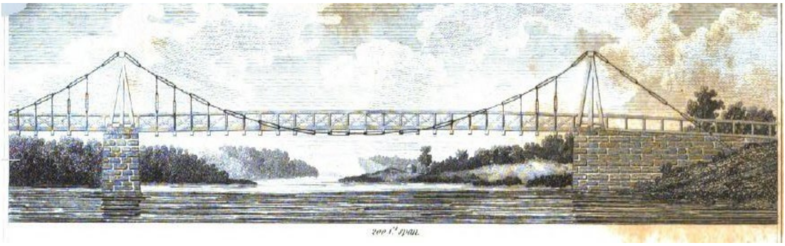
One of the most important cast iron bridges to be built on the continent was the Pont du Carrousel across the Seine in Paris in 1834. Like the Southwark bridge, it had to be replaced 100 years later.



Pont du Carrousel, Paris (1834)

Iron chain Bridges

The first modern suspension bridge with iron chains was built (and patented!) by James Finley in 1801 at Jacob's Creek in Pennsylvania and he built a very similar one 7 years later at Schuylkill Falls. While the bridge at Jacob's Creek had a span of 21 m the second bridge had a span three times longer. Sadly, neither bridge was successful and had to be replaced within a couple of decades. Nevertheless, the concept was sound, only the execution was lacking.



Schuykill Falls Bridge (James Finley 1808) – 61 m

One of the first chain link suspension bridges to be built in the UK was at Llangollen in Wales over the river Dee in 1818. It was originally built to carry coal across the river but now serves as a convenient footbridge. Although it has been rebuilt several times, it is still supported by several of the original wrought iron chain links.

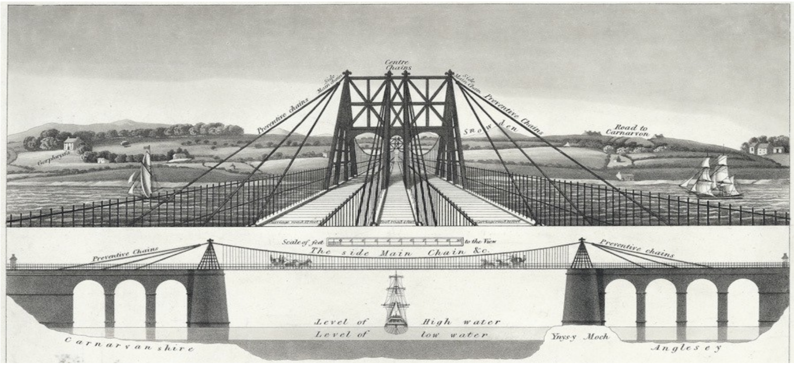
Llangollen footbridge (1818) - 50m

Another similar bridge was built at Dryburgh Abbey in the same year but that one did not survive.

The first really successful road bridge was built in 1820 by one Captain Samuel Brown over the river Tweed near Berwick. It had an incredible span of 137 m (the longest in the World at the time) and it is still carrying light traffic. Brown had previously served in the Royal Navy and had experimented with using wrought iron for the rigging of warships and he subsequently went on to manufacture large quantities of chain for the Royal Navy and for Brunel too.

The Union Bridge over the Tweed (Brown 1820) – 137 m

One of the people most impressed by Brown's bridge was Thomas Telford who was then in the process of building a road from London to Holyhead. Two major obstacles stood in his way – the river Dee at Conway and the Menai Straits between Wales and Anglesey. Telford decided to use wrought iron chain link suspension bridges to overcome these. Construction of the Menai Straits bridge started in 1819 but took 7 years to complete. Astonishingly it was a dual carriageway road (a fact which is made clear by the two post carriages racing towards each other in the following illustration!) with a footway as well. The main span was 175 m wide and the deck was 30 m above the water – high enough for the Navy's tallest ships to pass beneath. The bridge was not without its problems but it served its purpose admirably for over 100 years and although all of its metalwork has now been replaced (the chains in 1938 and the deck several times) it is still carrying road traffic to this day. An incredible achievement.



The original design for the Menai Straits Suspension Bridge (Telford 1819-26)

It is curious to note that in Telford's original design (above), the cables which support the main span split into three and are attached to the stone piers which carry the approaches. Telford does not seem to have grasped the full potential of the design in which the approach roads can also be carried by the same cables. In the event, the bridge was built with the cables attached to the abutments and hangers appear to have been added, presumably in the interest of symmetry and aesthetics.

The Menai Straits Suspension Bridge (Telford 1826) – 175 m

The bridge over the river Dee at Conway was an altogether smaller affair with a span of only 100 m but with its impressive castellated towers, it is one of Telford's finest creations and was in regular use .until 1958. It is now in the care of the National Trust.

The Conway Suspension Bridge (Telford 1822) – 100 m

During the decade of the 1820's several more wrought iron chain-link suspension bridges were built. The Hammersmith Bridge over the river Thames was designed and built by William Tierny Clark in 1824.

The original Hammersmith Bridge (Clark 1824) – 122 m

In 1880 the bridge was deemed too small to carry the required volume of traffic and was rebuilt by Joseph Bazalgette but one of Clark's original suspension bridges remains at Marlow.

Marlow Bridge (Clark 1829)

Clark then went on to build the huge Chain Bridge in Budapest which is essentially a scaled up version of the Marlow Bridge. With a span of 202 m it was the longest suspension bridge in the world at the time.

The Chain Bridge, Budapest (Clark 1840) – 202 m

But perhaps the most famous suspension designed (but not actually built) at this time was Brunel's suspension bridge over the Avon gorge near Bristol. Various designs had been proposed but Brunel's was one of the most audacious as well as being one of the cheapest. He proposed to leap across the gorge in a single span of length 214 m. Work began in 1830 but riots and financial trouble brought the work to a halt with only the towers built.

The Clifton Suspension Bridge (Brunel 1830-64) – 214 m

In 1860, a year after Brunel's death, work resumed. Brunel had built a suspension footbridge in 1845 over the Thames at Hungerford but in 1860 the South Eastern Railway wanted to use the site for a railway bridge so the suspension bridge was demolished and the chains were purchased for use at Clifton. The bridge was completed in 1864 albeit with a beefed up specification.

Many more iron link suspension bridges were built in the next couple of decades, particularly in France, and a surprising number still survive carrying vehicular traffic to this day. The list includes

L'île Barbe, over the Saône near Lyon (1827)
Fourques and Arles (1830)
Beauregard, Ain (1831)
Masaryk, over the Saône near Lyon (1831)
Chasse-sur-Rhône (1835)
Horkstowe UK (1836)
Kalemouth UK (1836)
Vianne (1838)
Ingrandes (1843)
Sira, Norway (1844)
Lafox and Sauveterre-Saint-Denis (1845)
Donzère (1847)
Tours (1847)
Podoli, Czech Republic (1848)
Bridge of Oich, Invergarry (1849)

One of the most remarkable of these survivors is the Albert Bridge which links Battersea and Chelsea. It was designed by Robert Mason Ordish in 1860 using a novel design. In a conventional suspension bridge the deck is simply suspended from the catenary using vertical hangers. Ordish's idea was to use a catenary to support the centre of the bridge but to support the deck on either side using diagonal stays as shown in the following photograph. (The original design had no central pier. This was added in 1970).

Albert Bridge (Ordish 1873) – 117 m

Unfortunately the bridge was a financial disaster, and it was not really an engineering success either. It came close to being demolished several times but somehow it survived and carries light traffic to this day. It is important, however, because the cable-stayed bridge has become very popular these days and for a very good reason. The cable of a suspension bridge obviously has to be immensely strong – but also it has to be fastened to something; an anchorage, in fact, which also has to be immensely strong. But in a cable-stayed bridge, the forces in the stays on each side of the tower balance each other and the whole weight of the bridge simply rests on the two piers.

The downside of the design is that the deck has to be capable of withstanding the huge forces of compression which the stays exert on it. This obviously adds to the weight of the deck and effectively ruled out the cable-stayed design for large spans for the next hundred years.

Ordish built a very similar bridge in Prague at the same time but this bridge was demolished in 1941.

Franz Joseph Bridge, Prague (Ordish 1865)

All the suspension bridges described so far used wrought iron chains but on the continent many bridges were being built with iron wire cables, a technique pioneered by the Séguin brothers and used on their bridge across the Rhône at Tournon.

Rhône Bridge at Tournon (Séguin 1825)

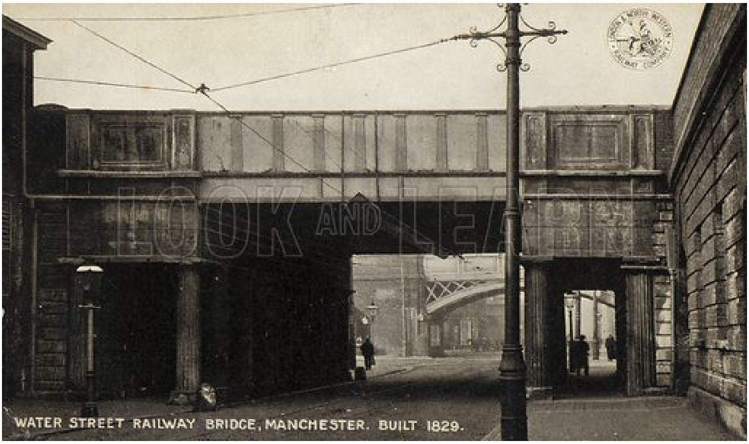
This bridge is unusual in that its central pier is taller than the piers on the shore.

One of the most remarkable of these cable bridges is the Pont-de-la-Caille in the French Alps. With a span of 190 m it carried a single carriageway 147 m above the river bed and remained the highest bridge in the world until the Royal Gorge bridge was built across the Arkansas river in 1929.

Pont de la Caille (1839) – 190 m

Railway Bridges

As is well known, the Liverpool to Manchester railway opened on 15th September 1830. There were no less than 64 bridges along its length but only one was built using iron. It used a number of simple cast iron beams and was relatively short. It was replaced with a steel bridge in 1905. The photo below shows the original span with its Doric columns.

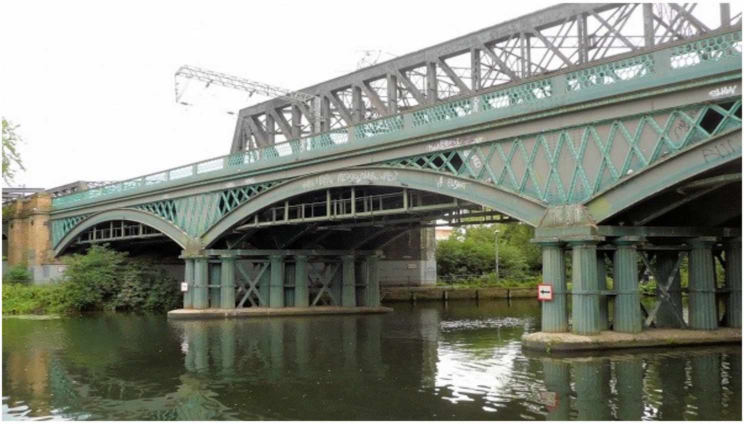


Water Street Bridge, Manchester (Stephenson 1830)

Many other cast iron railway bridges were built but few have survived because cast iron is quite brittle and does not take kindly to the pounding of a railway locomotive.

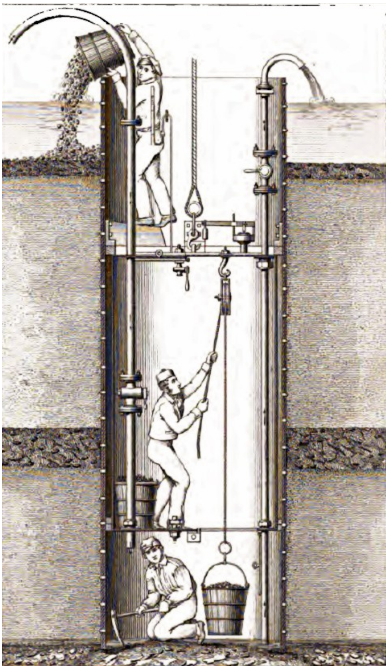
One remarkable survivor, however, built by Joseph Cubitt in 1859, carries the East Coast Main Line over the river Nene near Peterborough. It consists of three 20 m cast iron spans with wrought iron lattice work supporting the deck. The bridge is also remarkable because it was one of the first bridges in the world where a pneumatic caisson was used in the construction of the bases on which the lovely Doric cast iron piers stand.

Before 1800 the only method of building a pier in a body of water known was to drive timber piles into the river bed and to fill the space between the piles with rocks and stones or concrete.



Nene Viaduct, Peterborough (Cubitt 1850) – 3×20 m

By 1840 it was standard practice to construct a watertight coffer dam and pump the water out so that workers could excavate the river bed and hopefully reach bedrock.



Triger's caisson (1846)

But what if the river bed is too deep for a coffer dam? What then? The answer was first devised by Jaques Triger, not for building bridges but for mining coal under water.

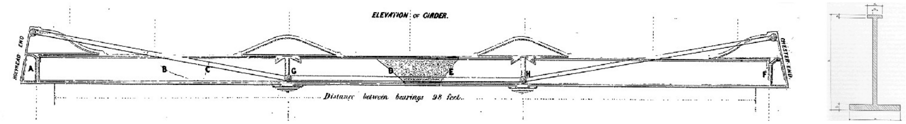
His idea was to build a vertical iron cylinder, divided into three compartments, the central one forming an air lock. It would then be lowered into the river and pressurised so as to to expel all the water. When it rested on the river bed, miners could enter and start digging.

Sand and gravel in the form of a slurry was pumped to the surface; rocks and stones would be taken through the airlock.

When used as an arch, as in the Nene bridge, cast iron is a perfectly satisfactory material with which to build a bridge because the whole arch is under compression. In general, though, cast iron is not an ideal material from which to build a railway bridge because a railway bridge should be flat – but a flat girder such as that used in the Water Street bridge is under compression at the top but tension at the bottom and cast iron cannot stand much in the way of tension. In fact it is quite brittle. A cast iron bath can be smashed with a hammer and when it fractures, quite large crystals can be seen on the broken surfaces.

Wrought iron, on the other hand, has been worked in such a way as to remove nearly all its impurities and has an almost fibrous structure which makes it both stronger in tension that cast iron and much more likely to deform rather than simply break when put under excessive load which is why it was used exclusively in the manufacture of chains. By the 1840's, however, it became possible to make relatively large struts of wrought iron making entirely new designs of bridge possible.

In 1844 Robert Stephenson was put in charge of building the Chester and Holyhead Railway and for many of the bridges he used a design which also utilised the compressive strength of cast iron with the tensile strength of wrought iron. One of the major challenges on the route was the crossing of the river Dee near Chester. Here he decided to use three spans, each 30 m in length, each span consisting of three 10 m cast iron girders of traditional I-shaped cross section. Recognising the limitations of the material, Stephenson made the lower flange (the one in tension) a lot larger than the upper one and also provided reinforcing rods of wrought iron.

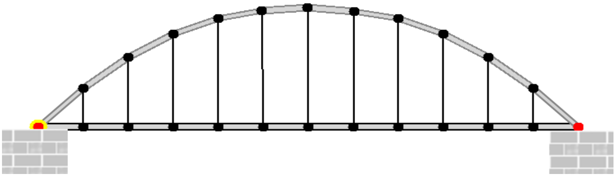


Robert Stephenson's design for the Dee railway bridge (1846)

Now I am not a structural engineer and it is not my place to criticise Stephenson but I can't help feeling that there is a flaw in this design. The rod which runs along the bottom of the central beam is supposed to relieve the tension in the bottom flange of the beam.; but it can only do this if a) the joints at each end are rigidly attached to the beam and b) the rod is attached to the beam when it is under the appropriate tension. (For example this could have been be achieved by heating the rod before attaching it to the beam – a technique widely used later to pre-stress concrete). If, on the other hand, the joints are rather flexible, the structure turns into a kind of suspension bridge in which the three cast beams are merely supported at each end; in which case the rods are not providing any tensional support at all, they are only relieving the bending moments which are placed on the butt joints between the beams.

In the event, the bridge collapsed on 24th May 1847 just 8 months after it was completed with the loss of 5 lives. This disaster in effect spelled the end for cast iron in the construction of railway bridges. Within a short time, all the bridges built to this design were replaced.

For the Manchester and Leeds Railway, where it crosses the Rochdale canal in Todmorden, Robert Stephenson's father George had used a much better design which also combined the compressive strength of cast iron with the tensile strength of wrought iron but in a different way – the bow-string arch.



A Bowstring Arch

The two ends of the cast iron arch are tied together by the actual deck of the bridge which is therefore under immense tension. The deck itself is hung from the arch by tie rods, also under tension. The only support which the structure needs are simple masonry pillars at each end.


Gauxholme Viaduct (G. Stephenson 1840)

The essential structure is clearly seen in the above photograph but it should be appreciated that the Gothic arched parapet and the castellated towers are only decorative. Also one must remove, in one's mind's eye the huge steel girders which have since been added underneath to carry the weight of modern trains.

