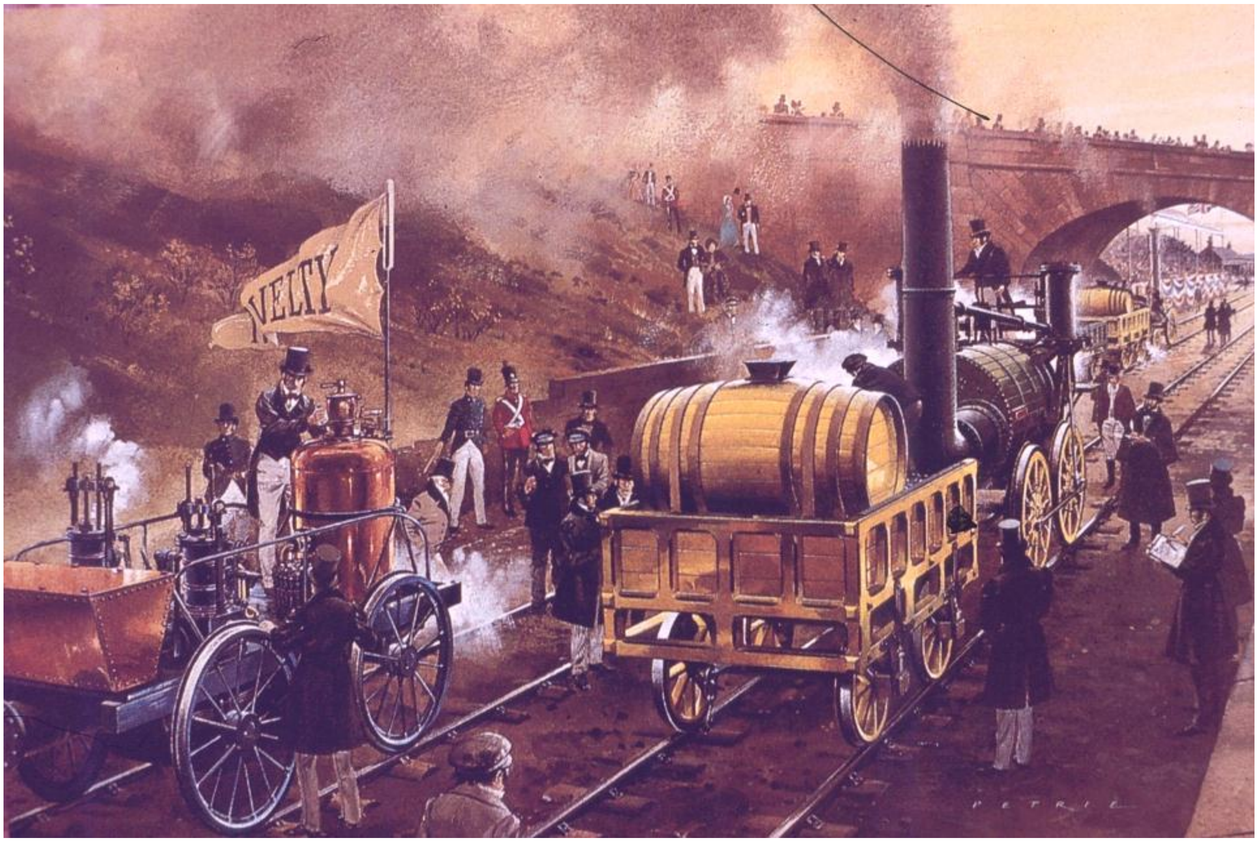
THE RAINHILL TRIALS ON THE LIVERPOOL AND MANCHESTER RAILWAY



AN INTERNATIONAL CIVIL AND MECHANICAL ENGINEERING LANDMARK

INSTITUTION OF CIVIL ENGINEERS

AMERICAN SOCIETY OF CIVIL ENGINEERS 1852

RAINHILL, ENGLAND
14 SEPTEMBER 2016

Institution of MECHANICAL ENGINEERS

ASME SETTING THE STANDARD

INTERNATIONAL HISTORIC
CIVIL AND MECHANICAL ENGINEERING LANDMARK

LIVERPOOL AND MANCHESTER RAILWAY

OPENED ON 15 SEPTEMBER 1830, THIS RAILWAY PROVED TO BE ONE OF THE MOST SIGNIFICANT DEVELOPMENTS IN TRANSPORTATION HISTORY. IT WAS THE FIRST PUBLIC RAILWAY FOR THE SCHEDULED TRANSPORTATION OF PASSENGERS AND FREIGHT BETWEEN REMOTE CITIES. A TEAM LED BY GEORGE STEPHENSON (1781-1848) DESIGNED THE 35-MILE, DOUBLE-TRACKED LINE, OVERCOMING NUMEROUS ENGINEERING CHALLENGES, INCLUDING OLIVE MOUNT, THE SANKEY VALLEY AND CHAT MOSS. THE RAILWAY ESTABLISHED THE HISTORIC REPUTATIONS OF MANY ENGINEERS ASSIGNED TO ITS VARIOUS SECTIONS.

THE FIRST EVER LOCOMOTIVE TRIALS AT RAINHILL DURING 6-14 OCTOBER 1829 PITTED THE HORSE TREADMILL ***CYCLOPED*** AGAINST FOUR STEAM LOCOMOTIVES, ***NOVELTY, PERSEVERANCE, ROCKET*** AND ***SANS PAREIL. ROCKET***, DESIGNED AND BUILT BY ROBERT STEPHENSON (1803-1859), OUTPERFORMED THE OTHERS AND PROVED THAT LOCOMOTIVE PROPULSION WAS PRACTICAL. STILL OPERATING ON ITS ORIGINAL ALIGNMENT WITH MANY ORIGINAL STRUCTURES, THIS RAILWAY ESTABLISHED THE BASIC FORMAT FOR ALMOST ALL SUBSEQUENT RAILWAYS AND ROLLING STOCK WORLD-WIDE.

