From Shovels to CTs – Measuring the Energy of Trains

By Doug Landau

Introduction

How much energy does a train use? From the earliest days, promoters of the first steam railways were concerned, not so much with energy, but its close proxy, the cost of fuel, often expressed in terms of shovelfuls per mile. This primitive measure set a tradition that continued, especially in the hands of footplate inspectors, almost to the last days of steam. By degrees, more sophisticated approaches and methods were evolved, and although the development of testing techniques almost continued until the dying days of steam, they never quite reached a state of technical perfection. The steam locomotive proved to be a difficult customer for scientific analysis, always challenging in multiple ways the available metrological "know how".

This struggle was inevitable. Until about 200 hundred years ago, technology (the ability to make things that work), generally marched a long way ahead of the science (a formal understanding of how things work). A good example would be the ubiquitous bow and arrow contrived around the world thousands of years ago, an invention devised with no knowledge whatever of Newton's Laws of Motion, or Hooke's Law of Elasticity. It was not until the Renaissance that a symbiosis between engineering and science steadily evolved; ultimately delivering the many remarkable technologies we take for granted today.

It is not without some irony, that whereas monitoring the performance and energy demands of the relatively primitive technology of steam trains, ultimately involved sophisticated and expensive dynamometer cars, stationary test plants, considerable instrumentation, and test teams involving about a dozen or so engineers, electric traction requires little more than a current transformer, voltage transformer and a kilowatt-hour (KWH) meter, which would fit comfortably into a suitcase.

I'll be setting out this story in two parts; firstly a brief history of developments in testing practice and technology, and secondly an account of what was discovered and some of the problems encountered along the way.

Part I - A Brief Summary of Testing Techniques and Scientific Understanding

Shovels

From the fireman's standpoint, likely concerned with the effort of his labours, shovelfuls per mile or per minute, was a fair measure of his workload. It was a work rate often noted by locomotive inspectors almost to the last days of steam. Beyond this is the problem of how big is a shovel, and what potential energy was delivered as a result? An oft quoted rule of thumb was 10lb per shovelful; an inspectors report of a high power test run with 60532 *Blue Peter* in the early 1950s put the figure a little more precisely at $10^{1}/_{4}$lb. The *Great Western Railway*, ever individualistic, boasted a more challenging shovel (Broad Gauge?), delivering about 14lb, or one stone. As we shall see, shovelfuls per mile remained a matter of interest to railway engineers as late as the 1950s.

Pounds Per Mile

By the time of the Rainhill Trials in 1829, the promoters of the *Liverpool & Manchester Railway* were mindful of the economic realities, and pounds per mile was the order of the day for assessing the economy of the contenders. The *Rocket* ran 70 miles on half a ton of coke; 16 lb/mile. The *Mechanics Magazine* for 31 October 1829 reported: "On railways laid down upon the high road from London to Liverpool, the mails drawn by a slight locomotive carriage might travel the distance, 194 miles with facility in 12 hours (25.5 mph), carrying double their present complement of passengers, and this at a cost of fuel not exceeding 10 shillings or scarcely one half-penny per mile, while 2½d. per mile would amply cover the interest of capital for engines, water, stations, & c." "Pounds per mile" was to remain, rather like miles per gallon, a useful comparator to the end of steam.

Force

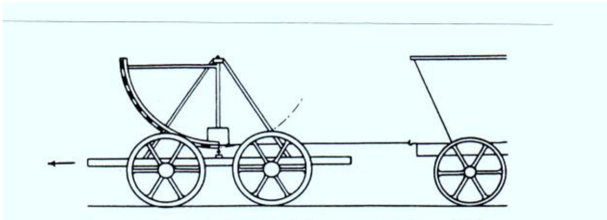


Figure 1 The Stephenson-Wood Dynamometer Wagon 1818

The first attempts to measure drawbar pull date from 1818, when a simple pendulum displacement dynamometer vehicle was developed by George Stephenson in association with his friend Nicholas Wood. On level track this basic piece of apparatus recorded a wagon resistance of 9Lb/ton at 5 mph.

Work Done

Pounds per mile, although obviously a more meaningful measure than shovelfuls per mile, was more focussed on cost implications than the scientific. It provided only a coincidental indication of work done and the energy expended in doing it. The work problem was first tackled by the eminent scientist Charles Babbage, who experimented on behalf of the Great Western Railway with a moving paper roll on which was traced the traction force, vertical and horizontal carriage motion, distance, and time at half second intervals. Babbage reported his findings in 1839; his work had laid the foundations for what was to become the dynamometer car. Daniel Gooch took up Babbage's ideas and added an indicator to record cylinder performance (Figure 2), and produced rolling stock resistive curves. His paper was never published, but his results were to derive equations that appeared in Clarke's *Railway Machinery*.