Wisely, Robert chose the same basic design for the High Level Bridge over the Tyne at Newcastle. This was to be a combined road and rail bridge with the railway on the top. The arches are cast iron, as are the risers which support the railway above it. For aesthetic reasons, Stephenson used cast iron hangers as well but in fact these are not load bearing, the real wrought iron hangers being concealed behind.


High Level Bridge, Newcastle (R. Stephenson 1849) – 6×38 m

With a total length including approaches of 408 m this bridge must surely be classed as the World's first mega-bridge – a staggering achievement. It also has the distinction of being the world's first and, for four decades, the world's only double decker, road/rail bridge.

While the bowstring design has the advantage of not pressing the abutments sideways, the traditional cast iron arch could still be adapted for the railway as illustrated by the bridge over the Loire at at Nevers. This had 7 spans each of length 42 m and was completed in 1850. It is in regular use today.

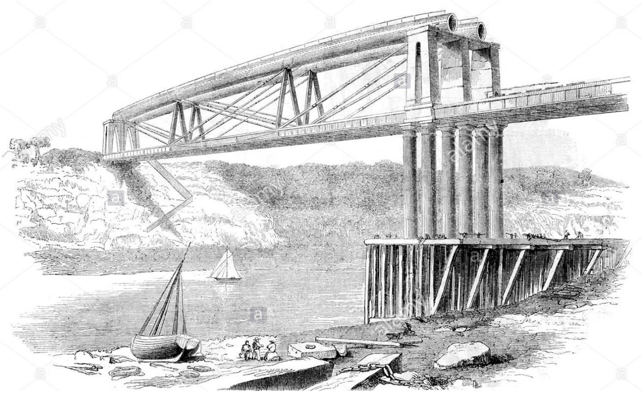
Bridge over the Loire at Nevers (1850) – 7×42 m

Isambard Kingdom Brunel and Robert Stephenson were both rivals and friends. While Stephenson was building bridges in the North of England, Brunel was facing challenges in the West country.

The first problem was crossing the Thames at Windsor. Brunel decided to do away with cast iron altogether and experimented with various designs for a really strong wrought iron girder, suitable for a bowstring arch. The result was the world's first truly modern iron bridge – that is to say, the first bridge which used both modern materials and proper structural analysis to create a design which is both light and immensely strong. Not surprisingly this design has been copied thousands of times since all over the world – from the Hell Gate bridge in New York to the bridge over the harbour at Sydney in Australia.

Windsor Railway Bridge (Brunel 1848) - 62 m

Brunel's next challenge was crossing the river Wye at Chepstow. This was complicated by the fact that the Admiralty insisted on a clear span of 91 m at a height of 10 m above the river level at high tide. We do not know why Brunel decided against a bigger version of his bridge at Windsor – or a box girder bridge such as Stephenson had built at Conway. Instead Brunel decided to build something quite unique. One might describe it as a box girder bridge partially suspended from a shallow bow string arch. You could also describe it as the ugliest bridge every devised!

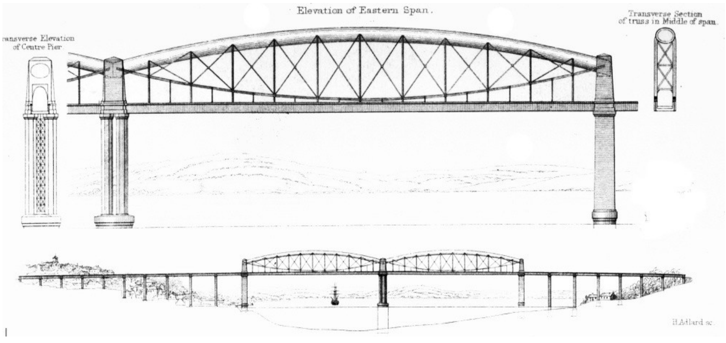


Chepstow Railway Bridge (Brunel 1852) – 91 m

The deck of the bridge is a fairly stiff box girder supported at its ends and at two points in the middle from a shallow arch with a circular cross section made of riveted wrought iron plates. The arch is braced by diagonal tie rods but it is unclear to what extent these rods were really necessary. In the event, the bridge was entirely successful and carried trains until 1962 .(It is doubtful whether the modern inverted truss which has replaced it is any less ugly).

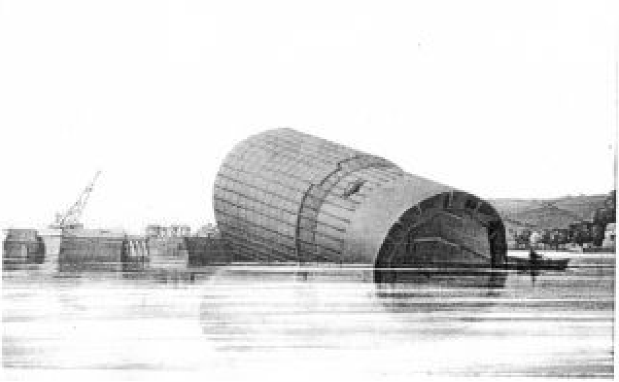
The Great Tubular Bridge at Chepstow was really only a practice run for what proved to be Brunels's masterpiece, the Royal Albert Bridge across the river Tamar at Saltash linking Devon and Cornwall.

Once again, the Admiralty had something to say about the design of the bridge. They rejected several designs with moderate spans and multiple piers and forced Brunel to go for a two span bridge with a single central pier. This required two massive spans 139 m long on each side. For some reason, Brunel seems to have been very distrustful of box girder bridges in spite of the resounding success of Stephenson's bridges over the Conway and the Menai Straits (see below). Instead he opted for a development of his bridge at Chepstow which is a remarkable synthesis of the box girder, the bowstring arch and the suspension bridge. A single massive girder of elliptical cross section curves between the piers; cables mirror this arch and tie the ends together while simultaneously providing support for the box girder deck via vertical hangers.



Royal Albert Bridge (Brunel 1859) – 2×139 m

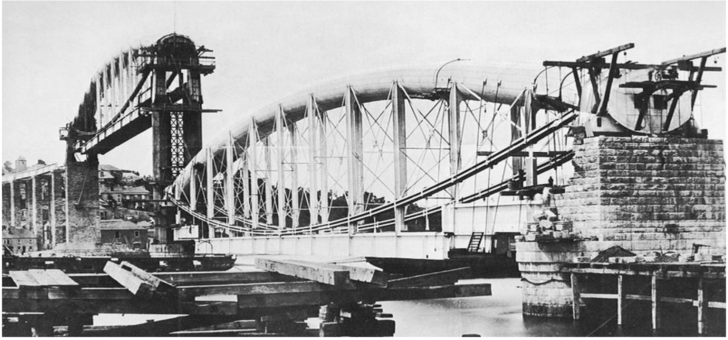
One of Brunel's biggest problems was the building of the central pier. Here the river is over 20 m deep and Brunel decided to use a pressurised caisson 11 m in diameter and 27 m tall. Once it was positioned in the river, the water was pumped out and workers could enter it to build the foundations of the pier.



Brunel's caisson being floated into position

Recreational divers are permitted to dive to a depth of 20 m without any special precautions against the 'bends' but it is probable that some of Brunel's worker may have experienced mild symptoms as they took no precautions to depressurise slowly.

The two great lenticular arches were constructed on the banks of the river. The photograph below shows how they were jacked into position, the masonry piers being built underneath it as the girder rose.



The Royal Albert Bridge under construction

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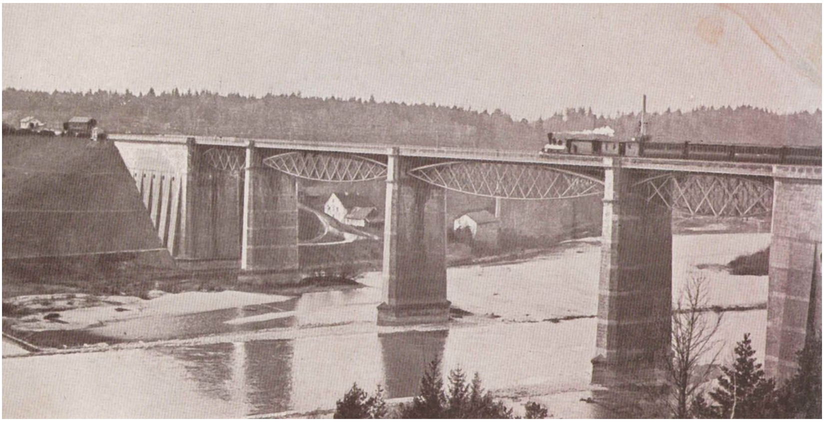
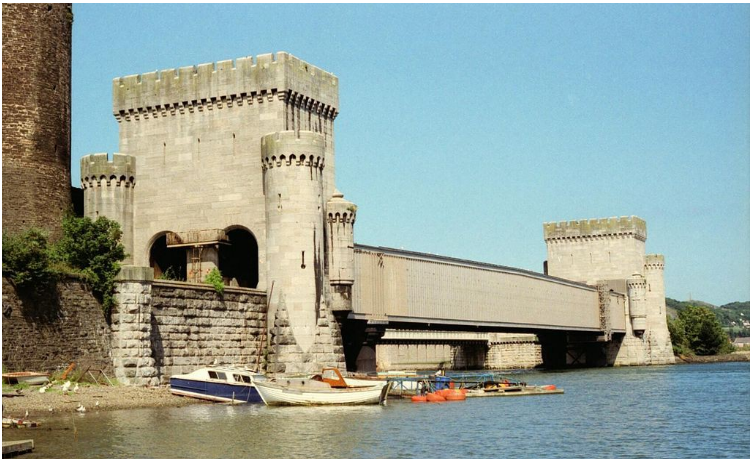
Brunel was not the only engineer to utilise the lenticular design. Friedrich von Pauli built a fine bridge over the Isar river near Munich in 1857 with lenticular trusses.



Grosshesseloher Bridge (Pauli 1857)

Meanwhile, two similar challenges faced Stephenson on the route from Chester to Holyhead. - the same obstacles that faced Telford two and a half decades earlier in fact – firstly the crossing of the river Conway and even more daunting, the crossing of the Menai Straits. After extensive experimenting Stephenson dreamed up a radically new concept – he would span the 140 m gap across the Conway with a pair of box-shaped girders made of wrought iron plates so huge he could run the trains inside it!



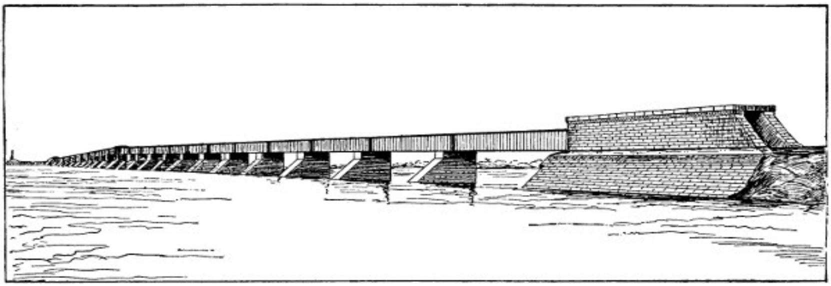
The Conway box bridge (Stephenson 1849) - 141m

And for the Menai Straits, he would use four such pairs of girders, the central pairs being 140 m long flanked by two shorter spans of 90 m. The bridge over the Conway was completed in 1849 and the Britannia Bridge over the Straits a year later.

The Britannia Bridge (Stephenson 1850) – 2×90+2×140m

Unfortunately, the Britannia Bridge caught fire in 1972 and had to be demolished. It was replaced with a combined rail and road bridge which still uses Telford's original towers. The bridge over the Conway, however, has proved more than adequate for the job and still carries the main railway line to Holyhead to this day.

Stephenson used the box girder concept again to build the first bridge over the St Lawrence River at Montreal. This staggering bridge, which was completed in the same year as Brunel's Royal Albert Bridge, was 3 km in length and had no fewer than 25 box girder sections, the longest of which was 105 m in span. Largely to accommodate trains with a larger loading gauge the tubular spans were replaced with steel trusses in 1897 but the original piers remain.



Victoria Bridge, Montreal (Stephenson 1859) – 24 × 80 +105 m

Even with all these advances in the use of wrought iron, the cast iron arch was not quite dead. In 1864 John Fowler built two graceful bridges in Shropshire, both of which are still in active use today.

Victoria Bridge (Fowler 1864) – 61 m

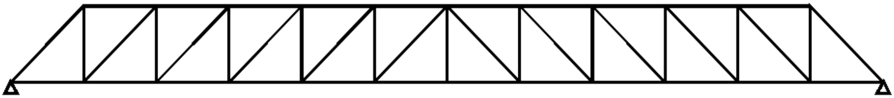
Albert Edward Bridge (Fowler 1864) – 61 m

Truss and trestle bridges

Whereas in Britain, railway companies could generally afford to build large bridges and viaducts in brick or stone, railways in the United States were built on the cheap and usually relied on readily available timber with which to construct huge trestle bridges. Often these structures would completely fill the valley over which the railway was to pass but in the 1840's a number of designs appeared which held out the promise of a different sort of bridge using what is called a truss.

A truss is a latticework of relatively thin members which, unlike a beam, are never subjected to bending – only either tension or compression. Moreover the joints between the members can be regarded as being merely pinned, not rigid. The structure gains its rigidity from the fact that it contains nothing but triangles. A truss has a further advantage over an arch or a suspension bridge – it requires no anchors or abutments; the truss simply sits on its supports (called trestles) which can themselves be built out of a triangular lattice of ironwork.. This makes it very cheap to build.

In 1840 a certain William Howe of Massachusetts patented the following design:



Howe's patent truss (1840)

Many other designs soon followed – probably motivated more by the need to circumvent Howe's patent than owing to any particular merits of the new design.

Initially these trusses were built in wood (which is equally good in tension and compression) but soon, trusses were being built using wrought iron. Few if any of these early iron bridges survive, not because of any weakness in the concept but simply because, when the time came to beef them up it was cheaper to replace the whole structure. An example of an early truss bridge which has survived is the Bollman Truss Railroad Bridge in Maryland. It was built in 1869. It has clearly been strengthened at some stage with extra cable stays.


Bollman Truss Railroad Bridge (Unknown 1869)

Another way to make a rigid truss is to use a diagonal lattice work of wrought iron strips. This concept was demonstrated in a spectacular way at the village of Crumlin in South Wales where a huge bridge over the Ebbw valley was needed to enable coal to be extracted from the nearby Rhondda valley coalfields. A masonry structure was impractical so Thomas W. Kennard designed a bridge with 10 46 m trusses carried on 8 iron trestles the tallest of which was 61m above the valley floor. It was throughout its 105 year life the highest viaduct in the UK and the third highest in the world


The Crumlin Viaduct (Kennard 1855) – 3+7×46 m

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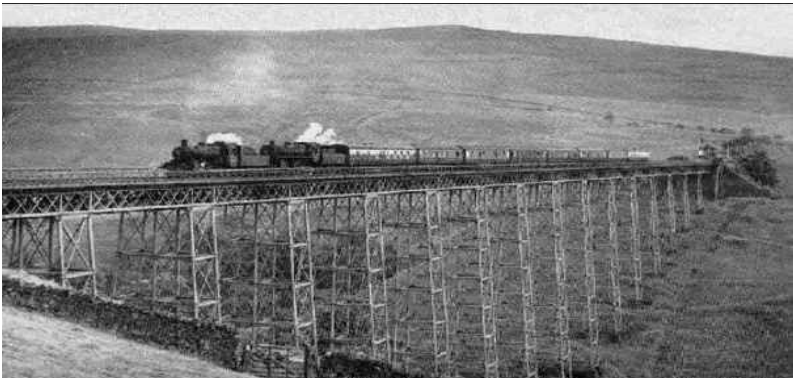
Regrettably the structure had to be demolished in 1964, partly because the structure was becoming too costly to repair but mainly because its function had largely been superseded by other forms of transport.

Another viaduct built in the UK was on the Stainmore line at Belah to carry coal from the mines in Durham to the steel works at Barrow. It too was quite unnecessarily demolished in the 1960's.



Belah Viaduct (1860)

Only two early wrought iron truss and trestle bridges survive in the UK the Meldon Viaduct in Devon built in 1874 and the Bennerley Viaduct in Nottinghamshire built in 1827.

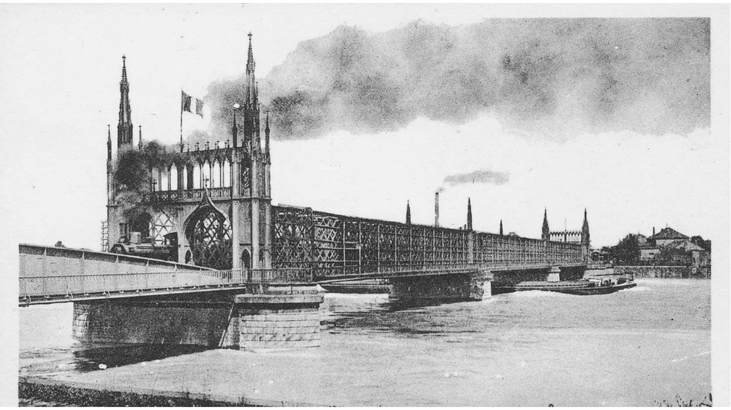
Meldon Viaduct (1874) – 6 × 27 m

Bennerley Viaduct (1877) – 16 × 23.5 m

On the continent many truss bridges were built but only one has survived the ravages of war. This is the bridge over the Rhine near Waldshut. Technically it is a box girder bridge but unlike Stephenson's bridges, it is constructed from a lattice work of wrought iron strips. The single line railway is carried on the top and is still used by the S-bahn albeit with speed restrictions.