INSTITUTION OF CIVIL ENGINEERS

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DEDICATED ON 14 SEPTEMBER 2016

AMERICAN SOCIETY OF MECHANICAL ENGINEERS

Forward

The Liverpool and Manchester Railway (L&MR), the world's first inter-city railroad designed and built between its namesake cities for the efficient, commercial transportation of passengers and freight, was designated an International Civil and Mechanical Engineering Landmark by the Institution of Civil Engineers, the Institution of Mechanical Engineers, the American Society of Civil Engineers, and the American Society of Mechanical Engineers on 14 September 2016. While this was a joint designation, only ASME's History and Heritage Program requires a written document describing a landmark's features and significance. Accordingly, this brochure will focus on the mechanical engineering aspects of the railway, with the most significant aspect being the locomotive trials held at Rainhill during October 1829. The Rainhill Trials are one of the earliest known examples of an engineered program to evaluate competing machines in a real-world environment.

All aspects of the Liverpool and Manchester contribute to its significance as an engineering landmark, including the company's early decision to use only steam power to move trains. Any railway is an intimate combination of both civil and mechanical engineering, as neither the track nor the train would be of any use without the other. Significantly, this railway remains in active service. The rolling stock has changed many times since the line opened, and the modern trains are much heavier and faster than the line's builders could have imagined, but the modern trackage is still supported by the original roadbed and most of the original bridges.

It must be regarded ... as opening the epoch of railways which has revolutionised the social and commercial intercourse of the civilized world.

—John B. Jervis

Industrial Britain before the railway

The growth of Manchester, England, during the Industrial Revolution of the late 18th and early 19th centuries, largely due to the rapid expansion of its textile production, led to a serious transportation problem. Located some 35 miles (56 km) inland to take advantage of waterpower in the hilly Lancashire Region, the growing city found itself uncomfortably distant from the closest port facilities, which were in and around Liverpool on the River Mersey to the west. As Manchester's cotton mills expanded, efficient, economical access to Liverpool's port was increasingly essential to receive imported cotton and to export finished cloth, along with other goods. The Lancanshire Region also possessed considerable coal reserves, and the transportation problem affected it as well. Moving the coal from mine to market was slow and expensive.

For centuries the wind or animals had furnished power for transportation, with wind power primarily used for seagoing ships. Away from the coast, boats moved by animals or sails conveyed freight and passengers through natural or man-made waterways wherever practical. Competing interests improved channels in rivers and dug numerous canals across the country to handle the growing volume of traffic. These companies required charters from Parliament, and investors often tried to obtain charters that prevented the establishment of competing companies. Manchester, with its growing industry and need for access to Liverpool, was a primary target for canal companies.

The Mersey and Irwell Navigation Co. built eight locks and several channels in the rivers that connect Manchester to the Mersey Estuary at Warrington, about 15 miles (24 km) from Liverpool. It opened in 1734, but often suffered from insufficient water for navigation.

In 1759, Parliament granted Francis Egerton, 3rd Duke of Bridgewater, who owned significant coal reserves under Worsley (northwest of Manchester), permission to build and operate a canal from Worsley to Manchester. This opened in 1761, and the Duke extended it to Runcorn, on the River Mersey southeast of Liverpool, in 1776. The Bridgewater Canal drastically reduced the cost of the Duke's coal in Manchester, and its extension to near Liverpool furnished dependable transportation that allowed the city's industries to flourish.

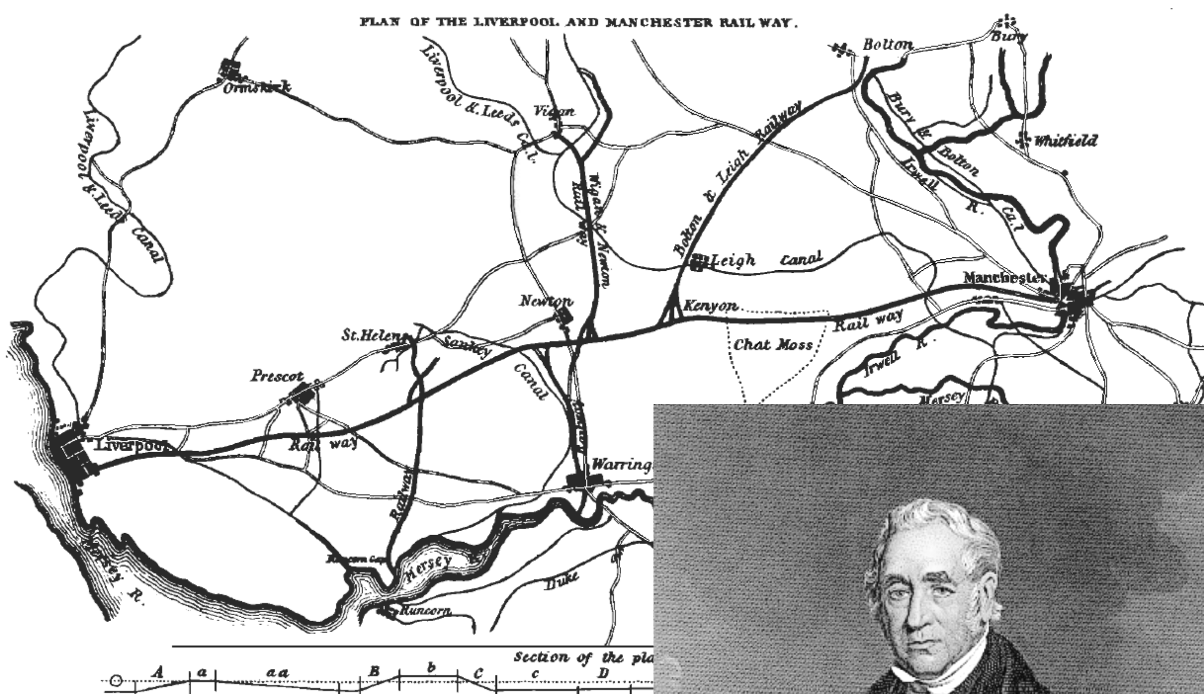
With a virtual monopoly of transportation between the two cities, the canal earned its investors handsome profits that soon had Manchester businessmen suspecting those profits might be excessive. Traffic on the canal had increased to the point that transit times had become longer as well. Three men, a Liverpool corn merchant named Joseph Sandars; John Kennedy, owner of the largest spinning mill in Manchester; and a land speculator and sometime surveyor named William James, decided that a railway might well furnish effective competition to the canal. James even envisioned a network of railways throughout England, although the technology, introduced in a few collieries, was still new, and no one yet had a realistic idea of how an inter-city railway should be built and operated.