Energy

The energy of fuel was first determined (Bertholet's Oxygen Bomb Calorimeter, 1881), over three decades before the formalisation of the Law of the Conservation of Energy (Noether's Theorem, 1915, first published 1918).

The Dynamometer Car

In the 1840s Daniel Gooch, the first locomotive superintendant Great Western, introduced further developments, notably the recording of cylinder pressure and the production of indicator diagrams. His experimental work was presented in a paper to the Institution of Civil Engineers in 1848, and included coaching stock and locomotive resistance curves represented as pounds per ton. He was able to show that resistance involved both a fixed element, and an element that increased as a function of speed, producing graphs of resistance up to 60 mph. The apparatus included the recording of wind speed and direction.

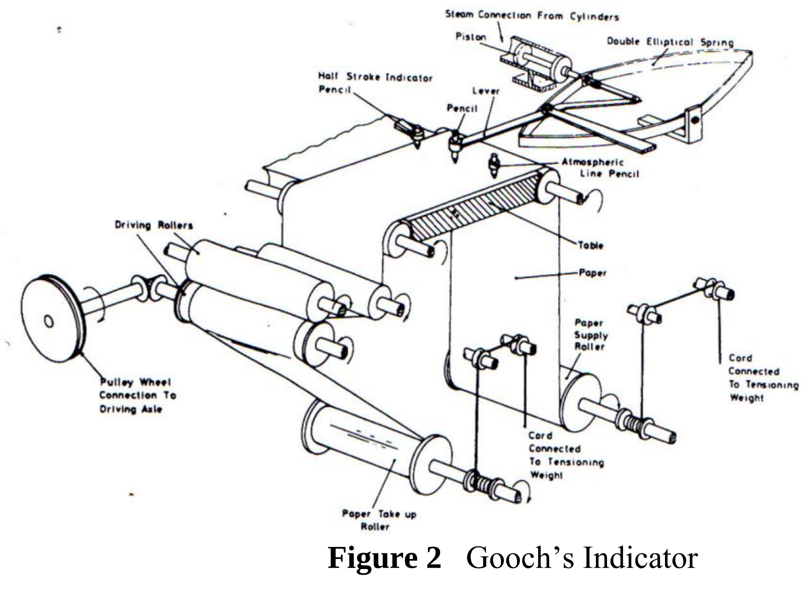


Figure 2 Gooch's Indicator

Below is a list of UK dynamometers cars. Down the years, all the cars dating from 1901 were given extensive refits to accommodate new and improved test apparatus, such as the work/time mechanical integrator and gas analysis equipment.

C1847 Gooch's GWR "Measuring Van".

1894 LNWR 6 wheel car. Recorded pull and speed

1901 GWR 8 wheel, w/d 1961

1906 North Eastern Railway, preserved at NRM

1906 LNWR, became LMS Dynamometer Car No.2, w/d 1967

1912 L & Y, first with mechanical integrator, became LMS Dynamometer Car No.1, w/d 1970, preserved at Butterley.

1948 LMS Dynamometer Car No.3, w/d 1975.

1961 Western Region Dynamometer Car, conversion of obsolete Hawksworth GWR 1947 stock, coach no. 796, w/d 1981.

It is now 30 years since a dynamometer car was last operational.

The Inertia Ergometer

This was an elegantly simple pendulum device invented circa 1905 by the Belgium engineer Joseph Doyen. With the train at rest or at constant speed on level track zero deflection/force was indicated. When in motion the pendulum obligingly deflected in strict accordance with Newton's laws of motion, summating the twin gravitational effects of gradient and acceleration, be they negative or positive. At the 14th International Railway Congress in March 1909 this new and inexpensive invention, used in conjunction with an integrating roller, was presented with some hype, as representing a major breakthrough in the testing of trains.

The reality was rather different, in practice its accuracy was significantly compromised by the random secondary forces generated by the motion of the train, and its operation did not register the acceleration energy component of the rotating masses. It nevertheless became the part of the standard fit-out for dynamometer cars, but was used more as a useful adjunct, rather than a primary function of the test procedure.

Locomotive Testing Stations

The first locomotive testing station was built in Kief, Russia, in 1881; it was a somewhat primitive set up and was defunct by 1886. The first test plant operating on rollers was established Purdue. USA in 1891, by 1914 there were no less than 5 test stations in the USA. The first UK test station was opened at Swindon in 1901, and was modernised in 1935, the Rugby plant, significantly delayed by WWII, was not commissioned until 1948. The famous French plant at Vitry opened in 1933.

The great advantage of stationary test plants was the facility to test at constant speed under strictly controlled conditions. The great disadvantage was that it did not fully represent, and could not replicate, the conditions obtaining out on the line.