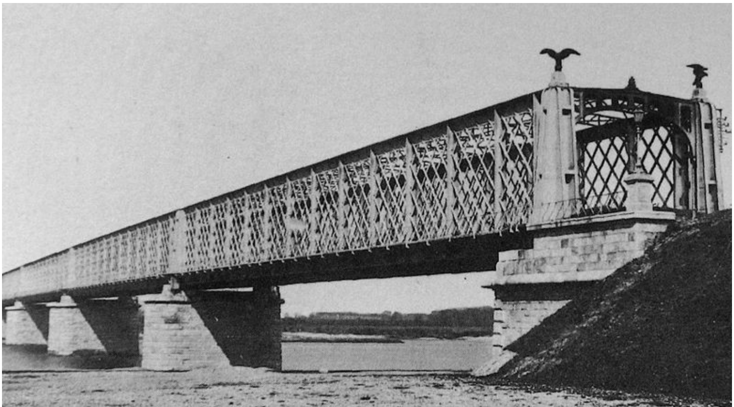
The Waldshut-Koblenz Bridge (1857) – 37-55-37 m

A major railway bridge over the Rhine was completed in 1861. It was a double track bridge and consisted of three major spans, each 59 m long with fabulous Gothic arches and pinnacles at each end.



The Rhine Bridge, Strasbourg (1861) – 3×59 m

A very similar major railway bridge over the Danube was completed in 1870. It was a double track bridge and consisted of five major spans, each 76 m long.



The Stadlauer Bridge, Vienna (1870) – 5×76 m

Even longer was the first railway bridge over the Mersey at Runcorn. This had three box-girder spans with lattice-work panels, each of length 93 m supported on two piers each sunk to a depth of 14 m in the middle of the river with the use of pressurised caissons..

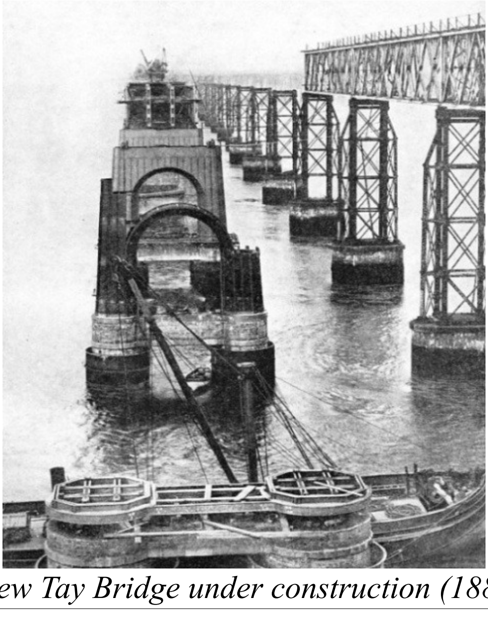
Runcorn Railway Bridge (1869) – 3×93 m

The most infamous truss bridge was the first bridge to cross the Firth of Tay in Scotland. Designed by Thomas Bouch and completed in 1878, it was an impressive structure being over 3 km in length and having 74 spans (not counting the approaches), the middle 13 being longer (and higher) than the others at 75 m.

The first Tay Bridge (1878) – 3010 m

It was originally intended that the piers would be solid masonry but part way into the construction of the bridge it was discovered that the river bed was not sufficiently solid to carry the weight so Bouch decided to use cast iron piers filled with cement instead to carry the wrought iron trusses. The bridge was inspected and all seemed to be well but only 19 months later, during a stormy night with a strong westerly gale, all 13 of the central high girders were blown into the river along with a train and 75 people lost their lives. Subsequent investigations showed that the lugs on the cast iron flanges which were bolted to the base of the piers had failed due to the enormous lateral forces exerted by the wind on the high trusses and the train. Never again would cast iron be used in any significant structural way in the building of bridges.

Within 10 years the old bridge had been replaced by a completely new one with much better foundations, wrought iron piers and a double, rather than a single track. It was built by W. H. Barlow and Son and is still in use today. The superstructure of the old bridge was transferred onto the new piers and the foundations of the old ones can still be seen.



The new Tay Bridge under construction (1887)

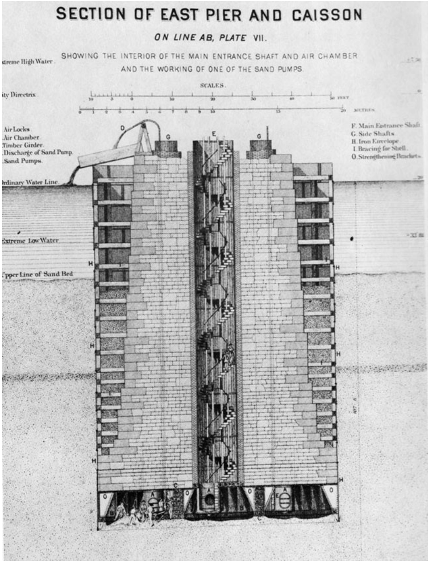
(The Tay bridge was not the first iron railway bridge to fail. In 1876 a 47 m long truss bridge carrying the Michigan Railway over the Ashtabula River in Ohio collapsed with the loss of over 90 lives. The cause was essentially poor design.)

Arch bridges

From this time on, wrought iron was gradually replaced by steel and structures became more and more daring and what is sometimes known as 'the world's first steel bridge' was opened in 1874 across the Mississippi river at St Louis. Consisting of three spans each 138m wide (the longest in the world at the time) what would have been built in stone or cast iron 30 years before is now a delicate lattice work of criss-crossing struts (most of which are actually wrought iron, not steel).

Eads' Bridge, St Louis (1874) – 3×138 m

Brunel had used a pressurised caisson to build the Royal Albert Bridge over the Tamar. Now the Tamar may be deep but the Mississippi is a different beast altogether and to build the massive central piers on which the arches rest, Ead's workers on the bridge at St. Louis had to work at an effective depth of 35 m. It this pressure, the bends can be severe and the symptoms got worse as the caisson sunk deeper and deeper. In the end, six 'submarines', as they were called, died in the construction of the piers.



Ead's caisson (1867)

As can be seen from the diagram on the previous page, the caisson has a pressurised chamber at the bottom, Access to the chamber is via a spiral staircase with an air lock at the bottom. Spoil was pumped out of the chamber through vertical pipes discharging into the river at the top. The masonry of the pier is built on top of the roof of the chamber and as more masonry is added to the top and more spoil is removed from the bottom, the caisson sinks lower and lower until bedrock is reached. Finally the chamber beneath the pier is filled with concrete.

Another arch design in particular became popular in the 1870's, many of them associated with the name Gustave Eiffel. His seminal bridge was built over the Duoro river in northern Portugal.

Ponte Maria Pia (Eiffel 1877) – 160 m

A huge 160 m arch of wrought iron, the longest in the world at the time, spans the river carrying a single railway line on a continuous truss supported by four piers. Note that the arch is thicker at the top than at the bottom. Indeed, the upper and lower ribs actually meet at the anchorage.

The bridge survives but is no longer in use.

Just half a mile downstream is a second bridge also built by Eiffel which was completed 9 years later.

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Dom Luis I Bridge (1886) – 172 m

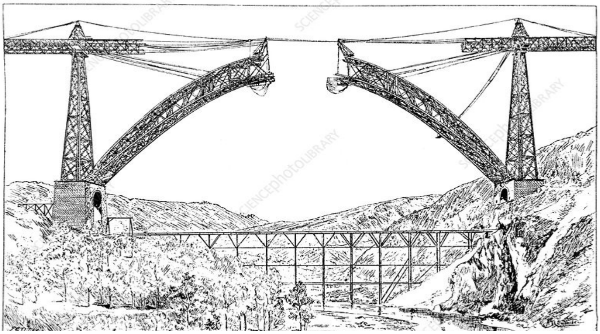
Like the Ponte Maria Pia, the Dom Luis I bridge is an arch bridge but it has a lower deck as well as an upper one. Originally both decks carried roadways but since 2003 the upper deck has carried a metro.

Eiffel's masterpiece, however, is the Garabit Viaduct over the Truyère in the Auverge.

Garabit Viaduct (Eiffel 1885) – 165 m

The span of 165 m is impressive enough but it is the height of the bridge which is truly staggering. At 124 m above the river, the Garabit viaduct was the highest arched bridge in the world until modern times.

The biggest problem in constructing a metal arch like the Garabit viaduct is how to support it when it is only half completed.



Garabit Viaduct (Eiffel 1885) – 165 m

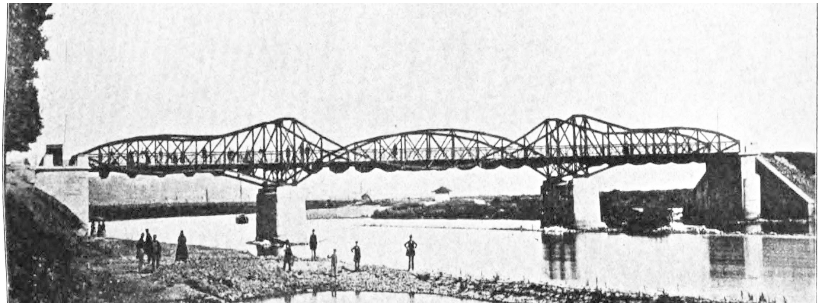
To build a stone arch it is necessary to build a timber structure called falsework on which the stones can be laid. Only when the final keystone is in place can the falsework be removed. But with an arch as big as Eiffel's it is impossible to fill the whole gorge with timber. If you did, you might as well leave it there and use it instead (which is, of course, how many gorges in the States were bridged). Instead you use temporary cables and stays to hold the truss in place until it can be joined in the middle.

In Italy a fine bridge was built by Jules Röthlisberger over the river Addo at Paderno. Its arch has a span of 150 m and rises 85 m above the river. It is of particular interest because it is a double decker bridge with a railway line travelling through the box girder and a roadway on top.

Ponte San Michele (Röthlisberger 1889) – 150 m

Cantilever bridges

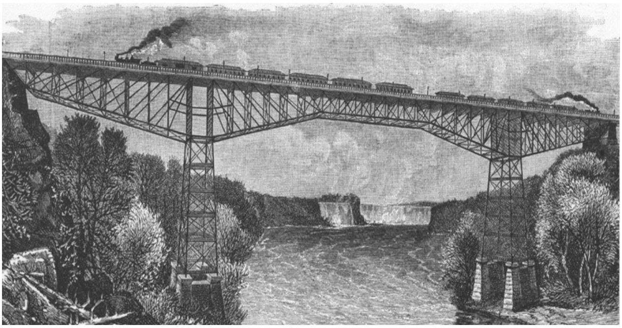
This technique of building out from the two sides is called cantilevering. Another approach is to start from a central pier and build outwards in both directions, at all times keeping the structure balanced. This idea was pioneered by a German engineer called Heinrich Gerber who built two bridges over the river Main in 1867. His design is pretty well unique.



Hassfurt Bridge (Gerber 1867) – 38 m

Two piers carry a pair of cantilever trusses which support a lenticular truss between them, reminiscent of Brunel's bridge over the Tamar.

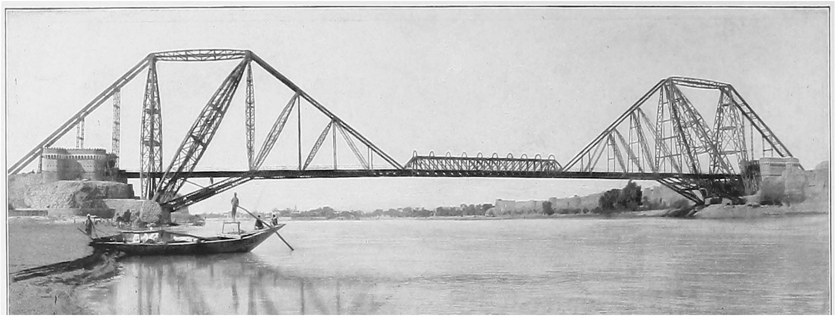
In 1883 Charles Conrad Schneider was asked to build a bridge across the Niagara Gorge. He chose a balanced cantilever design resting on two iron piers extending 53 m on each side. The bridge was completed with a central truss of length 45 m.



Niagara Canyon Bridge (Schneider 1883) – 151 m

Schneider built an almost identical bridge over the Fraser River for the Canadian Pacific Railway. (Confusingly, this bridge was dismantled in 1910 and reassembled at Niagara Canyon on Vancouver Island.)

In 1989 the Indus river was bridged at Sukkur in Pakistan using a giant cantilever bridge whose central span was 243 m

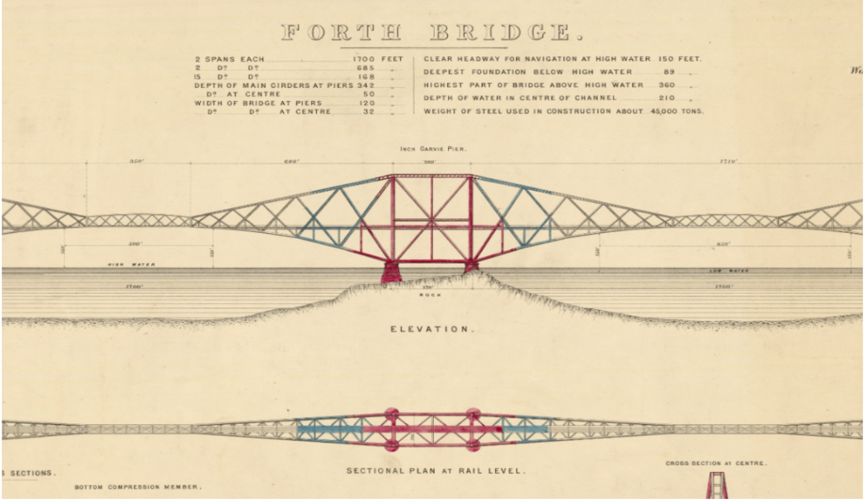


Lansdowne Bridge (Alexander Raynolds Mendel 1889) – 243 m

At the time of building its central span was the longest in the world but the record did not last long. In December of 1889 the Firth of Forth railway bridge opened with not one but two spans of 523 m each.

The problems facing the engineers, Sir John Fowler and Sir Benjamin Baker, the designers of the railway bridge over the Firth of Forth were formidable. Owing to the depth of the estuary, a truss bridge like the bridge built over the river Tay was impractical; and a suspension bridge cannot cope with the exceptionally concentrated and dynamic loads of a moving train. Fortunately, the estuary contained a small island in the middle of the channel called Inchgarvie on which a pier could be built. But this still left a massive gap of at least 500 m on each side. Fowler realised that the gap could be bridged with three huge cantilevered trusses. Each cantilever arm would extend out 210 m on each side and would be joined by a central truss of length 108 m.

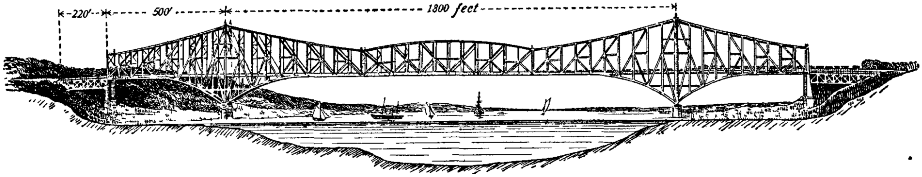
Viewed obliquely, the bridge can seem to be a maze of incomprehensible struts and girders – but viewed from the river, as seen in the following elevation, its design is supremely logical and elegant.



Firth of Forth bridge (1889)

If you have ever wondered why Fowler and Baker didn't build a simpler bridge like the one across the Tay, a glance at the profile of the river bed tells you everything you need to know. Built entirely from steel, it probably is a tad over engineered but with the Tay disaster fresh in everyone's memory, they can be forgiven for making absolutely sure that the structure was not going to fall down in the next gale.

Sadly, the lesson was not taken on board by the designers of the first Quebec Bridge. Here the St. Lawrence river is 800m wide and a single span of 554 m was required.



Quebec Bridge (1907)

The proposed solution was a pair of balanced cantilevers supporting a central truss of length 180 m but when the bridge was all but complete in 1907, the whole structure collapsed into the river with the loss of 75 lives. Its replacement still stands, however, and is the largest cantilever bridge in the world.

Another notable cantilever bridge which survives to this day was built over the river Elbe in Dresden but although it was considered a masterpiece of design when it was built, it does not compare with the bridge over the Firth of Forth.