Sandars, Kennedy, and James persuaded another Liverpool corn merchant, Henry Booth, who also had some engineering experience, to join the enterprise, along with his father. These men, supported by other

Manchester and Liverpool merchants, formed the Liverpool and Manchester Railway (L&MR) on 24 May 1823, and elected Booth to lead the company as secretary and treasurer. They—primarily Booth—began preparing a bill for Parliament to authorize construction, and William James started to make a preliminary survey for the line. When presented with the bill in 1825, Parliament initially rejected it due to a faulty survey. The body ultimately passed the bill—with a correct survey—in May 1826. The world's first common carrier railway was born. In the initial subscription, 308 shareholders purchased 4,233 shares of the company's stock.

Designing and building the railway

By 1826, hand- and animal-powered wagons on plank tracks had been employed in European mines for some two centuries, and a few rudimentary railways were operating at English collieries to carry coal from mine heads to docks or local users using animals, early steam locomotives, or rope systems with stationary steam engines in various combinations. Each was unique, and they worked with varying degrees of effectiveness, but there were no uniform ideas about such things as gauge, whether the wheels or the rails should be flanged, how severe curves and grades could be, or the best means of propulsion over long distances. For those building the Liverpool and Manchester, finding answers to these questions was an important preliminary to the detailed design of the track and rolling stock.



*On this map from the mid-1830s, the L&MR is the heavy line between the two cities. Note that additional railways had already been built that connected to it. The section drawing shows how George Stephenson designed it to be as level as possible. The portion labeled **b on the profile portion of the map above** is the Rainhill Level, where the locomotive trials were held.*

As the design and construction of roadbed, bridges, cuts, embankments, tunnels, and track progressed during 1826-29, several impressive structures took shape and became prototypes for subsequent ones around the world over the next century. To minimize grades and curvature, a two-mile (3.2-km) marle-and-rock cut up to 70 feet (21.3 m) deep was required through Olive Mount east of Liverpool, and two multi-arch viaducts spanned the Sankey and Newton valleys. They measured 600 feet (182.8 m) long by 70 feet (21.3 m) high and 144 feet (43.9 m) long by 40 feet (12.2 m) high respectively, and both were approached over substantial embankments. Sixty-two additional masonry bridges—many quite impressive in their own right—conveyed roads across the railway or the railway over streams, and a cast-iron beam bridge across Water Street gave the railway access to its Manchester terminal. Equally impressive were Wapping Tunnel, a 6,750-foot (2,057-m) bore under the city of Liverpool, the first large tunnel dug under a metropolis, and a 4.75-mile (7.6-km) crossing of a soft peat bog known as Chat Moss. The entire railway was double-tracked. The original track consisted of 15-foot (4.6 m) cast-iron rails laid on stone blocks, except for the Chat Moss portion that used wooden sleepers.

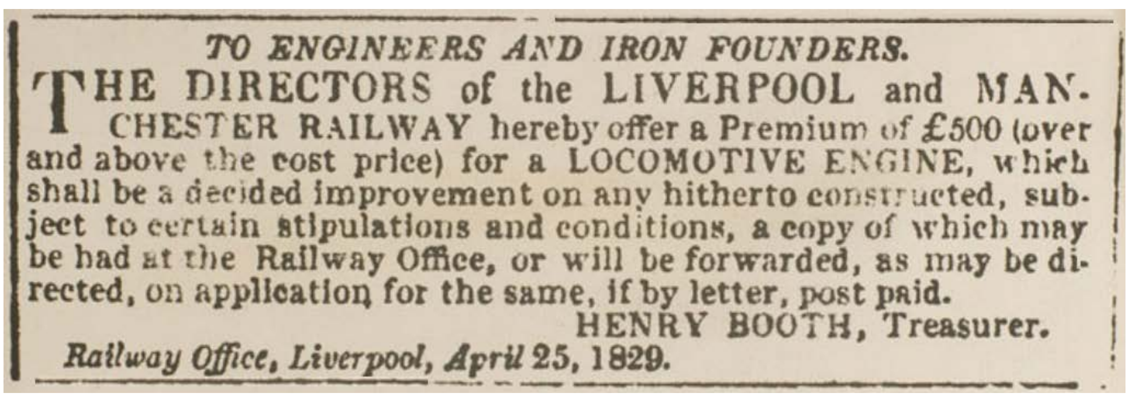
The Power Problem

While construction of the line progressed well, one nagging question remained unanswered. Early in the process, the railroad's directors decided to utilize steam power rather than animals, but the L&M's engineers continued to debate the merits and demerits of fixed steam engines with rope funicular systems to pull the cars versus steam "loco-motives," as company engineer George Stephenson first called them, that moved on the same track as the cars they pulled, with neither side demonstrating any particular advantage. The big unknown was whether a locomotive that depended solely on adhesion—the static friction between a smooth iron wheel and a smooth iron rail—could pull a useful train, even on level track, much less climb any grade.

The limitation of steel-on-steel traction was being investigated at this time by Isambard Kingdom Brunel, who began in 1840 to experiment with a fanciful system using evacuated tubes and vacuum pumps. The "Atmospheric Railway" was actually to carry passengers for a brief period beginning in 1843. The idea ultimately proved impractical and was added to Brunel's short list of spectacular failures.
The company's directors assigned James Walker and J.U. Rastrick, both practicing engineers, to undertake a study of existing operations using both locomotives and fixed winding engines. After evaluating the advantages, disadvantages, and costs, they presented their report to the directors on 9 March 1829. The men concluded that neither had a significant financial advantage. However, the two engineers, still unsure of adhesion's effectiveness, concluded that fixed winding engines spaced along the line would be preferable.