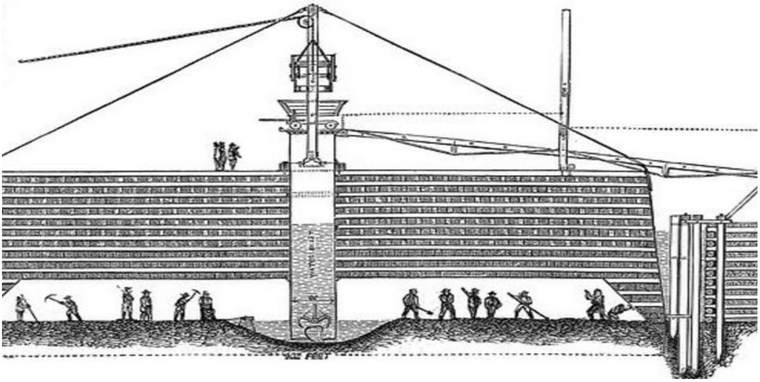
Loschwitz Bridge, Dresden (1893) – 146 m

The Brooklyn Bridge

Cut off from New Jersey by the great Hudson river on the west and from Brooklyn by the East River, in 1880 Manhatten was still virtually an island. A bridge was badly needed and in 1883 John A. Roebling and his son completed what was then the longest suspension bridge in the world – the Brooklyn Bridge.

Brooklyn Bridge (1883) – 486 m

Pressurized caissons were used to build the foundations of the two piers, the one on the Manhatten side being particularly deep at 35 m.



The Brooklyn Bridge Caisson

The illustration shows how the spoil was extracted using a big 'well' in the centre and incidentally also indicates, by the difference in water levels, why the chamber needed to be pressurised. (The illustration does not show how the workers entered and left the chamber).

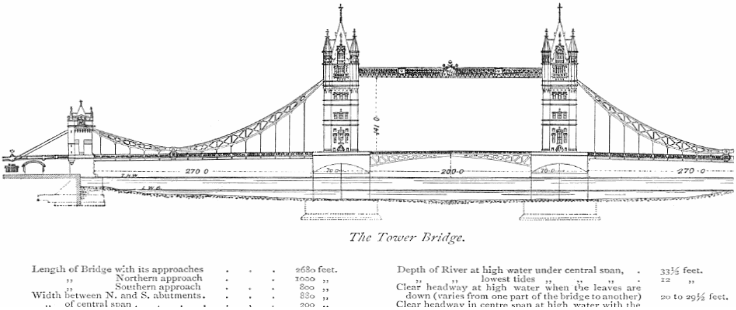
At this depth, many workers succumbed to what was known as 'Caisson disease' or 'the bends' – because often sufferers could not straighten their limbs properly. Much was learned about the causes and effects of the bends during the construction of the Brooklyn Bridge but it was not until the invention of the decompression chamber in the 1920's that 'the bends' was fully understood and in the meantime, many workers (including my wife's great grandfather who worked on the caissons for the Runcorn Railway Bridge) suffered and died needlessly.

Tower Bridge

London also needed a new bridge to cross the Thames, to service the huge commercial developments taking place in the East End. A low level bridge was ruled out because ships needed to reach the Pool of London below London Bridge; but a high level bridge would also be impractical because the Thames does not have high banks so the approaches would have been vast. A competition was launched and a variety of solutions were proposed, none of them very elegant. Horace Jones proposed building a bascule bridge (i.e. a bridge with a kind of drawbridge which could be raised.) with two Gothic towers.

Jones' original idea for Tower Bridge

Presumably the bascules were deemed to be too flimsy and together with the Engineer John Barry (son of Sir Charles Barry) the following design was adopted.



The Tower Bridge.

Length of Bridge with its approaches	2680 feet.	Depth of River at high water under central span, .	33½ feet.
,, Northern approach . . .	1000 ,,	,, ,, lowest tides ,, ,, ,, .	12 ,,
,, Southern approach	800 ,,	Clear headway at high water when the leaves are down (varies from one part of the bridge to another)	20 to 29½ feet.
Width between N. and S. abutments. . . .	880 ,,	Clear headway in centre span at high water with the	
,, of central span	200 ,,		

Tower Bridge (1894) – 83, 61, 83 m

Very little of this bridge is what it seems. Virtually nothing above the deck level is essential. The towers contain the machinery for the raising and lowering of the bascules but their main purpose is aesthetic. The two 83 m spans on either side could easily have been bridges with a conventional truss but that would have been very boring. Instead, Jones had the idea of using asymmetrical suspension bridges on each side with a high level walkway at the top of the towers to transfer the tension. The chains themselves are, not to put too fine a point on it, bizarre. Instead of using steel wire, Jones and Barry have used what amounts to an inverted arch girder. Why they thought the chains had to be rigid when the only force they have to withstand is one of tension beats me. They do, however, give the finished design a pleasing rhythm and grant the chains an architectural relevance which they would not have if they were a lot thinner.

Finally, it should be pointed out that all of the masonry is wholly decorative. It could all be removed in its entirety and the bridge would still stand because inside the masonry towers there lurk two invisible steel towers which do all the work of supporting the chains and the walkways. It was the City of London commissioners who insisted on the then fashionable 'Gothic' style, to 'fit in' with the style of the nearby Tower of London. (Did they think that that famous landmark was 'Gothic' too?).

But when all is said and done, it has to be admitted that the bridge has not only served its purpose both as a bridge and as a gateway to the Pool of London during its heyday, it has become an icon – one might say *the* icon – of the city of London, as instantly recognizable as the Eiffel Tower of the Statue of Liberty.

Water Works

London

The first pumping station whose purpose was to supply drinking water to a city was built by the Chelsea Waterworks Company in the 1730's using a Newcomen steam engine. The company was also the first to use sand filtration beds in an attempt to purify the water but a hundred years later, the Thames was so polluted that the water was all but undrinkable. In 1838 the company moved to a new site upstream at Kew where, it was hoped, the water would be less polluted. Two 'Cornish' (i.e. high pressure) beam engines, originally built in 1820, were moved to the new site one of which is preserved in the Kew Bridge Steam Museum.

Boulton & Watt engine at Kew Bridge Steam Museum

(In 1846, a truly massive engine was installed at Kew with a piston of diameter 90 inches capable of lifting 20 tons of water every minute and in 1871 an even bigger engine was built with a piston of diameter 100 inches. Both of these engines have been preserved and the former is still in working order.)

By the middle of the nineteenth century it was also becoming clear that many diseases, in particular cholera, were transmitted through contaminated water supplies. In 1852 the Metropolis Water Act forced the water companies to find sources of water above the tidal reaches of the Thames. Three of these companies joined forces to build a large water treatment works at Hampton just upstream from Hampton Court designed by Joseph Quick who installed state-of-the-art settling and filtration tanks to purify the water and several large engine houses to pump the water up to a level from which it could be distributed by gravity to the city. The fine Victorian buildings are now being sympathetically redeveloped.

Hampton Water Treatment Works under construction

Glasgow

The city of Glasgow had a different problem. Pure water was readily available in the lochs and streams of the Trossachs 25 miles to the north, but how was it to be conveyed to the city? Several engineers including Robert Stephenson and I.K.Brunel were consulted and it was decided to raise the level of loch Katrine by 1.5 m and to construct an aqueduct, 13 miles of which would be in a tunnel, 9 miles in a 'cut and cover conduit' and 3¾ miles in cast iron pipes. The longest of the 70 tunnels was 1½ miles in length; in addition there were 25 aqueducts and three inverted siphons (where the water is conveyed across a valley in pipes under pressure).

Most of this engineering is, of course, completely hidden from view but it can be seen anywhere the water course crosses a small valley. In the photograph below the water flows from an open cast iron trough into a covered wrought iron tube set at a slightly lower level so that the tube is completely filled with water at all times. This reduces turbulence and corrosion.

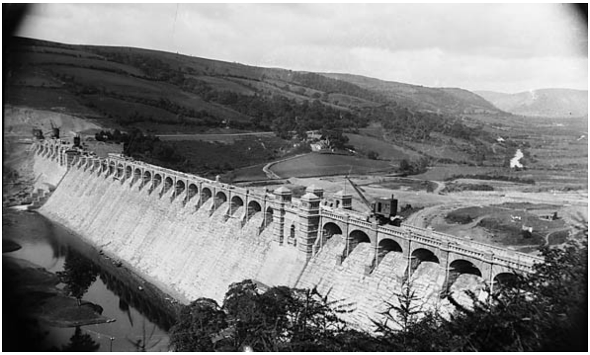
Loch Katrine Aqueduct

This aqueduct was designed and built by John Frederick Bateman, and it was formally opened by Queen Victoria in 1859. It still supplies Glasgow with much of its fresh water.

Liverpool, Manchester and Birmingham

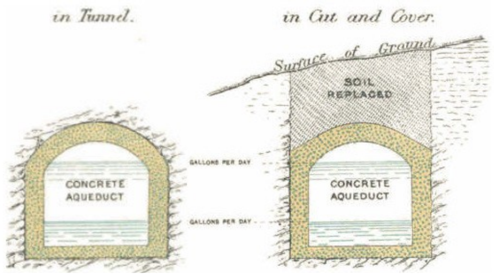
It wasn't until the 1890's that the great cities of Liverpool, Manchester and Birmingham got their water supplies from mountain lakes. First was Liverpool with the construction of the Lake Vyrnwy Dam which was completed in 1888. It was the UK's first large masonry dam and is 358 m long and 44 m high.

The 70 mile Vyrnwy aqueduct, which was the longest aqueduct in the world at the time connected the lake to the city of Liverpool. The most significant engineering feature of this aqueduct was the tunnel which carried the pipes underneath the Mersey and the Manchester Ship Canal. The 4 mile tunnel was built using Greathead's patent shield which used compressed air to hold back the waters. The first water reached Liverpool in 1892.



Vyrnwy dam under construction

Only a couple of years later, the first water from Thirlmere in the Lake District reached Manchester via the 96 mile long Thirlmere aqueduct. The first 3 miles flowed through a rock cut tunnel under Dunmail Raise; then a series of cut and cover sections, tunnels, bridges and piped siphons bring the water to its destination.



Cross sections of the Vyrnwy and Thirlmere aqueducts

Birmingham got its water from the dams in the Elan valley in 1904.

Nottingham

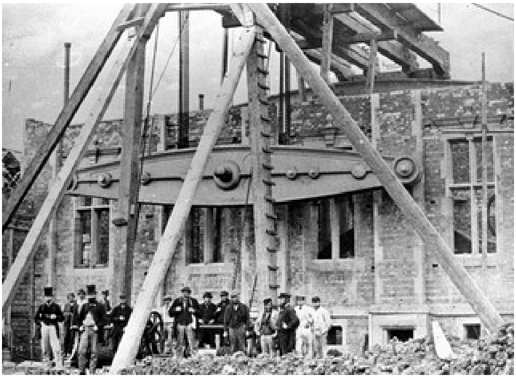
That Nottingham had one of the purest supplies of drinking water in the first half of the nineteenth century was due to a remarkable, self taught engineer called Thomas Hawksley who designed and built several pumping stations for the city of which the finest was the Basford Waterworks. He also built a number of underground reservoirs one of which at Papplewick can now be visited.

Papplewick underground reservoir

Also at Papplewick (but built in 1884 shortly after Hawksley's retirement) is one of the finest water pumping stations outside London. Here two 46 inch Watt engines each of which raised water from the aquifers which lie 200 feet below the surface at a rate of 7000 cubic metres (nearly 3 Olympic swimming pools) per day.

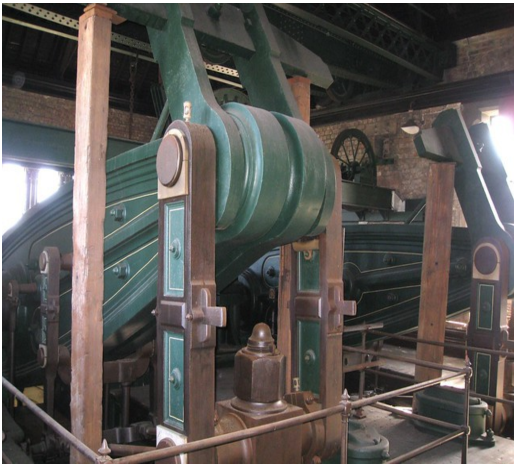
Papplewick pumping station

One of Hawksley's many pumping stations which survives largely intact is at Ryhope in Sunderland. It was built in 1868 and houses a pair of original double acting compound beam engines which are steamed regularly. The photograph below shows one of the 22 ton beams being hoisted into position while the engine house was being built.



Ryhope pumping station

Hawksley also built Dalton pumping station near Dalton-le-Dale in county Durham where two 72 inch beam engines dating from 1879 can still be seen.



Dalton pumping station

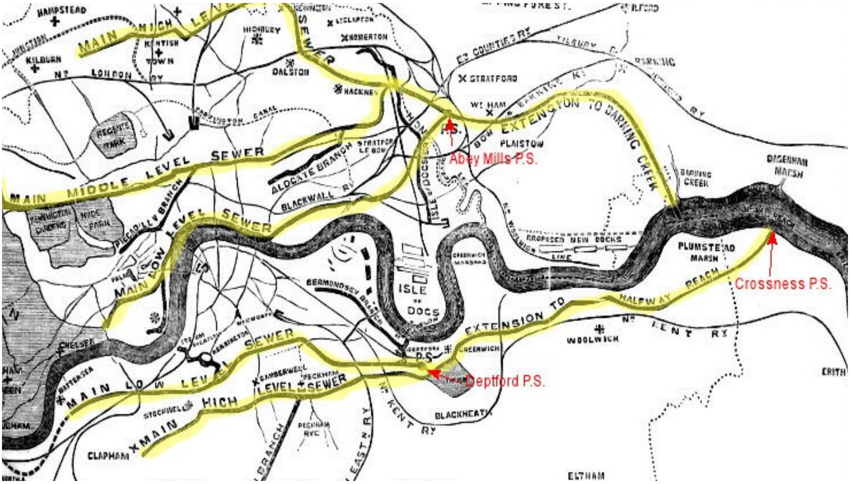
Yet another of Hawksley's projects was the Goldstone pumping station near Brighton. It is now home to 'British Engineerium' – a museum of technology which is currently closed.

Sewage works

London sewers

One of the most popular attractions at the Great Exhibition of 1851 were the public toilets which exhibited George Jenning's patented flush toilet, a device which was proving very popular and was being widely installed into the homes of the middle classes at the time. Now while the traditional earth closet required nothing except regular emptying by the night soil man, the flush toilet required both a copious supply of water (see page 152) and a sewer to carry the waste away. All these minor sewers simply discharged into the river Thames which, in consequence, soon became one large sewer. In the hot summer of 1858 things came to a head during the 'Great Stink' when the smell became so bad parliamentary business was disrupted. In effect parliament was forced to accept that the City of London could not afford to finance the necessary improvements and that the scheme of new sewers proposed by Bazalgette and others would have to be adopted.

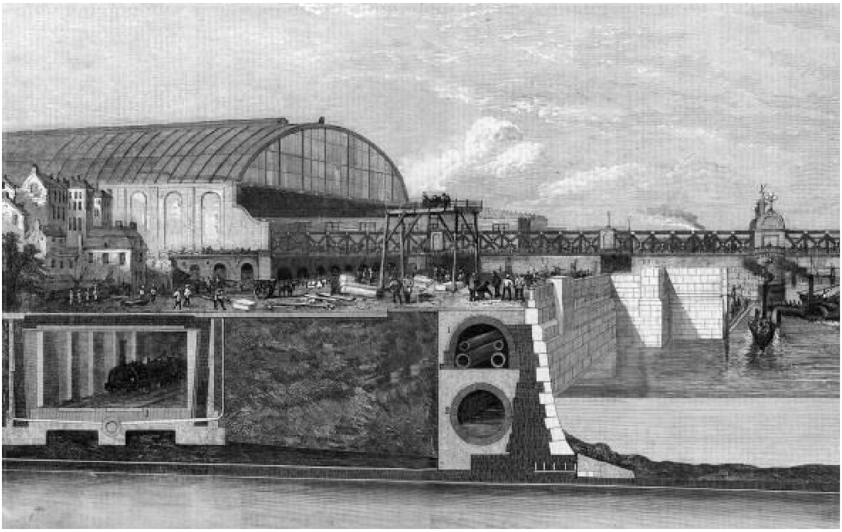
The plan was to build five new sewers which would 'intercept' the existing sewers – a high, middle and a low level sewer on the north side of the Thames and a high and a low level sewer on the south.



Bazalgette's plans for the main intercepting sewers

Since the low level sewers would be below the level of the water in the Thames, the water would have to be pumped up to the high level using pumping stations at Abbey Mills near Stratford and Deptford near Greenwich. From there the sewage would fall under gravity to be discharged into the Thames Barking Creek and at Crossness where a third pumping stations would be needed.

Where the northern low level sewer ran along the bank of the Thames at Westminster, an embankment was proposed which would have several advantages. Firstly by narrowing the river it would increase the rate of flow of water; secondly, in addition to the low level sewer, the embankment would incorporate a subway (for pedestrians or water pipes etc.), an underground railway (the Metropolitan and District Line) and space on top for a road,gardens and a promenade.