Stephenson had maintained all along that he strongly preferred locomotives over fixed engines, and he was not swayed by Walker and Rastrick's report. The latter, he argued, would be cumbersome to use, slow, and prone to problems with their long ropes. They would also present problems with maintaining each train's steady pace over the railway. Worst of all, a breakdown of any one of these engines would paralyze the entire railway. In contrast, Stephenson noted that locomotives would eliminate the starting and stopping needed to switch ropes between winding engines and offer more operating flexibility as traffic grew. Fixed engines would have a maximum capacity that could not be easily increased, but new locomotives could easily be added as needed, and improvements would likely render newer, more powerful designs within a few years. In addition, he believed that safety would be enhanced by having an operator in direct control of each train, instead of relying on communication between the train and a remote operator of the fixed engine. Finally, should any single locomotive fail, another one could take its place, and the railway would continue to operate while the first locomotive was being repaired at a shop.

After more than a year of debate over motive power for the L&MR, the directors were no closer to a decision than when the subject was first raised. But construction of the railway continued at a pace pointing to completion by the end of 1830, and they were running out of time to make a critical choice. One of the directors, R. Harrison, had previously proposed the idea of holding a competition with a reward to stimulate innovation. Locomotives designed and built by anyone who wished to enter would be subjected to an "ordeal," as it was first termed, to determine the best design for the L&MR. The ordeal would not be a race, *per* se, but rather a test of each locomotive under controlled conditions doing work as close as possible to what it would do in actual service. With no resolution in sight, the other directors finally warmed to the idea, and on 25 April 1829, the following announcement appeared in the *Manchester Mercury*:



TO ENGINEERS AND IRON FOUNDERS.

THE DIRECTORS of the LIVERPOOL and MANCHESTER RAILWAY hereby offer a Premium of £500 (over and above the cost price) for a LOCOMOTIVE ENGINE, which shall be a decided improvement on any hitherto constructed, subject to certain stipulations and conditions, a copy of which may be had at the Railway Office, or will be forwarded, as may be directed, on application for the same, if by letter, post paid.

HENRY BOOTH, Treasurer.

Railway Office, Liverpool, April 25, 1829.

The engineers realized that without direction the entrants would likely vary considerably in size and power, making selection a difficult task. Thus they developed test criteria that allowed variations in a manner that did not favor or penalize any particular design. The Stipulations and Conditions, shown below, clearly described how the tests would be conducted, the criteria to be measured, physical constraints such as gauge and maximum weight, material the company would furnish, and the nature of the winner's reward.

"*Railway Office, Liverpool, 25th April*, 1829.

"STIPULATIONS AND CONDITIONS

"*On which the Directors of the Liverpool and Manchester Railway offer a premium of £500. for the most improved Locomotive Engine.*

"1st.—The said Engine must "effectually consume its own smoke," according to the provisions of the Railway Act, 7th Geo. IV.

"2nd.—The Engine, if it weighs six tons, must be capable of drawing after it, day by day, on a well-constructed Railway, on a level plane, a train of Carriages of the gross weight of twenty tons, including the Tender and Water Tank, at the rate of ten miles per hour, with a pressure of steam in the boiler not exceeding 50 ℔. on the square inch.

"3rd.—There must be two Safety Valves, one of which must be completely out of the reach or control of the Engine-man, and neither of which must be fastened down while the Engine is working.

"4th.—The Engine and Boiler must be supported on springs, and rest on six wheels; and the height, from the ground to the top of the chimney, must not exceed fifteen feet.

"5th.—The weight of the Machine, *with its complement of water* in the boiler, must, at most, not exceed weight of the Engine, &c. do not exceed *five tons*, then the gross weight to be drawn need not exceed fifteen tons; and in that proportion for Machines of still smaller weight—provided that the Engine, &c. shall still be on six wheels, unless the weight (as above) be reduced to four tons and a half, or under, in which case the boiler, &c. may be placed on four wheels. And the Company shall be at liberty to put the boiler, fire tube, cylinders, &c. to the test of a pressure of water not exceeding 150℔. per square inch, without being answerable for any damage the Machine may receive in consequence.

"6th—There must be a mercurial guage affixed to the Machine, with index rod, showing the steam pressure above 45℔. per square inch; and constructed to blow out a pressure of 60 ℔. per inch.

"7th.—The Engine to be delivered complete for trial, at the Liverpool end of the Railway, not later than the 1st of October next.

"8th.—The price of the Engine, which may be accepted, not to exceed £550., delivered on the Railway; and any Engine not approved, to be taken back by the owner.

"N. B. The Railway Company will provide the *Engine Tender*, with a supply of water and fuel, for the experiment. The distance within the rails is four feet eight inches and a half."

Between April and October, potential contenders raised some questions that this announcement had not anticipated, and L&M officials amended the criteria as necessary to deal with the new considerations. Refinements included:

- A more useful definition of the "proportionate weight" each entrant was to pull.
- A provision for locomotives that did not require a tender for fuel and water.
- More specific information on the trial protocol, particularly details about the portion of track to be used in the trials and how each locomotive and train was to be operated to simulate a complete round trip over the entire railway.

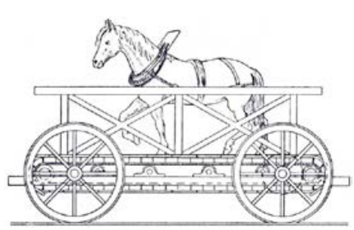
This was a new way to evaluate competing designs of machinery, and it is the earliest known example of measured, head-to-head performance trials in a real-world environment being used to select the best of multiple options. Such evaluation programs are now common practice, notably in the procurement of military equipment, but the concept was truly innovative in the early days of the Industrial Revolution. While simple and basic by current standards, these specifications were well thought out and quite comprehensive given the limited knowledge and experience in the field at the time.

Some of the criteria presage topics that are often thought to be of only recent concern. Of particular interest is the requirement that each locomotive "effectually consume its own smoke." Parliament evidently was concerned about air pollution even then. Equally interesting is the company's concern over safety, seen in the requirement for *two* safety valves on each boiler. The stipulation that one of them had to be beyond the operator's reach says much about engineers' early recognition of human factors in machinery design, as well as their understanding that endeavors such as steam power and transportation involved safety risks that had to be managed, even if the people using such machines did not fully understand or appreciate those risks. The company also set a conservative limit on the maximum allowable steam pressure, fifty pounds per square inch (3.45 bar), and it reserved the right to perform hydrostatic tests on the boilers at three times the working pressure. The work of an earlier British engineer, Richard Trevithick (1771-1833), clearly influenced these stipulations. He had already built boilers and engines using pressures of more than twice that, and he also pioneered the use of dual safety valves, fusible plugs, and mercury manometers to measure boiler pressure. In specifying a modest maximum pressure, it seems that the L&MR's directors and engineers must have realized the importance of their undertaking and the natural apprehension on the part of people who would be exposed to any of the inherent risks as bystanders or passengers. These provisions to enhance safety, along with a number of other features designed into the railway and its operating regimen, are early evidences of the importance engineers have placed, and still place, on safety.

The trials would actually settle two questions. In the event that no participating locomotive could meet the performance requirements, the question of locomotives versus fixed winding engines would be answered in favor of the latter, and their design and installation could begin immediately. On the other hand, if, as Stephenson expected, one or more of the locomotives met or exceeded the specified requirements, the way would be clear to adopt that technology with confidence, and the railway would be equipped to support their operation. At the same time, the best of several locomotive designs would be apparent as well, giving the directors additional confidence that they had the best available technology.

The "Ordeal" at Rainhill

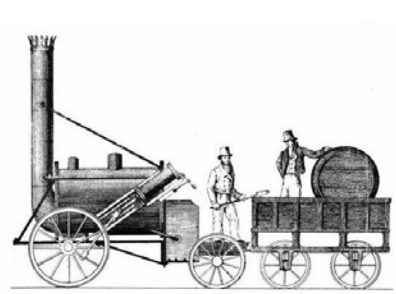
The L&MR's announcement generated considerable interest throughout the industrial areas of England. As many as ten individuals or partnerships indicated interest within the first two months, but on 6 October 1829, the first day of the tests, builders brought five machines to Rainhill for evaluation:



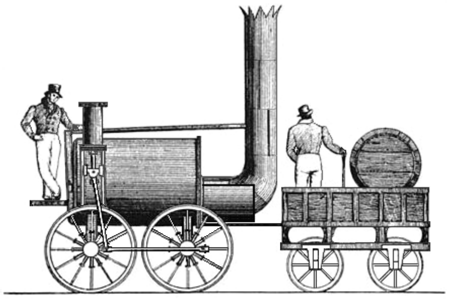
Cycloped, built by Thomas Brandreth of Liverpool, was entered as a "legacy technology." The sole non-steam entrant, the four-wheel vehicle employed two horses walking on a treadmill. *Cycloped* did not satisfy the requirement for a steam-powered machine, and it was not expected to meet the performance specifications, but it was allowed to enter as a courtesy to Brandreth, one of the company's directors.

Novelty, built by John Ericsson and John Braithwaite of London, had the most innovative boiler of the entrants, and it quickly garnered the most popular support. *Novelty* featured a vertical, forced-draft firebox with a horizontal fire-tube boiler and two vertical cylinders. It rode on four wheels, two of which were powered. *Novelty* carried its fuel and water on the locomotive.

Perseverance, built by Timothy Burstall of Edinburgh, had a vertical boiler and two vertical cylinders. Like *Novelty*, it rode on two powered and two non-powered wheels, and it carried its fuel and water on the locomotive.



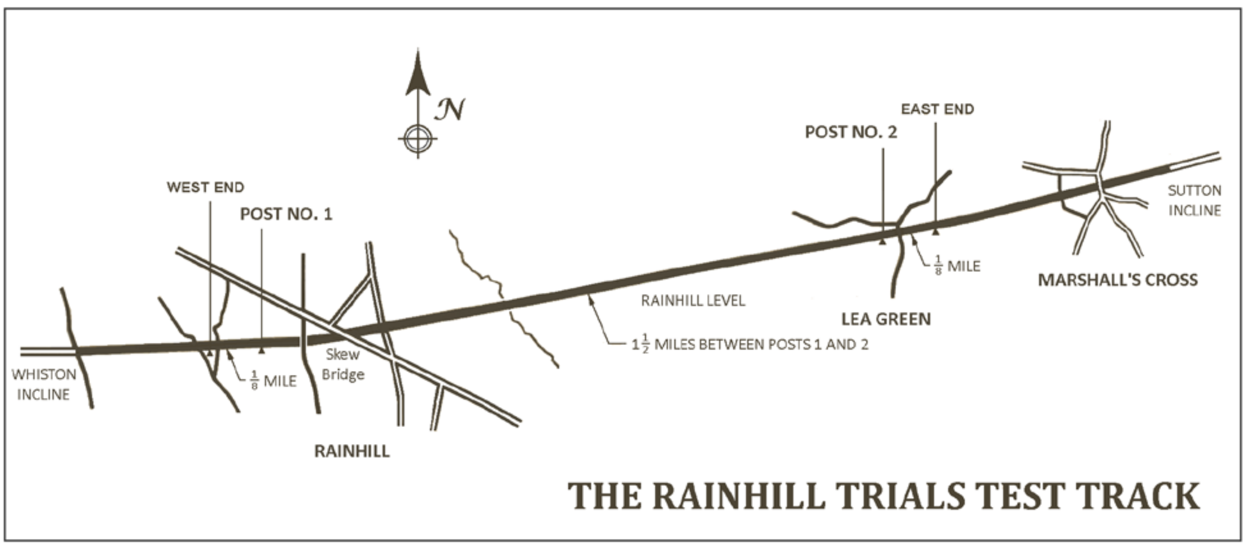
Rocket, built by Robert Stephenson (George's son) of Newcastle, was built around a horizontal, multi-fire-tube boiler whose design had been suggested by L&MR Treasurer Henry Booth. Unlike the other entrants, *Rocket* used two inclined cylinders that acted directly on its two drive wheels. A second, smaller pair of wheels supported its



firebox and operator platform. *Rocket* carried its fuel and water in a railway-supplied tender.