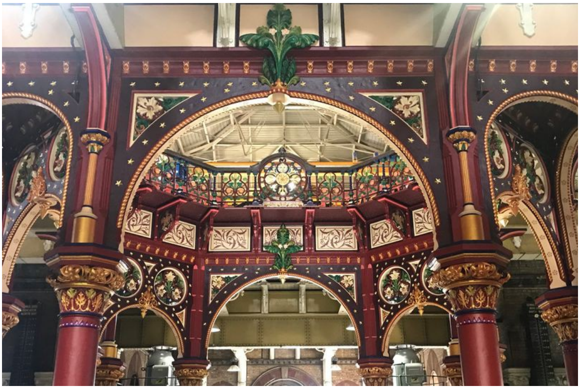


Section through the Victoria embankment

(In the above engraving a section of the proposed pneumatic railway can be seen running under the embankment and the river. This was never completed.)

London Pumping Stations

Abbey Mills Pumping Station has been described as the 'Cathedral of Sewage' and with good reason. Cruciform in shape, it used to house no less than eight beam engines in a space that would completely fill the central crossing of St Paul's Cathedral. It was decorated in a style that would befit a cathedral too with elaborate columns and finely detailed wrought ironwork. Sadly, the beam engines were removed in the 1930's.



Abbey Mills pumping station

If anything the pumping station at Crossness was even more elaborate. Both were completed by 1868.

Crossness pumping station

Happily, when the time came to upgrade the four huge beam engines at Crossness it was deemed uneconomic to remove them. In consequence it has been possible to restore one of them to working order and the others are in the process of restoration. The specifications of these engines are staggering. Each had a beam weighing 47 tons and a 52 ton flywheel. Operating at a leisurely 11 strokes to the minute, each was capable of lifting 4000 cubic metres of water (1½ Olympic swimming pools) up the required 10 m height every *hour.*

(Surprisingly perhaps, the power output of each engine works out to be only 150 hp – about the same as that of a modern family car)

The pumping station at Deptford also had four beam engines but whether it was as elaborately decorated as the other two I do not know.

In 1888, the north London borough of Tottenham had its own sewage works at Markfield and installed a beam engine in 1888. Later it was used to pump sewage into the Bazalgette's Northern high level sewer. Its magnificent engine has recently been restored to full working condition.

Markfield pumping station

Provincial pumping stations

A pumping station similar in size to that at Crossness was built in Leicester in 1890 with four single cylinder beam engines rated at 200 hp). All four engines have been restored to working condition.


Abbey pumping station, Leicester

Burton-on-Trent solved its sewage problems in 1885 with the opening of the Claymills pumping station. Three of its four beam engines are in working condition and the fourth is currently being restored.

Claymills pumping station, Burton-on-Trent

Other Victorian sewage pumping stations which can be visited include the Cheddars Lane pumping station built in 1894 (now part of the Cambridge Museum of Technology) and Coleham pumping station near Shrewsbury

Drainage

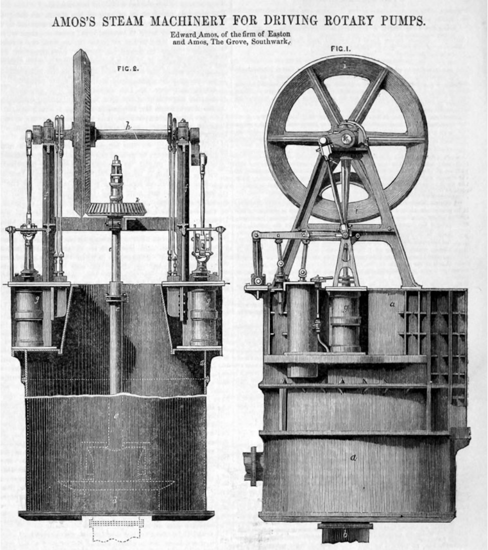
The first successful attempts to drain the fens in Cambridgeshire took place in the early 17th century. This was achieved by using simple tidal sluices which only opened to the sea at low tide. But as the earth dried out, the level of land fell and soon wind powered pumps were needed to stop the land from flooding. Eventually steam engines were employed one of which remains at Stretham. It had a double acting rotative beam engine powering a wooden scoop wheel installed in 1831.

Stretham pumping station, Cambridgeshire

The Somerset levels were also drained with the use of steam engines. At Westonzoyland a beam engine was used for 25 years but in 1861 a new type of steam engine was installed which drove a centrifugal pump which was much more efficient. Indeed, it is a mystery to me why the beam engine remained so popular and was still being installed in pumping stations right up to the end of the century. It has been noted that, after the Great Exhibition of 1851, the pioneering spirit exemplified by the great innovators like Brunel and Stephenson was conspicuously lacking in British engineering. Beam engines were familiar, easy to maintain and incredibly reliable and so they just went on being used.

The engine installed by the firm of Easton and Amos at

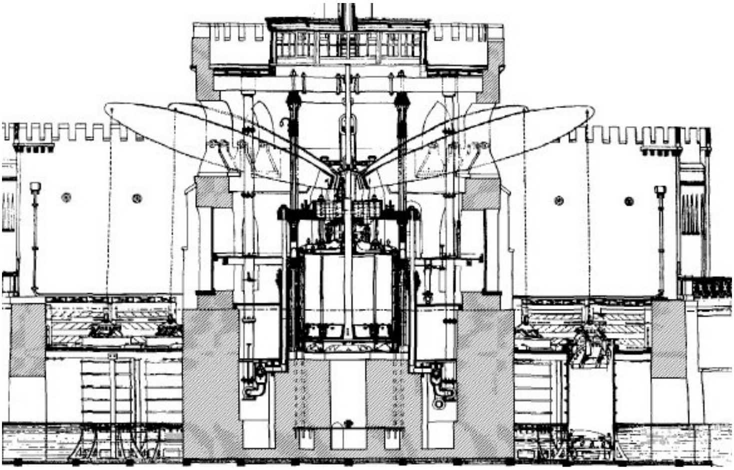
Westonzoyland had two double acting cylinders driving a shaft using connecting rods at right angles in the manner of a steam locomotive. A large bevel gear on this shaft engaged with a smaller bevel which rotated at high speed driving the centrifuge.



Easton & Amos engine, Westonzoyland

Easton & Amos engine, Westonzoyland

But draining the fens and the Somerset levels is like emptying a bucket compared to the task faced by the Dutch engineers who wished to drain the Haarlem lake in North Holland. Three pumping stations were built, the largest being at Cruquius. Here a simply gigantic single cylinder Watt engine, built by Harvey & Co of Hayle, Cornwall, with a piston of diameter 144 inches acted simultaneously on eight beams arranged radially working eight reciprocating pumps. The engine started work in 1850 and the lake was drained three years later.



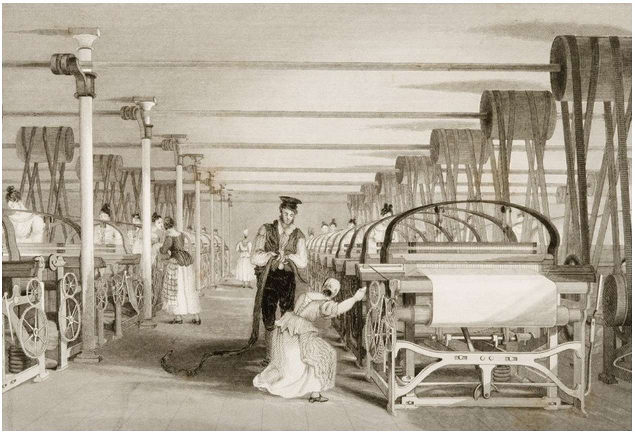
Cruquius pumping station

Cruquius pumping station

Machinery

Mills

Throughout the nineteenth century steam engines both small and large were used to power the industrial revolution throughout the world. In addition to pumping water they were used to power machinery in the textile mills and ironworks of the north of England. Power was transmitted to the individual machines by belts and pulleys.



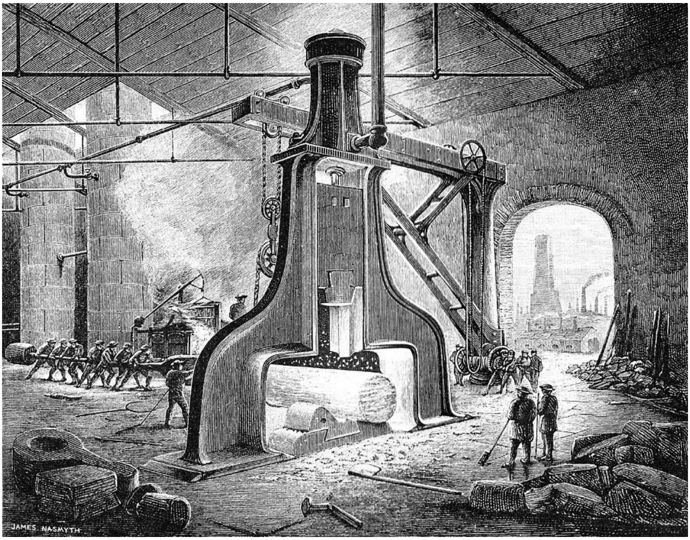
Cotton Mill (c1830)

Possibly the largest mill in the world was built at Ancoats in Manchester. According to Wikipedia it had '276 carding machines, and 77,000 mule spindles, 20 drawing frames, fifty slubbing frames and eighty one roving frames', all powered by two 40 hp Boulton & Watt beam engines.

Many of the early mills were destroyed by fire because the cotton dust in the air was extremely flammable. A number of mills built in the first half of the nineteenth century were built using a 'fireproof' design pioneered by William Strutt. Instead of using timber joists, Strutt used cast iron beams supported by cast iron columns with shallow brick arches spanning the gap between the beams. This method of construction can be seen in the above illustration.

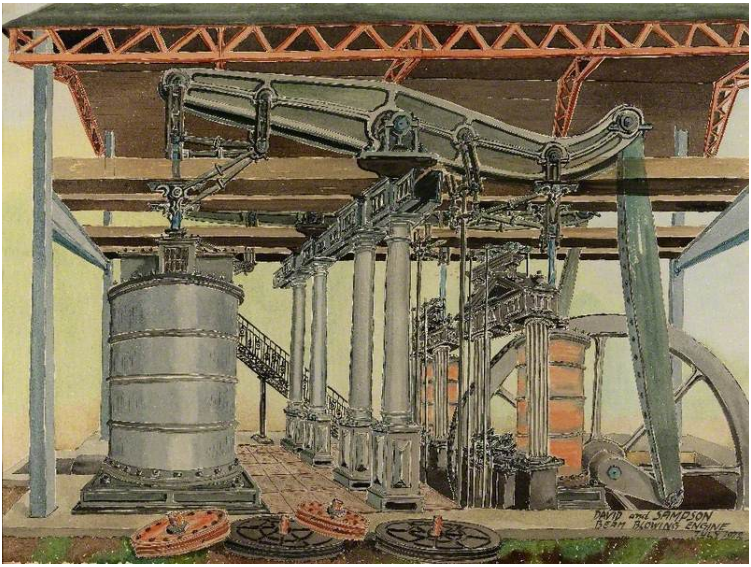
Factories

Some of the machinery used in Victorian factories was truly impressive. For example, in 1843 James Nasmyth built a steam hammer which could deliver 10 ton blows on a casting several times a minute. The illustration below probably depicts the forging of the main 30 inch diameter shaft of Brunel's Great Eastern.



Nasmyth's steam hammer

In order to power the furnaces for such huge castings, enormous steam engines were used to power the bellows. One such pair of engines called David and Sampson is preserved at Blists Hill in Shropshire. The present weatherproof cover makes it difficult to see the engines in toto but the 1972 drawing below shows the two steam cylinders in red, the curiously shaped beams which are cranked at right angles to the single flywheel and one of the two blowing pistons at the other end of the beam. The engines were built in 1851 for the Lilleshall Company at Oakengates and were moved to Blists Hill in 1970.



David and Sampson blowing engines

Another innovation of great importance was the invention in 1855 of a method of converting pig iron into high grade steel by Henry Bessemer. The photograph shows Bessemer's original prototype converter preserved in the Science Museum in London.

Bessemer's prototype converter

Nasmyth's great steam hammer and Bessemer's giant converter are two of the most impressive innovations to be found in the Victorian factory but no less important was the revolution that was occurring literally on a minute scale. In 1800, virtually every manufactured item whether it was a huge beam engine or a tiny watch was unique. Every component was individually cast, bent, riveted, filed, polished individually by hand. There was no such thing as the standardisation of components. A piston made for one machine would never fit another. Nuts and bolts were almost never used because they were almost impossible to make.

But in 1797 a young engineer called Henry Maudslay built a screw cutting machine that outclassed anything that had gone before. Its success was due to three factors; firstly it was absolutely rigid; secondly the frame along which the cutting tool was to slide was perfectly flat and thirdly the master screw and the linking gears were cut with absolute precision. The beauty of the machine was that, once you had built one machine that could cut screws to a high degree of accuracy, you could use those very screws to manufacture other screws to the same accuracy. Maudslay also invented the micrometer – a device which uses an accurate screw to measure things to an accuracy of a thousandth of an inch or better. Now, for the first time, it was possible to manufacture nuts which would fit any bolt of the same size and make pistons which would fit more than one cylinder. Another invention of his was the process whereby by grinding three metal plates against one another in pairs, a perfectly flat surface could be obtained.

Maudslay died in 1831 but his ideas were taken a lot further by one of his employees, Joseph Whitworth, who started up his own company manufacturing precision machine tools in 1833. The lathes, mills and planing machines that his factory produced were second to none and essentially made possible the cheap mass production of smaller precision items such as small arms, clocks and watches, padlocks and eventually cars.

In 1841 he published proposals for a set of standard screw threads which was adopted became known as the British Standard Whitworth (BSW).

Farms

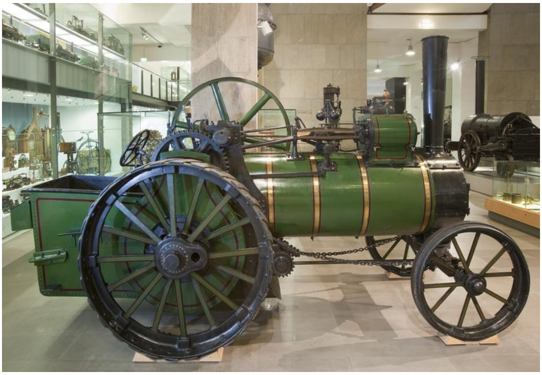
The revolutions taking place in England's Mills and Factories were not repeated on her farms to anything like the same degree. The horse and the ox remained the main source of power throughout the nineteenth century. But the steam engine did have a minor role to play all the same.

One of the most labour intensive activities on an arable farm was threshing – the process whereby the grain is separated from the husk. By 1800, simple horse driven threshing machines had been invented which greatly speeded up the task. Robert Trevithick built a small portable steam engine to power one of these machines as early as 1812. This machine was so successful that it was in use for 70 years and is now preserved in the Science Museum in London.

Between 1830 and 1850 several inventors including Fowler, Burrell and Ransome developed ways in which one or two portable steam engines could drag a multiple bladed plough across a field.

Ploughing with steam

It was only a matter of time before someone had the idea of making these machines capable of propelling themselves. That person was Thomas Aveling who built the first proper Traction Engine in 1859. An early example is preserved in the Science Museum in London.



Aveling & Porter traction engine (1871)

By 1850 the combine harvester had been developed which, when pulled through a field of grain, combined the actions of reaping, threshing and winnowing but it wasn't until the development of the internal combustion engine and the modern tractor that the real revolution in agriculture was established.

Traction engines were also used for road haulage and for road rolling and towards the end of the century, when electric generators had been invented, they became a familiar site when the travelling fun fair came to town. One of the oldest surviving showman's engines is Burrell's 'Emperor; built in 1889. The generator with its red driving wheel can be seen mounted at the front.

Burrell showman's engine (1898)

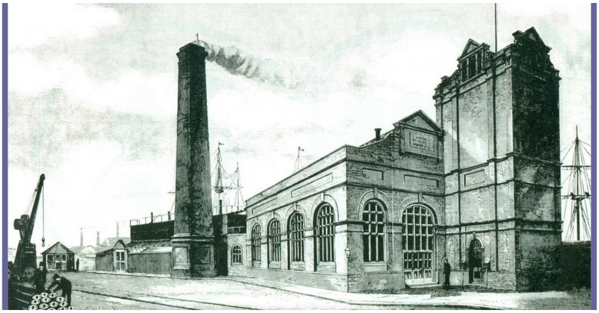
Energy Supplies

Hydraulic power

In 1845 Newcastle was looking to improve its water supplies and a young lawyer called George William Armstrong became involved in the project. The water was piped from a number of reservoirs above the city and the pressure in the mains was sufficient to ensure that the water could reach the highest parts of the city.