Sans Pareil, built by Timothy Hackworth of Shildon, resembled locomotives that Hackworth previously had built for the Stockton and Darlington Railway (a colliery railway). It featured a large, horizontal, fire-tube boiler and two vertical cylinders driving four wheels. *Sans Pareil* was overweight, but the judges allowed it to compete. It used a railway-supplied tender to carry its fuel and water.

While these builders worked on their locomotives, the company made arrangements to host, conduct, and evaluate the trial program. The directors and engineers had determined that the best location for the ordeal was a level stretch of the railway, known as the Rainhill Leel, almost two miles (3.2 km) in length south of St. Helens. Allowing one-eighth mile (0.2 km) at each end for starting and stopping the train, each locomotive could run at full speed for 1½ mile (2.4 km) between markers. Ten trips, five of them pushing the train in reverse, would approximate the 35-mile (56-km) railway. After refueling, ten additional trips would complete a round trip.



To ensure impartiality, he directors asked three notable individuals not associated with the company to judge the ordeal. John Rastrick was a locomotive engineer from Stourbridge, and Nicholas Wood was a mining engineer with locomotive experience from Killingsworth. John Kennedy, a Manchester cotton spinner and proponent of the railway, completed the panel of judges.

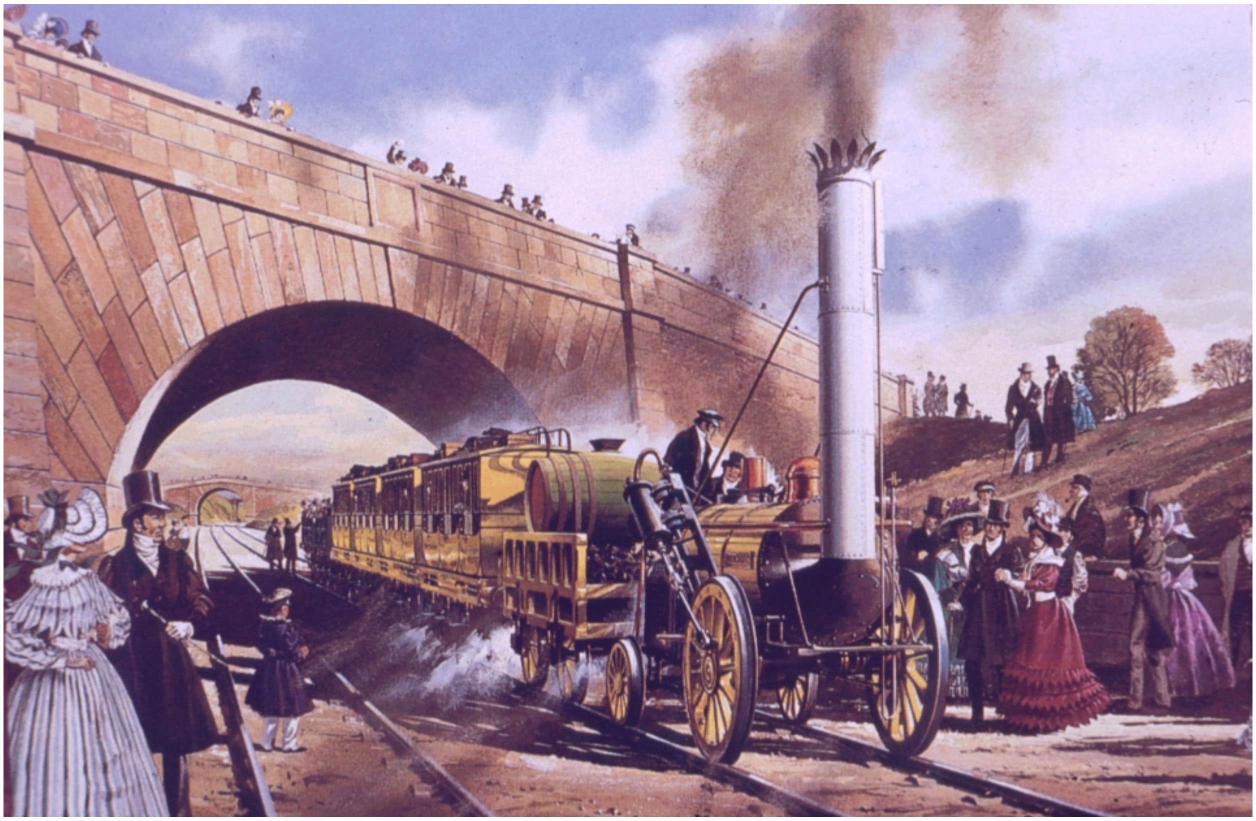
Interest in the trials was immense, including not only engineers and builders, but also the general public. It soon became evident that the trials would be an event attended by hundreds, if not thousands, of spectators, so the company ordered a large tent to provide some shelter for the ladies. An estimated 10,000 to 15,000 people witnessed at least some portion of the trials.

The ordeal was scheduled to start on Tuesday, 6 October 1829. It would begin with some preliminary demonstration runs to show each locomotive's general capabilities, then continue over the next several days with the measured runs. The judges anticipated that two—perhaps three—locomotives could be tested per day, an estimate that proved overly optimistic. To minimize smoke generation, the company supplied clean-burning coke to all of the steam contestants.

Several thousand spectators were on hand for the start of the ordeal. Stephenson's *Rocket* was the first to perform, and it pulled its 12¾-ton train a total of 12 miles (19.2 km) at an average speed of 13½ miles per hour (21.6 kph) to suitably impress the crowd. Ericsson and Braithwaite's *Novelty* was the next to run, and it ran without a train at speeds up to 24 miles per hour (38.4 kph). Brandreth's *Cycloped* then ran alone for some distance, but the weight of the horses was too much for its structure, and it retired after the horses broke through the treadmill and floor. Hackworth's *Sans Pareil* was exhibited late in the day, but not operated. After *Novelty* operated without a tender, some dispute arose about the proper weight of its train, since the tender was included in the weight of the train. The judges agreed to review the method used to compute the load for each locomotive.