Now at that time the cranes along the dockside were probably powered by horses or even man power; a few might have been steam powered. Armstrong had the brilliant idea that cranes could simply be powered by water under pressure and he arranged with the authorities to lay water pipes along the dockside. His hydraulic cranes were so successful that he gave up his lawyers practice and started a factory building cranes and other hydraulic machinery. (Armstrong later turned to the manufacture of guns. His house, Cragside, was one of the first ever to be lit by electricity.)

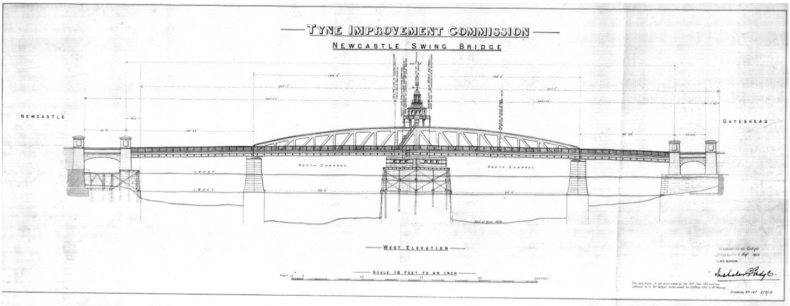
The enterprise was so successful that hydraulic power companies were started in London, Liverpool and Manchester and the power was used to operate not only machinery but lifts, lock gates, theatre machinery and the bascules of Tower Bridge.



Wapping hydraulic power station (1893)

The tower in the illustration above is a hydraulic accumulator – a device invented by Armstrong to ensure that the water in the pipes is under a constant high pressure.

At the time of its completion in 1876 Newcastle's swing bridge was the largest in the world. It was designed by William Armstrong and used his hydraulic technology. The movable span in 85 m long and weighs 3000 tonnes.



Newcastle swing bridge (1876)

In 1877 a competition was launched for a design for a bridge opposite the Tower of London. In order to allow large ships into the Pool of London, a bascule bridge was chosen and Armstrong was contracted to supply the machinery. Like the Newcastle bridge, he opted for a hydraulic mechanism.

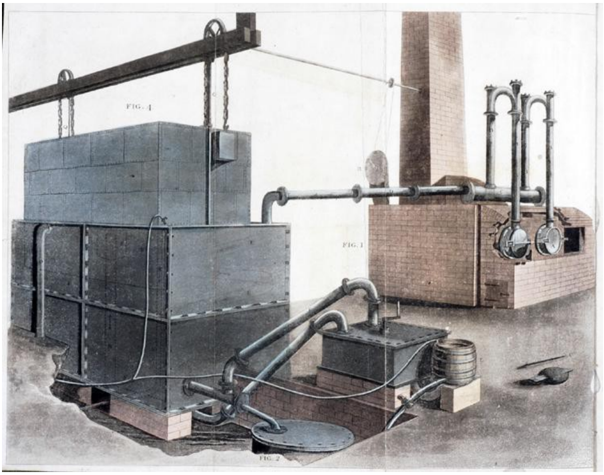
Two 360 hp horizontal steam engines pumped water into two hydraulic accumulators at a pressure of 60 atmospheres (6×10^6 Pa). Each accumulator consisted of a cylindrical piston half a metre in diameter 16.5 m long with 120 tonne iron weight on the top. Each accumulator could store 20 million joules of energy – enough to raise and lower the 1000 tonne bascules without the use of the steam engines if required. When the bascules needed to be raised, water under pressure was fed to the four hydraulic motors which turned the pinions which engaged the racks on the counterbalanced bascules.

The Victorian machinery worked flawlessly for nearly 100 years and most of it is preserved and can be viewed today.

Hydraulic jacks were used to lift the great tubular spans of Brunel's bridge over the Tamar at Saltash and Stephenson's box girders over the Menai Straits and the river Conway. They were also used to launch the Great Eastern.

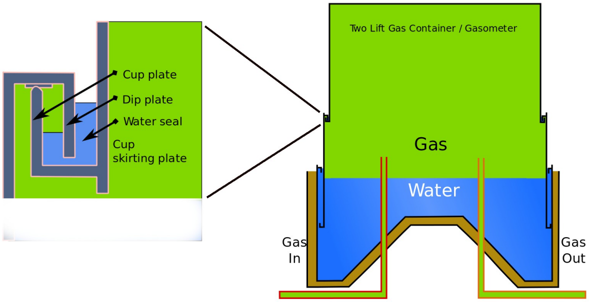
Gas works

One important feature of the Victorian industrial scene which has largely been forgotten is the Gas Works. The London-based Gas Light and Coke Company was incorporated by royal charter in April 1812 and supplied coal gas for street lighting and domestic use. The advantages of gas light were so apparent that within a couple of decades, virtually every town in the country had a gas works. These could vary in size from a small gas plant as illustrated below to a large and complex industrial site.



Gas plant (1815)

The most conspicuous feature of a large gas works was the gas holder. At its most basic this is simply a large iron cup place upside own in a basin of water. This method of trapping gases has been used ever since Lavoisier invented the device in the eighteenth century. He used it to measure volumes of gas and called it a *gazomètre* – which is why gas holders have often been called gasometers in England. Later, in 1824, telescopic gas holders were invented with two, three or four sections which rise and fall according to the amount of gas in the holder.



Telescopic gas holder

Hundreds of these were built all over the country. Most have now been demolished but two of them have been converted into luxury flats at Kings Cross in London.

Kings Cross gas holders (c1870)

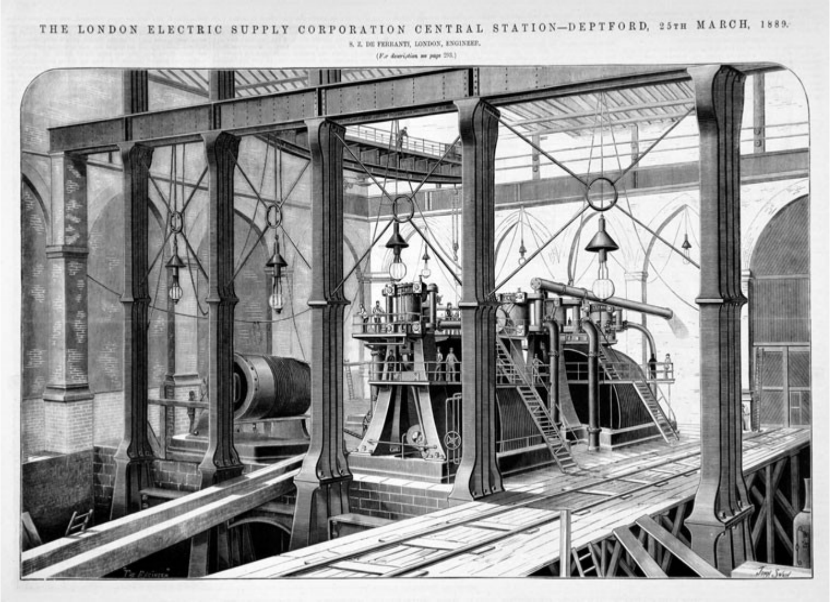
Kings Cross gas holders in 2018

Michael Faraday discovered the principle by which rotary motion could be turned into electricity in 1832. But half a century was to pass before a proper public supply electrical power station was built. The reason for the delay was that there was little point in generating electricity until there was some way of using it. The 'killer application' arrived in 1880 with the invention – independently by Edison and Swan – of an incandescent light bulb which lasted more than just a few hours.

It is often stated that the first power station to supply electricity to paying customers was the Pearl Street Power Station in New York, designed and built by Thomas Edison, which opened in September 1882. It had 6 generating sets each rated at 100 kW and produced DC at 110 V (the highest voltage which Edison deemed 'safe'). In fact Edison had opened a similar (but much smaller) plant in London in January of that year in Holburn. It produced 93 kW (125 hp) of electrical energy at 110V DC which was used to power a thousand light bulbs on the streets of London and nearby houses. Neither venture was a commercial success and both stations were closed a few years later. In any case, it turned out that local generation of low voltage DC was not the way forward as the world's first high voltage AC power station was soon to open in Deptford designed by one Sebastian Ziani de Ferranti.

In spite of his Italian name (his father was Italian) Ferranti was born in Liverpool in 1864. He was fascinated by the recent developments in electrical engineering and became an expert in the design of alternating current devices. In 1884 three Hungarian engineers worked out the essential principles behind a properly efficient AC transformer and Ferranti realised that, instead of generating low voltage DC on site, it would be much more efficient to generate high voltage AC at a central power station and transform it down locally to a usable voltage.

The four alternators which he supplied for the first AC power station at Deptford were probably rated at 200 kW (270 hp) each and were powered directly by a pair of piston engines, one on each side of the alternator, presumably cranked at right angles. They produced electricity at 11,000 V at a frequency of 5000 cycles per minute (83.3 Hz). In the following illustration, dated March 1889, one unit is complete and probably operational; number 2 is ready to be connected to the steam pipe while units 3 and 4 are in the process of being installed.

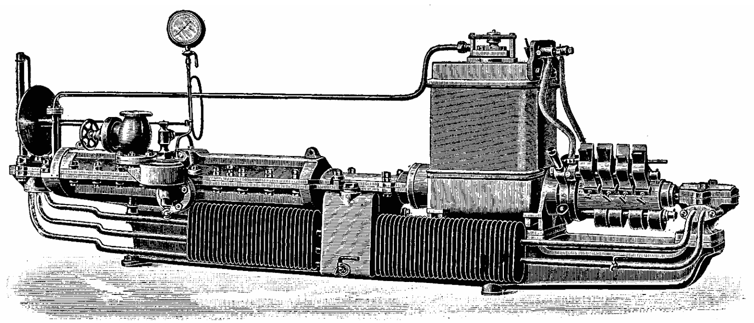


Deptford Power station under construction

Naturally as with any new technology there were serious teething problems but in time the technology proved itself and the modern world would be inconceivable without Ferranti's pioneering achievements.

In 1893 a much larger power station, Bankside Power Station, was built on the south side of the Thames with 6 generating sets with a total generating capacity of 1.8 MW powered by a vertical inverted compound steam engine similar to the marine engines of the day (see page 188). Over the years more and more and larger generators were added until at its peak in 1945 it was producing 89 MW. The old buildings were then demolished and a new power station, designed by Sir Giles Gilbert Scott, was built but that closed in 1981. Scott's building now houses Tate Modern.

Reciprocating engines were not really suitable for powering alternators which ideally need to rotate at speed up to 50 times a second. In 1884 a young engineer called Charles Parsons was working in the electrical section of a Gateshead engineering firm making marine engines. Having developed a suitable alternator he turned his inventive genius to the problem of rotating it at high speed. The result was the world's first efficient steam turbine – a device which was destined to dominate both electricity generation and ship propulsion to this day



Parson's turbine driven generator (1887)

Once it had been shown that electricity could be generated efficiently and cheaply it was quickly realised that one of its most important applications would be in transport; in particular in the London underground.

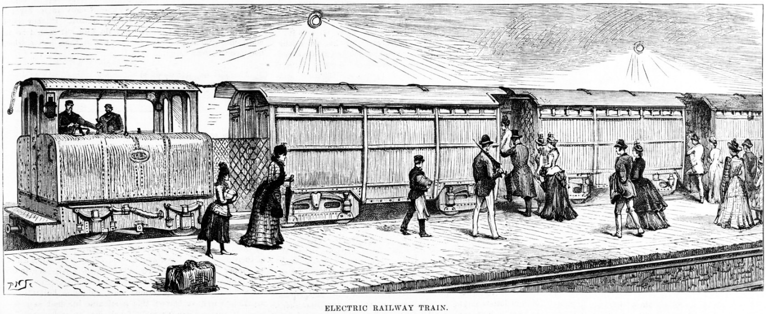
As has been mentioned, the first deep level 'tubes' were constructed in the 1890's using electrical equipment largely supplied by Siemens. Werner von Siemens was a German inventor who in 1867 had invented a new kind of self exciting dynamo. Up to then, dynamos used relatively weak permanent magnets and could only generate feeble currents. By using an electromagnet actually powered by the dynamo itself, Siemens was able to generate almost unlimited power. It was soon discovered that a dynamo would also work as a motor if supplied with current and the electrical motor industry was born.

The first application to transport was the construction of an experimental electric tramway in St Petersburg in 1880. Siemens saw this and opened the first successful public tramway in 1881 near Berlin.

Grosse Lichterfelde tram (1881)

This was followed by the Volk's Electric Railway in Brighton, opened in 1883 and the first trams in Blackpool in 1885, both of which are still in operation today. By 1900 electric trains were operating in many cities in Europe, America, Canada and Australia.

The first electric trains in London were operated by the City and South London Railway. Initially it was thought that there was no point in providing carriages with windows as the trains ran in tunnels throughout but this was not popular with travellers who referred to the carriages as 'padded cells'.



City and South London Railway (1890)

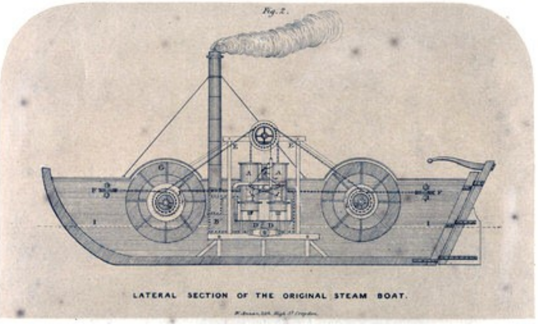
The locomotives operated on 500V DC and were supplied by the Manchester firm Mather and Platt who also supplied the steam engines and generators in the power station at Stockwell.

Ships

Early paddle steamers

The nineteenth century saw a total rethink in the art of ship building. Nelson's *Victory* is recognisably in the same tradition as Henry VIIIth's *Mary Rose* but the pre-dreadnought battleships and the ocean-going liners of the 1890's were as different a breed as could possibly be imagined. It all started in 1787 with the launch of the first iron boat – a barge, in fact – on the river Severn by John 'Iron-mad' Wilkinson. Everyone thought he was insane but to their astonishment, the barge floated. The idea did not catch on though.

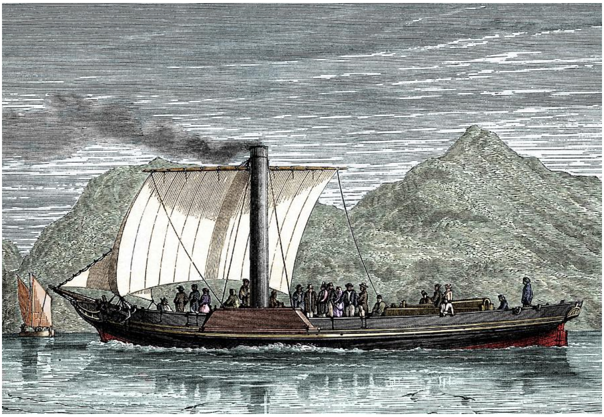
At about the same time, an experimental steam boat designed by William Symington was being tried on Dalswinton Loch north of Dumfries. It had two paddle wheels positioned on the starboard side of the boat powered by a two cylinder Watt engine. Robert Burns was on board at the time and the trial was a success – but like Wilkinson' barge, it was ahead of its time.



The Dalswinton Steamboat (1788)

In 1803 Symington was called upon again to design a steam boat for use on the Forth and Clyde canal. Named the *Charlotte Dundas* after his sponsor's daughter it had a horizontal steam engine driving a single paddle wheel at the rear. In a test run the boat pulled two 70 ton barges at a respectable speed of 2 mph but in spite of this, vested interests and a campaign of false claims that the boat would wash away the banks of the canal resulted in the vessel being forgotten.

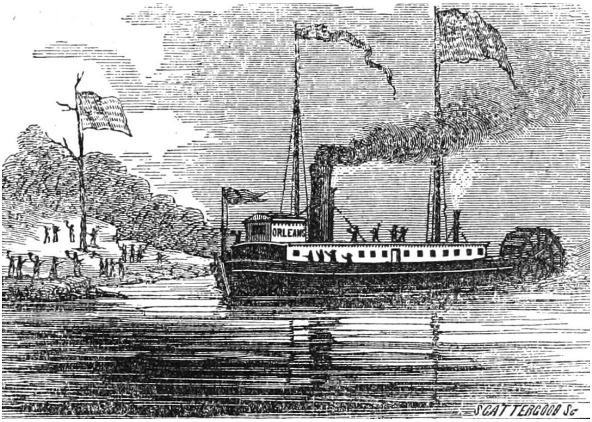
The cause of the steam powered ship was taken up by another Scotsman, Henry Bell, who built a wooden-hulled boat called the *Comet* which ran passenger services on the river Clyde for several years. The illustration shows that it had a pair of paddle wheels set on either side of the boat – an arrangement that was to become standard in the UK for decades.



PS Comet (1812)

Symington and Bell were by no means the only inventors experimenting with steam powered boats at this time. In 1807 Robert Fulton built a steam boat called the *North River* (also known as the *Clermont*) which ran passenger services on the Hudson river and later in 1812 he designed the first steam powered battleship – the *Demologos*. This was, in effect a floating gun platform. It had no sails and its single paddle wheel was sandwiched between a pair of hulls. In the event it was never used in action and was destroyed by an accidental explosion in 1829.

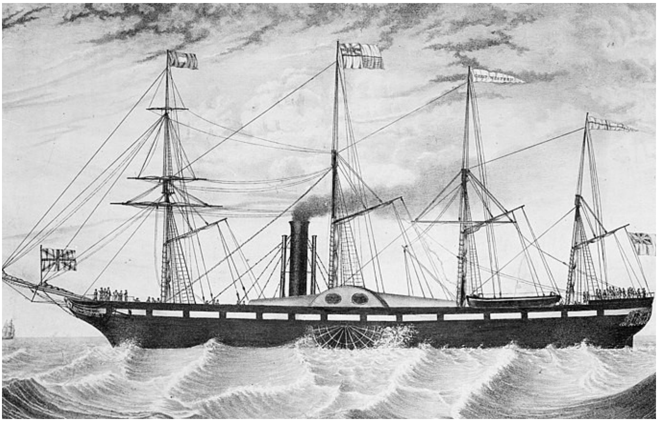
Of far greater importance was the steamboat *New Orleans* which Fulton designed and had built in Pittsburgh on the Ohio river. His plan was to sail the boat all the way down the Ohio, across the notorious 'Ohio Falls' – a 2 mile stretch of rapids actually – and down the Mississippi river to her eponymous home town. This he did successfully, arriving at New Orleans in January 1812. Fulton and his partner Livingston set up regular services above and below the Falls and soon there were dozens of stern wheelers plying their trade up and down the two rivers effectively opening up huge tracts of land in the mid-west. The Falls of the Ohio were bypassed by a canal in 1830.



PS New Orleans (1811)

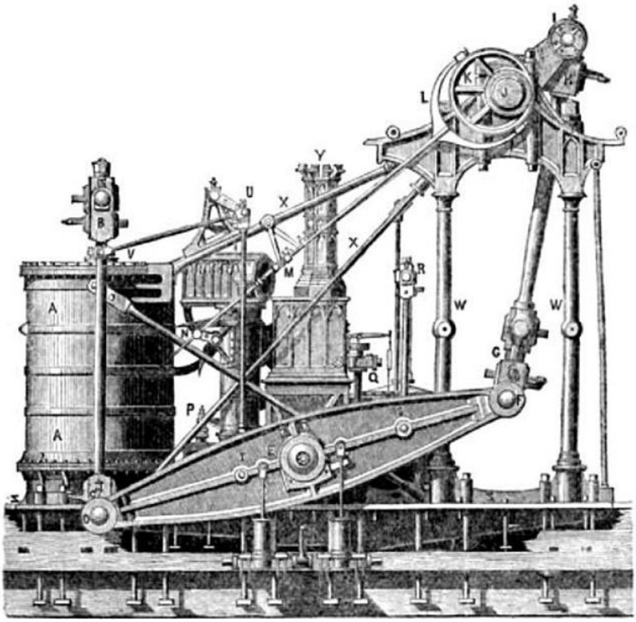
The SS Great Western

The world's first truly ocean-going steamer (though not the first steamer to cross the Atlantic) was I.K.Brunel's *SS Great Western*. She made her maiden voyage from Bristol to New York in 1838 and went on to complete 45 more round trips across the pond.



SS Great Western (1838)

Like the other paddle steamers of the day, *SS Great Western* was powered by a variant of the classic beam engine called a side lever engine in which the heavy overhead beam is replaced by two beams placed at the bottom of the engine, thus lowering the centre of gravity and making the engine much more compact.

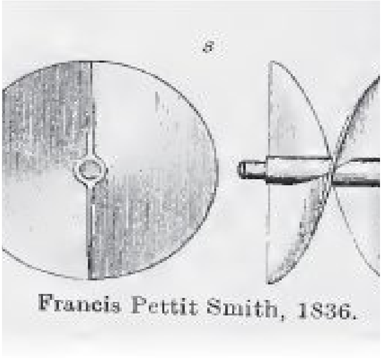


Side lever engine (1849)

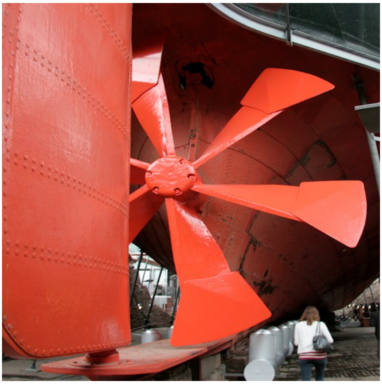
The SS Great Britain

Several more side wheel paddle steamers were built to service the Atlantic trade but Brunel himself had other ideas. His next ship, the *SS Great Britain*, was to have been a traditional wooden hulled paddle steamer albeit significantly larger than the Great Western but in 1838 the iron-hulled steam packet *Rainbow* called in at Bristol and Brunel immediately saw the possibilities of the new material. Two years later with the wrought iron hull of the new vessel already partially complete, another ship, the SS Archimedes, was launched using a literally revolutionary method of propulsion – the screw propeller.

The propeller of the *SS Archimedes* had been designed by the inventor Francis Pettit Smith and is obviously based on the traditional Archimedean screw used since ancient times to raise water. From the patent drawing we can see that it had two blades, each rotating a full 180°. Brunel negotiated with Smith to borrow the *SS Archimedes* and together they tried out several different designs of propeller. They quickly discovered that it was not necessary for the blades to make even a half turn but that multiple blades were better. The original propeller fitted to the *SS Great Britain* (shown below) had six blades and looked more like a windmill. (Later Brunel reduced the number of blades to four.)[11]



Smith's patent propeller



SS Great Britain propeller

In order to drive the propeller at a suitably fast speed, Brunel had to completely redesign his ship and the engines too. The side lever engine was totally unsuited for driving a propeller. For a start, the propeller shaft was right down at the bottom of the ship; second it was parallel to the keel, not at right angles and third, it needed to be rotated much faster. Brunel's engine had four double acting pistons inclined at 60° driving a crankshaft at deck level. This was linked to the propeller shaft by a 'silent chain' which increased the speed of rotation from 18 rpm to 54 rpm.

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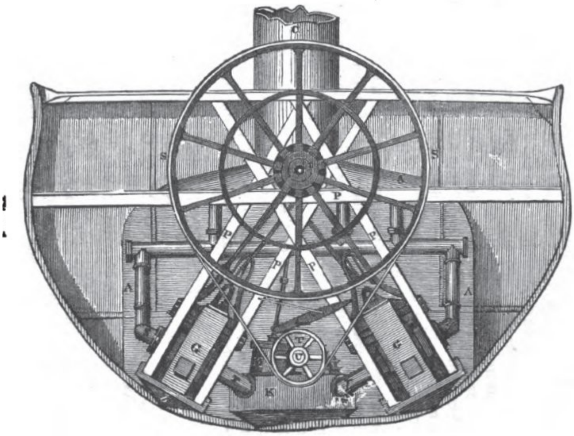
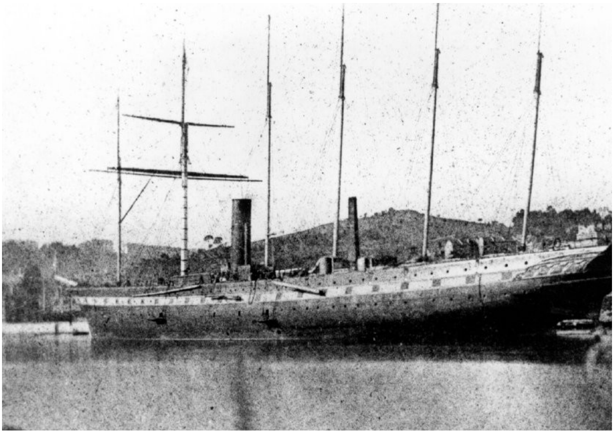
[11] The efficiency of the propeller was effectively demonstrated in 1845 when the paddle steamer *HMS Alecto* was unable to prevent propeller driven *HMS Rattler* towing her backwards at an ignominious speed of 2 knots.



SS Great Britain engine

Each piston had a diameter of 88 inches and a stroke of 72 inches and was supplied with steam at a pressure of around 5 psi giving a maximum power output of 800 hp.

The photograph below is possibly the first photograph ever to be taken of a ship and shows *SS Great Britain* in Bristol harbour being fitted out. She which was launched in 1843 and made her maiden voyage in 1845.



SS Great Britain (1844)

SS Great Britain had an eventful and not always glorious life eventually ending up in the Falkland Islands as a hulk but in 1970 she was brought back to Bristol, restored and is now one of the most important monuments to Victorian ingenuity and invention.

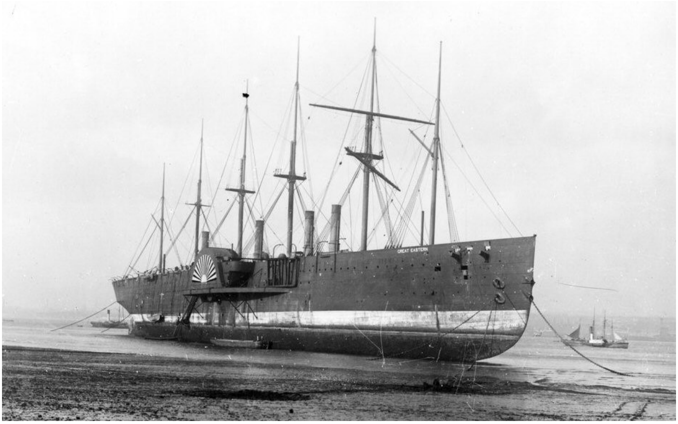
The SS Great Eastern

Undeterred by the difficulties he had faced with the launching and subsequent operation of the *SS Great Britain* Brunel went on to design and build a ship of quite staggering size, the *SS Great Eastern*. To get an idea of the quantum leap that the *SS Great Eastern* represented it is only necessary to glance at a few vital statistics:

	SS Great Western	SS Great Britain	SS Great Eastern
Launched	1837	1843	1858
Length	72 m	98 m	211 m
Beam	18 m	15 m	25 m
Displacement	2,300 tonnes	3,700 tonnes	32,000 tonnes
Passengers	150	360 - 700	4,000

In order to power this leviathan Brunel used both paddle wheels and screw propulsion, the latter providing most of the thrust, the former used in shallow water and for manoeuvrability. Her screw engines were arguably the largest steam engines ever built, the four 7 foot diameter pistons delivering 3000 hp. As far as I can tell, she only had one enormous propeller which was directly coupled to the engines and which therefore rotated at the same speed.

Like the *SS Great Britain*, the *SS Great Eastern* never got to do the job for which she was built – namely the transportation of large numbers of settlers to Australia. Instead she was used on the transatlantic route for which she was not ideally suited. She did, however, have a very important role to play in the laying of the first transatlantic cable (see page 192). She was scrapped in 1890.

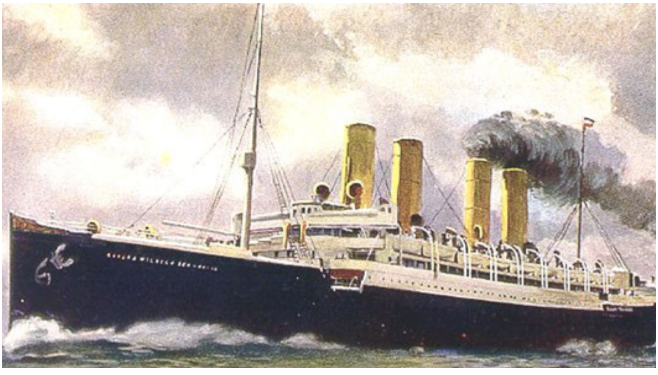


SS Great Eastern beached on the river Mersey

The age of the great Liners

The next three decades (1860-90) saw a gradual evolution in the size and design of ocean-going vessels both commercial and military but none of the many ships built during this period were anything like as big as the *Great Eastern*.

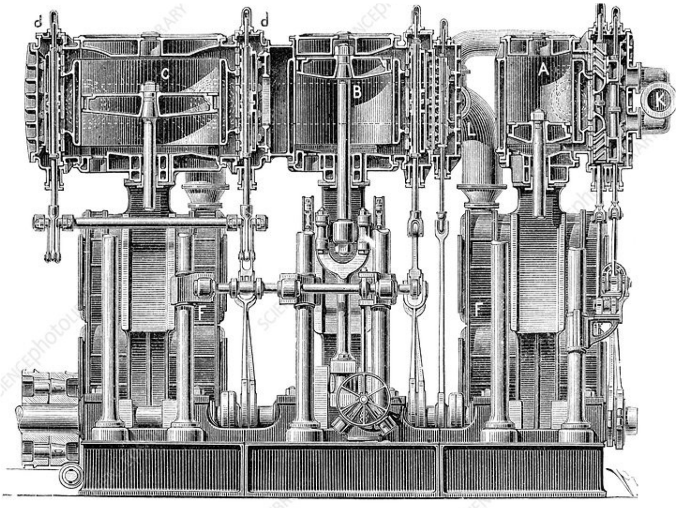
The first ship which could begin to compare in size was the *SS Kaiser Wilhelm der Grosse* whose maiden voyage from Bremmerhaven to New York took place in September 1897.



SS Kaiser Wilhelm der Grosse (1897)

With four funnels, no auxiliary sails and sumptuous on-board accommodation for over 1500 passengers she set the standard for the stream of super-liners which were to follow.

By this time, the standard method of propulsion would be a pair of vertical, inverted, direct acting, triple expansion marine engines driving two or more propellers.



Triple expansion marine engine

The German superiority in ship-building was only wrested back by Britain with the launch of the SS Lusitania in 1907. With a length of 240 m, beam 26.5 m and 44,000 tonnes displacement, she was the first ship to be larger in all respects than the *SS Great Eastern* and the first liner to be powered by steam turbines.

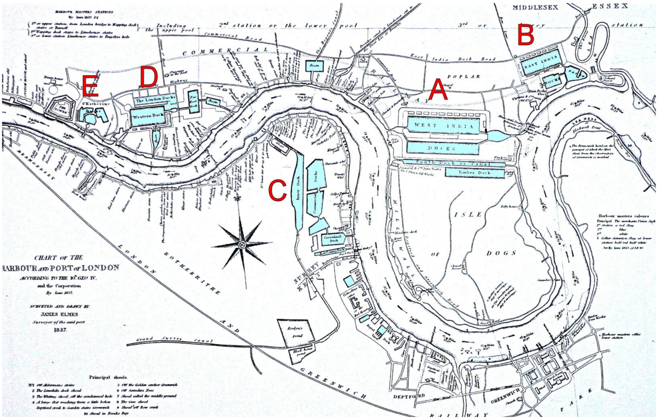
Mention has already been made of Charles Parsons' invention of the steam turbine in connection with the generation of electricity. That the turbine would also revolutionise marine engines was made abundantly clear when Parsons turned up at the Navy Review at Spithead on 26th June 1897 in a 100 foot launch powered by three turbines and nine propellers. Capable of a staggering 34 knots she ran rings round the navy vessels who tried to catch her. Within a decade, all large ships, particularly warships, were powered by steam turbines. Turbinia is preserved in the Discovery Museum in Newcastle.

Docks

London

In 1800 the Port of London was by far the busiest port in the world and hundreds of ships would be moored on both sides of the Thames from London Bridge down to Blackwall Reach. But the Thames is, of course, a tidal river and goods could only be discharged at certain states of the tide. What was needed was a wet dock – a body of water which was filled at high tide and enclosed by lock gates so that loading could take place at all times of the day or night.

Among these were the great West and East India docks, built in 1802 and 1803 respectively (A and B). By 1837, the date of the map shown below, numerous other docks had been built including the Surrey Docks (C), the London Docks (D) and the St Katherine Docks (E).



Docks in the Port of London (1837)

But the Port kept on growing and in 1855 the Victoria Docks were constructed a mile further downstream on an area of marsh land known as 'Lands End'. Even that was not enough and a second, even larger dock was constructed nearby called the Royal Albert Dock in 1880. It was considered to be the largest man-made enclosed body of water in the world and, together with the Victoria dock provided 11 *miles* of quayside.

Liverpool

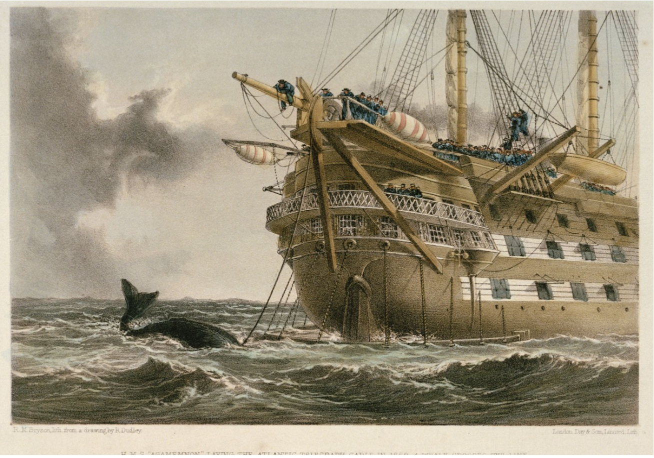
The traditional design of a dockside envisaged goods being unloaded from a ship into wagons which would be used to transport the goods to a more or less distant warehouse. The St Katherine Docks in London, built in 1828, were built to a different plan. Here the warehouses were placed directly on the quayside so that goods could be unloaded directly from ship to storage. The Royal Albert Docks in Liverpool, completed in 1846, implemented this idea on a huge scale. The warehouses too were highly innovative being constructed entirely of cast iron, brick and stone and therefore virtually fireproof. Like William Strutt's earlier Mill buildings, the stone floors were supported by cast iron columns and the interior brick walls were relieved of any structural function.