When the judges arrived on 7 October, *Novelty* had been prepared and attached to the train already determined for it. It completed its first test run, but the bellows of its forced-air pump failed on the second run, rendering it inoperable. This had to be repaired before *Novelty* could continue, so her trial was postponed to another day. *Sans Pareil* was then called, but Hackworth had discovered a boiler defect. The judges allowed him some time to make repairs. Apparently to avoid disappointing the crowd, Stephenson steamed up *Rocket* and attached it to coaches that could accommodate thirty people. He then offered rides, and spent most of the day pulling the loaded coaches at speeds up to 30 miles per hour (48.1 kph) up and down the test track.

Robert Stephenson (1803-1859), the son of George Stephenson, designed and built Rocket *at his works in Newcastle, the first factory built specifically to manufacture railway locomotives.*



This painting by Jim Petrie shows Rocket *pulling coaches under the skew bridge in Rainhill during the second day. During the measured trial runs,* Rocket *was the only entrant to successfully complete the entire test. The cover painting, also by Petrie, shows* Novelty *and* Sans Pareil, *with* Rocket *in the background.*

The following day, 8 October, was *Rocket*'s trial day. In contrast to the earlier entries, *Rocket* performed flawlessly, completing the first round of tests at an average speed of 13.4 miles per hour (21.5 kph). After less than 15 minutes for servicing, *Rocket* began the second part of the test and finished it in slightly less time, averaging 14.2 miles per hour (22.7 kph). Stephenson's locomotive experienced no difficulties during the ordeal, and it achieved speeds above the required minimum of 10 miles per hour (16.0 kph). The data obtained even suggested that the train had more resistance when being pushed than when being pulled, something not previously realized.

EXPERIMENT SECOND.

	Time of stopping and getting up the speed. WEST END.		Time going west from Post No. 2 to Post No. 1.		Time going east from Post No. 1 to Post No. 2.		Time of stopping and getting up the speed. EAST END.	
	Min.	*Sec.*	*Min.*	*Sec.*	*Min.*	*Sec.*	*Min.*	*Sec.*
Started at	1	38	...	...	6	15	...	...
2° 3′ 12″	...	...	7	32	...	...	2	08
	2	25	...	...	5	57	...	...
	...	...	7	20	...	...	2	23
	2	30	...	...	5	17	...	...
	...	...	6	12	...	...	2	59
	2	47	...	...	7	06	...	...
	...	...	6	47	...	...	3	40
	2	41	...	...	6	05	...	...
	...	...	6	33	...	...	2	11
	2	48	...	...	5	51	...	...
	...	...	7	18	...	...	2	32
	2	02	...	...	6	09	...	...
	...	...	7	46	...	...	2	29
	2	18	...	...	5	23	...	...
	...	...	8	19	...	...	3	38
	2	13	...	...	5	25	...	...
	...	...	6	32	...	...	2	06
Ended at	1	57	...	...	3	44	...	...
5° 0′ 21″ ×	0	45	5	18	...	...	2	10
Whole time 2° 57′ 09″	24′ 04″ 26′ 16″		1° 9′ 37″		57′ 12″ 1° 9′ 37″		26′ 16″	
Total stoppages ....50′ 20″			Time when in motion		2° 6′ 49″			

This is the table of Rocket*'s running times during the second half of its trial. Note that the times pushing its train west are consistently greater than pulling the train east. Fuel and water consumption were also recorded.*

Neither *Sans Pareil* nor *Novelty* were ready to run—their repairs not yet finished—so the judges decided to postpone their trials until Monday, 12 October. (No tests were run on Sunday.) Burstall's *Perseverance* had been dropped while being unloaded at Rainhill, and the damage was too severe for it to run when scheduled. (Burstall hoped to be ready before the tests ended.) Thus, no tests could be run on 9 October. Ericsson and Braithwaite, however, notified the judges that *Novelty* could be ready on the tenth, and the judges accepted their offer.

A suitable means of computing the proper weight train for *Novelty* had been developed by the morning of 10 October, so *Novelty* was prepared and attached to its train. Its trial began before noon, and it made its first pass without difficulty, however, the boiler feed pipe from the pump burst on its return pass, taking it out of service. It had run well, albeit for a very short time, and the judges granted *Novelty* yet another chance on 14 October. They also decided to grant Hackworth another day to affect his repairs to *Sans Pareil*, scheduling that trial for 13 October.

When *Sans Pareil* appeared for weighing on 13 October, the scale showed it to be heavier than the allowed weight for four wheels. The revised test specifications required any locomotive over 4½ tons to have six wheels. The judges felt it should be ineligible for the prize. Hackworth, however, argued that the "weighing machine" was not correct. The judges finally allowed *San Pareil* to run, if only to see whether it merited further consideration. The test began well, with *Sans Pareil* posting marginally better times than *Rocket*, but that changed on the eighth trip when its boiler feed pump failed. The boiler's water level dropped to the point that a fusible lead safety plug melted, releasing the pressure and dramatically ejecting steam and water out the chimney. Despite good running times, test records indicated that *Sans Pareil* suffered from high fuel consumption due to excessive draft that sucked unburned coke out the firebox and up the chimney.

The last day of the trials, Wednesday, 14 October, attracted what was probably the largest crowd of visitors. *Novelty* had been repaired, but Ericsson and Braithwaite were worried that the cementitious packing material used to seal joints in the repaired pipes had not had time to fully cure. Their worries proved valid when a flue collapsed, causing loss of steam pressure and the train to stop. The collapse was not likely caused by a packing failure, but the effect was the same. Ericsson and Braithwaite had no choice but to withdraw from the competition. Hackworth wanted another opportunity for *Sans Pareil*, but the judges refused his request.
By this time, Burstall finally had *Perseverance* in operating condition, and he began a demonstration run to test the repairs. Unfortunately for him, *Perseverance* would not move faster than about five miles per hour (8 kph), even without a train. At that, Burstall withdrew from the competition.

Since *Rocket* was the only entrant to complete the trials, and to do so without incident, it was declared the winner of the ₤500 prize. In a manner that may have influenced later post-race "victory laps" after auto races, Stephenson steamed up *Rocket* and ran his locomotive back and forth over the test track twice, achieving speeds up to 35 miles per hour (56.1 kph).