The most distinctive feature of the warehouses is the row of massive cast iron columns supporting the walls above the first floor. These buildings were built to last, and last they have.

Royal Albert Docks, Liverpool

Communications

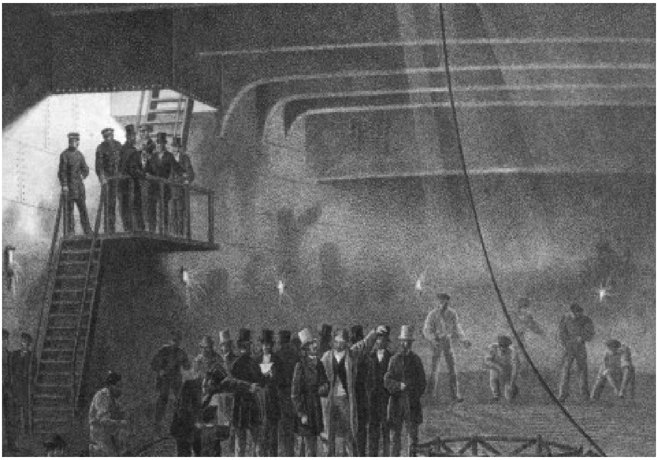
One of the greatest engineering achievements of the nineteenth century was the laying of the first transatlantic telegraph cable in 1858. This was the brainchild of an American financier Cyrus West Field. The first attempt in 1857 failed when the cable snapped 300 miles off the coast of Ireland. Further unsuccessful attempts were made in the spring and early summer of 1858. Success did however eventually come in August when the two ships the *HMS Agamemnon* and the *USS Niagara* who started the cable laying operation in mid Atlantic reached their home shores. Queen Victoria sent a message of congratulation to the US president James Buchanan on August 16th.



HMS Agamemnon laying the first cable (1858)

The euphoria was short-lived, however. Messages were sent by Morse code – essentially a series of DC pulses. It was soon found that when the pulses were received at the far end, they were greatly smoothed out and the maximum current was correspondingly small. It appeared that the only way to overcome this problem was a) to transmit the message very slowly (it took about 10 minutes to transmit a single word) and b) to use very high voltages at the transmitting end (up to 2000 V) so that the current detected at the other end would be measurable. The problem was that the high voltages used damaged the insulation and after three weeks the cable failed.

By the time finance was available for another try, three technical advances greatly increased the chances of success. Firstly the cable was much improved with better quality conductors, insulation, and armouring; secondly the cable laying equipment was redesigned so that, instead of relying on a human operator to regulate the tension in the cable, this was done automatically; and thirdly, William Thompson (later lord Kelvin) had invented a much more sensitive mirror galvanometer which enabled much lower voltages to be used. In addition, there was only one ship in the world big enough to carry the 4000 tonnes of cable needed, the *SS Great Eastern*, and her owners (who were losing money daily) were only too eager to see her put to some useful purpose.



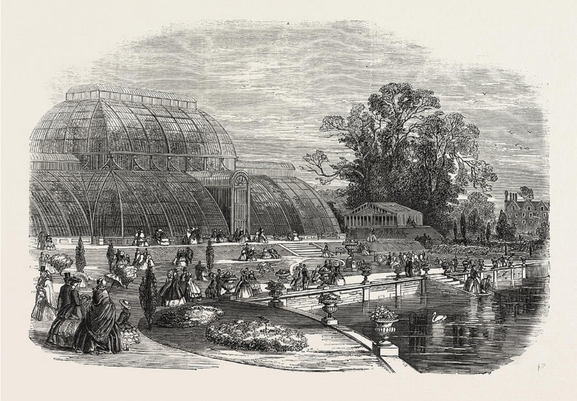
Loading the cable onto the Great Eastern (1866)

And so it was that in July 1866 the *Great Eastern* delivered the end of the cable to the Newfoundland shore and communication was re-established. Later that year a second cable which had previously been lost was recovered and also brought into use enabling two way communication at speeds up to 80 words a minute.

By the end of the century there were at least a dozen telegraph cables linking all the major cities of Europe to the States and indeed to the rest of the world.

Four Iconic Structures

The Palm House, Kew



The Palm House, Kew (1848)

The Palm House at Kew was the first building to be constructed of wrought iron and glass. It is 110 m long and 19 m high in the middle.

The Crystal Palace

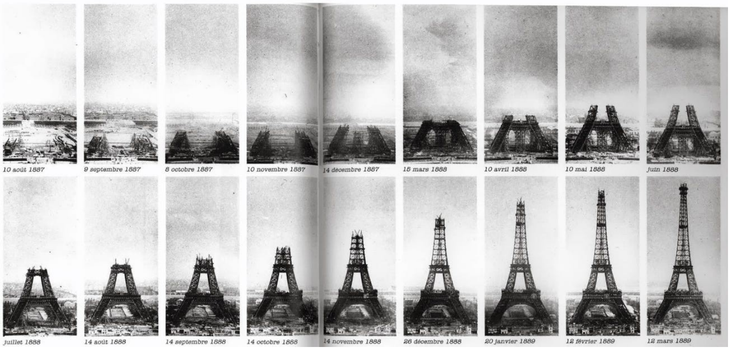
The Crystal Palace (1851)

Building on the experience he had gained constructing the glasshouses at Chatsworth, Joseph Paxton designed and built the Crystal Palace in under 11 months. It was 563 m long, 139 m wide and 41 m high at the crossing. After the Great Exhibition the building was dismantled and reconstructed on a new site in Sydenham and used for further exhibitions and events including in 1854 an exhibition of reconstructed dinosaurs some of which survive to this day. The palace burned down in 1936.

The Statue of Liberty

Designed by the French sculptor Auguste Bertholdi, this famous landmark was built on a wrought iron scaffold designed by Gustave Eiffel. It was built in France and shipped to the States in pieces where it was dedicated on 28th October 1886. The statue itself is 45 m high and she stands on a plinth of a similar height.

The Eiffel Tower



The Eiffel Tower (1889)

For the World's fair of 1889 the organisers wanted something special; what they got was controversy and abuse from the people of Paris who were appalled by what they saw rising from the Champs de Mar. However, by the time that Gustave Eiffel's 20 year contract for the commercial exploitation of the tower had run out, the tower was proving both profitable and useful in a number of ways, notably for scientific research and telecommunications – so it stayed.

Appendices

Preserved Locomotives in the UK

List taken from https://preservedbritishsteamlocomotives.com/

1814	Puffing Billy	William Hedley	NRM
1815	Wylam Dilly	Timothy Hackworth	RSM Edinbugh
1816	Killingworth Billy	Robert Stephenson	North Shields
1825	Locomotion No 1	George Stephenson	Darlington RC
1829	Agenoria	Foster Rastrick & Co	NRM[12]
1829	Novelty	Ericsson & Braithwaite	Manchester SM
1829	Sans Pareil	Timothy Hackworth	Shildon RM
1829	Rocket	Robert Stephenson	London SM
1830	Invicta	Robert Stephenson	Canterbury
1838	Lion	Todd, Kidson & Laird	Liverpool
1845	Columbine	Alexander Allen	London SM
1847	Cornwall	Frances Trevithick	Shildon RM
1845	Derwent	Timothy Hackworth	Darlington RC
1846	Furness R. No 3 (Coppernob)	Bury, Curtis & Kennedy	NRM
1857	0-4-0	George Stephenson	NRM
1863	Furness R. No 20	Unknown	Ribble Steam Rly
1865	4ft Shunter	John Ramsbottom	Ribble Steam Rly
1866	Class 156	Matthew Kirtley	Midland RC
1874	Class 1001	William Bouch	NRM
1885	Class E5	Tennant	Darlington HofS
1887	Precedent Class	Francis Webb	NRM

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[12] NRM = National Railway Museum in York

Preserved stationary steam engines in the UK

Compiled from various sources

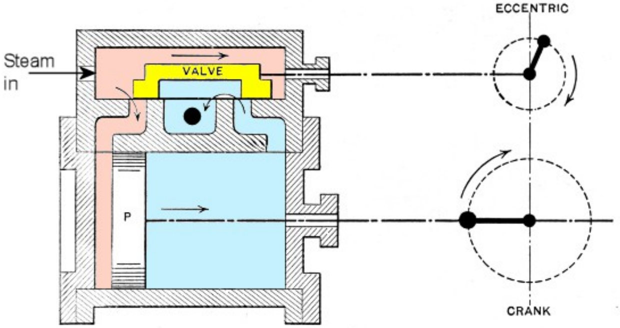
Abbey pumping station, Leicester	Page 162
Abbey Mills Pumping Station, London	Page 160
Armley Mills Industrial Museum, Leeds	
Astley Green Colliery, Greater Manchester	
Beamish, Co Durham	Page 35
Blagdon Pumping Station, Somerset	
Blists Hill Open Air Museum, Shropshire	Page 167
Black Country Living Museum, Dudley	
Bradford Industrial Museum, Bradford	
Calderdale Industrial Museum, Halifax	
Calvert's Engine, University of Glamorgan, S Wales	
Cambridge Museum of Technology, Cambridge	Page 162
Claymills Pumping Station, Burton upon Trent	Page 162
Coldhabour Mill. Devon	
Coleham Pumping Station, Shrewsbury	Page 162
Crofton Pumping Station	Page 12
Crossness Pumping Station	Page 160
Devon Colliery, Alloa, Clackmannanshire	
Discovery Museum, Newcastle-upon-Tyne	Page 188
Dogdyke pumping station, Lincolnshire	
Dorothea Quarry beam engine, Caernavon, N Wales	
East Pool Mine, Cornwall	
Eastney beam engine, Portsmouth	
Ellenroad Steam Museum, Greater Manchester	
Elliot Colliery, New Tredegar, S Wales	
Etruria Industrial Museum, Stoke-on-Trent	
Garlogie Mill Powerhouse Museum, Aberdeenshire	
Kelham Island Industrial Museum, Sheffield	
Kew Bridge Steam Museum	Page 152
Kidwelly Industrial Museum, Swansea (currently closed)	
Leawood Pump House, Cromford	Page 12
Levant Mine and Beam Engine, Cornwall	
Markfield pumping station, Haringay, London	Page 161

Middleton Top Engine House, Cromford	
National Museum of Scotland, Edinburgh	
National Coal Mining Museum, Wakefield	
Newcomen Memorial Engine, Dartmouth	
Papplewick Pumping Station, Nottingham	Page 156
Pinchbeck Engine, Lincolnshire	
Poldark Mine, Cornwall	
Prestongrange Industrial Heritage Museum, Prestonpans	
Queen Street Mill, Burnley	
Ryhope Pumping Station, Sunderland	Page 157
Stretham Old Engine, Cambridgeshire	Page 163
Science Museum, London	
Tees Cottage Pumping Station, Darlington	
Tower Bridge, London	Page 150
Trencherfield Mill, Wigan	
Thinktank, Birmingham	
Verdant Works, Dundee	
Wanlockhead Beam Engine, Dumfries and Galloway	
Westonzoyland Pumping Station, Somerset	Page 164
Wetheriggs Pottery, Clifton, Cumbria	

Other places to see 19th century engineering

Aberdeen Maritime Museum, Aberdeen
Amberley Museum, Arundel, W Sussex
Bristol Industrial Museum
Chatham Historic Dockyard
Dean Heritage Centre, Forest of Dean
HMS Warrior, Portsmouth Historic Dockyard
Hollycombe Steam, Liphook, Hampshire
National Mining Museum of Scotland, Newtongrange, Mid Lothian
National Waterways Museum, Ellesmere Port
New Lanark Mills, Lanarkshire
Peak District Mining Museum, Matlock Bath
Quarry Bank Mill, Cheshire
Scottish Maritime Museum, Dumbarton
Scottish Maritime Museum, Irvine, Ayrshire
SS Great Britain, Bristol
Summerlee museum, N Lanarkshire
Swansea Maritime and Industrial Museum
Thursford Steam Engine Collection, Norfolk
Waverley Paddle Steamer

'Lap' and 'Lead'



Slide valve with 'lap'

Comparing the above diagram with that on page 61 we can see that the yellow slide valve has been enlarged slightly and in order to compensate for this, the eccentric has been advanced beyond the 90° position. Normally, the amplitude of the eccentric would be such that the valve ports would be completely open only at the end of the travel (i.e. the eccentric equals the width of the port). If the size of the 'lap' (usually quoted in inches) was such that it was equal to half the width of the port, then the extra advance needed would be 30° (because sin 30° = 0.5). Under these circumstances, steam would be admitted to the piston for 75% of its travel and then the entry valve would close. The steam would continue to expand doing useful work until the exhaust port would open just before reaching TDC at the other end. (This would happen after 92.5% of its travel)

Often the eccentric was moved even further forward so that steam was admitted slightly *before* the piston reached TDC. This allowed a bit more time for the pressure to build up in the piston before the power stroke. This is known as 'lead' and although it is often quoted in inches too (so that it can be added to the 'lap') it is better to quote both of these in terms of degrees. The total advance angle required is therefore 90° + 'lap' + 'lead'.

Calculating the power output of a beam engine

The symbols used have the following meanings

d = diameter of the piston (in inches or cm)
s = stroke of the piston (in inches or cm)
P = maximum steam pressure (in psi or bar)
N = number of strokes per minute

In the case of an atmospheric engine (such as those of Boulton and Watt) it may be assumed that the working pressure is 1 atmosphere (1 bar) or 14 psi.

In all cases, the figure calculated can be regarded as the maximum theoretically possible. In practice, most of these figures would have been greatly reduced.

Using Imperial units

$$\text{Force on the piston F} = \frac{d^2 \times P}{2{,}850} \text{ tons wt}$$

$$\text{Power } Q = \frac{d^2 \times s \times P \times N}{500{,}000} \text{ hp}$$

Using metric units

$$\text{Force on the piston } F = \frac{d^2 \times P}{130} \text{ kN}$$

$$\text{Power } Q = \frac{d^2 \times s \times P \times N}{800{,}000} \text{ kW}$$

Calculating the force and power output of a steam locomotive

The symbols used have the following meanings

d = diameter of the piston (in inches or cm)
s = stroke of the piston (in inches or cm)
n = number of double acting pistons
P = maximum steam pressure (in psi or bar)
D = diameter of driving wheels (in inches or cm)
V = maximum speed of locomotive (in mph or kph)

Note that atmospheric pressure is approximately 14 psi or 1 bar, 1 ton wt is approximately equal to 10 kN and 1 HP is about 0.75 kW.

The power output is calculated by assuming that maximum power will be produced when the speed is about one third of the maximum speed.

In all cases, the figure calculated can be regarded as the maximum theoretically possible. In practice, most of these figures would have been greatly reduced.

Using Imperial units

$$\text{Tractive force } F = \frac{d^2 \times s \times P}{2{,}850 \times D} \text{ tons wt}$$

$$\text{Power } Q = \frac{d^2 \times s \times P \times n \times V}{2{,}400 \times D} \text{ HP}$$

Using metric units

$$\text{Tractive force } F = \frac{d^2 \times s \times P}{130 \times D} \text{ kN}$$

$$\text{Power } Q = \frac{d^2 \times s \times P \times n \times V}{2{,}200 \times D} \text{ kW}$$

Vital statistics of selected engines

Name	*Date*	*d* in cm	*s* in cm	*n*	*P* psi bar	*D* in cm	*V* mph kph	*F* Twt kN	*Q* HP kW
Pen-y-Darren	1804	4¾ 12	36 91	1 1	40 2.8	33 84	12	0.3 3.4	5 4
Rocket	1829	8 20	17 43	2 2	50 3.6	56 140	12 19	O.35 3.5	10 8
North Star	1839	16 41	16 41	2 2	50 3.6	84 210	30 48	0.91 9.3	60 50
Coppernob	1846	14 36	24 61	2 2	110 7.9	57 145	40 64	3.2 34	300 250
Iron Duke class	1850's	18 46	24 61	2 2	140 10	96 244	60 96	4 42	550 470
Kirtley 156 class	1866	18 46	24 61	2 2	140 10	75 190	60 96	5 53	730 600
Stirling single	1870	18 46	28 71	2 2	140 10	97 246	60 96	4.6 48	650 540
Johnson spinner	1896	19 48	26 66	2 2	170 12	93 240	60 96	6 61	870 690
Jone's Goods	1894	20 51	26 66	2 2	175 12.5	63 160	40 64	10 106	975 790

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1860	Beattie	Well Tank	73
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1870	Stirling	Single	75
1874	Webb	Hardwicke	76
1880	Adams	Precursor class	77
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