Rocket and the modern steam locomotive

Rocket not only won the ₤500 prize at Rainhill and secured a contract for Robert Stephenson to build seven similar locomotives for the L&MR, it also introduced a design that became the prototype for most subsequent steam locomotives built over the next 160 years. Key elements of Stephenson's design included a horizontal, fire-tube boiler with 25 flues connecting the firebox with the chimney, as the exhaust stack was originally known, and two cylinders directly connected to the drive wheels through a crosshead and main rod. Steam exhausted from the cylinders through a pipe to a nozzle at the base of the chimney to draw air through the firebox and flues to support efficient combustion. Surrounded by water, the 25 flues provided a much greater heating surface than the two or three flues in the other competitors. The direct cylinder-drive wheel arrangement discarded the more-complex system of cranks, rods, and sometimes gears used by many other early locomotives, improving efficiency and simplifying maintenance.

Stephenson did not rest on his laurels. By the time his firm finished the seventh additional locomotive, *North Star*, his team had introduced several improvements in the *Rocket*-type design. Chief among these were the addition of a smokebox chamber at the base of the chimney to improve gas flow through the boiler and a relocation of the cylinders from their original 45-degree angle to nearly horizontal. Operation quickly showed that reducing the downward force of the inclined cylinders greatly improved the tracking qualities of the locomotive and reduced stress on the track without any sacrifice in power or tractive effort. The railway made these modifications to the earlier locomotives, including *Rocket*, as well. (At Rainhill, *Rocket*'s inclined cylinders had already proven to be superior in these respects to the competitors' vertical cylinders. *Sans Pareil*, in particular, oscillated heavily as it moved because of the vertical forces and its high center of mass.)

For his ninth L&MR locomotive, *Planet*, Stephenson literally turned *Rocket*'s design around, placing the idler wheels and cylinders ahead of the drivers. The railway liked it and bought 19 more *Planet* –type locomotives between 1830 and 1834. While subsequent locomotives would continue to grow in size and power, all but a few would emulate this refined prototype until China's Datong Works built the last commercial steam locomotives in 1988.

Rocket *as it appears today at the Science Museum in South Kensington.*

A Rocket *replica at the National Railway Museum pulling replicas of first- and second-class coaches.*

Although it is missing some key components, *Rocket* amazingly survived and is now on display at the Science Museum in South Kensington (London). Several replicas have been built, all of them in the original configuration. Interestingly, *Sans Pareil* also survived. While it did not complete the trial, the L&MR decided to purchase it anyway, but the company only ran it for a short while before leasing it to a connecting line, the Bolton and Leigh Railway, where it remained in service until 1844. *Sans Pareil* subsequently served as a collier stationary boiler until donated to the Patent Office Museum in 1864. Today, it is displayed at the National Railway Museum's Shildon Facility, along with a replica built for the sesquicentennial of the Rainhill Trials in 1979. A replica of *Novelty* was built for the centennial in 1929. The wheels and one cylinder from the original had somehow survived, and they were used in the replica, which is now displayed in the Manchester Museum of Science and Industry.

Significance of the Rainhill Trials

The trial of these Engines, indeed, may be regarded as constituting a new epoch in the progress of mechanical science, as relating to locomotion.

— Joseph Locke

The Rainhill Trials achieved everything that the Liverpool and Manchester's directors hoped it would. Every locomotive tested showed that the adhesion between an iron wheel and rail was sufficient to allow a self-propelled vehicle to move itself and pull a useful load of railway cars. Stephenson's *Rocket* proved the merits of pistons acting directly on drive wheels without the need for gears and levers, and its multi-tube boiler set a precedent followed by almost all subsequent steam locomotives. The railway immediately abandoned any idea of using fixed engines to pull trains. (In the future, they would be limited to short railways with very steep inclines.) Having built the winner of the trials, Robert Stephenson received contracts from the L&MR for seven additional locomotives like *Rocket*, and he continued to develop improved motive power for the company until 1834, producing all but seven of the L&MR's first 33 locomotives. The early success of the railway is one indication that Stephenson's locomotives continued to perform admirably and economically.

The initial success of the Rainhill Trials was, however, only the first chapter of a story that continues to this day. Technologies evolve by building on successes and discarding not only failures, but frequently ideas that were successful, but less than the best in their field. Rainhill did both by discarding fixed winding engines, a successful but obsolete concept for relatively level routes, and locomotive designs that were clearly inferior to *Rocket*. This was possible because the trial program was, itself, well designed by engineers who developed a process to generate useful knowledge by focusing on performance. They thought about what information they needed to compare similar machines, and then designed a test program that would impartially measure the appropriate parameters and use standard calculations to yield additional values. Outlined in standardized tables, these data made it simple to compare the overall performance and economy of each entrant.

Modern engineers in all disciplines use test and evaluation methods that follow directly from Rainhill. While modern computational capabilities give engineers the ability to analyze virtually anything that can be quantified, many similar objects, systems, and processes still prove challenging to compare. Whether analyzed using computers or evaluated in a physical testing facility, engineering choices frequently involve a selection between similar, competing concepts. Since Rainhill, the field of test, or experiment, design continues to develop in sophistication, but the core concept remains valid.

The Liverpool and Manchester Railway, the world's first "common carrier" railway, remains in service, with almost all of it still on the original alignment. The Olive Mount Cutting has been enlarged to accommodate current rolling stock, and the Wapping and Crown Street tunnels are no longer in use under Liverpool, though the former still exists. Two bridges in Manchester remain in place, but not in service, and the Liverpool Road Station tracks are now isolated from the main line. Otherwise the railway still utilizes its original structures, including the major viaducts and bridges, as well as the roadbed foundation across Chat Moss, using track and trains many times heavier than the originals. In 1845, the L&MR was absorbed by the Grand Junction Railway, which became part of the London and North Western Railway in 1846. Through subsequent mergers, it ultimately became part of British Railways, now known as Network Rail, in 1948. Fittingly, when British Railways ended the use of steam locomotives on 11 August 1968, the final steam run was over the Liverpool and Manchester Railway.

Further Readings

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