Mechanical Engine Indicators

First conceived in the late 18th century, and subject to intermittent development and evolution well into the 20th, the mechanical indicator never quite overcame the inherent problems of inertia, hysteresis and backlash. It was device with hints of Heath-Robinson. The results were at best uncertain and at worst very poor. Even if an accurate diagram is assumed, precise determination of the mean effective pressure (MEP) was beyond practical reach, sensitivity to small errors was high.

For example, an error of just 1lb determining the mean effective pressure (MEP) for the LNER V2, would falsify the IHP by 33 HP at 70 mph, for a PLM compound pacific at the same speed, the error would be 72 HP. In the 1950s the Farnbro "balanced pressure" indicator was adopted as the preferred choice at the Rugby test plant, eliminating many of the problems associated with traditional indicators. Early experience was less than satisfactory, particularly in regard to mechanical failure. It was not until 1954 that improvements delivered the desired standard of reliability, sensitivity and consistency.

In recent years pressure transducers have come into play, the results appear to be promising.

The Counter Pressure Locomotive.

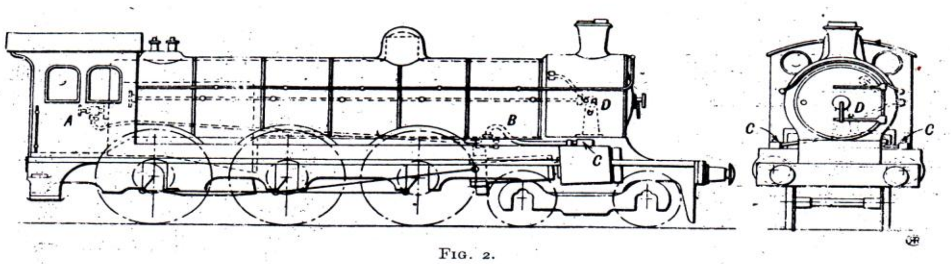


FIG. 2.

ARRANGEMENT OF COUNTER PRESSURE LOCOMOTIVE.

Weight on Coupled Wheels ... ... 47 tons.
Total Weight of Engine and Tender ... 106 tons 12 cwt.
Cylinders, two simple ... ... 20in. dia., 26in. stroke.
A. Water injector valve. B. Branch pipe to L. & R. cylinders.
C. Water inlet to cylinders. D. Live steam to blast pipe.

Figure 3 - The Ex NER S1 Class adapted by the LNER for counter pressure testing.

Counter pressure braking (which essentially, was putting the locomotive in reverse), was originally developed in the early days of steam, as a way of stopping trains. It became popular on railways with long, steep, descending gradients. It was later adapted for locomotive trials, enabling trains to be tested at constant speed, thus conferring some of the advantages obtained on stationary test plants. The counter pressure locomotive, forming part of the trailing load, provided a variable braking force, such that the total drawbar pull was adjusted to achieve constant speed irrespective of gradient changes, with the locomotive working at constant cut-off. Ideally, the procedure was much simplified if the tests were conducted on a level route.

A small quantity was of steam was delivered by a special pipe to the base of the blastpipe to prevent hot smokebox gases and char being drawn into the valves and cylinders. The cylinders, operating in reverse gear, acted as compressors. Some water was injected into the cylinders to prevent overheating. The braking force was varied by adjusting the cut-off. Considerable skill and experience was required to achieve constant speed.

Multiple Test Units (MTUs)

TABLE 1. RESULTS OF CONSTANT-SPEED TESTS

Speed, m.p.h.	Duration of test, minutes	Tacho voltage deviation, expressed as m.p.h.
75	6 6 7	±0·25 ±0·3 ±0·3
70	10	±0·4
60	27 24 17	±0·4 ±0·45 ±0·3
50	10 8 13	±0·35 ±0·15 ±0·2
30	26 4	±0·15 ±0·25
20	6	±0·15

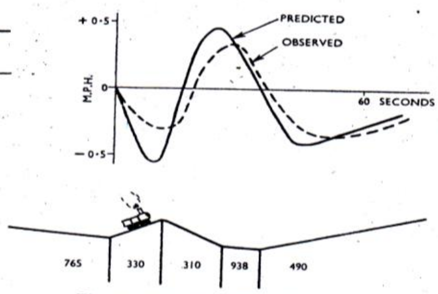


Fig. 34. Transient Speed Deviation

Figure 4 - MTU Constant Speed Resolution

Introduced by the LMS in 1947, the MTUs deployed traction motors operating in regenerative mode, discharging into resistance banks. The control system proved a great success. During the commissioning trials, deliberate power surges from the locomotive attempted to deviate the speed without success, the recorded deviation was fractional and short lived. With this system it was possible to simulate train formations of considerable length. This was the modern answer to the counter pressure locomotive.

Boiler Gas Analysis

The determination of boiler efficiency was a relatively simple matter: the energy required to evaporate a known quantity of water to a given temperature and pressure, divided by the total calorific value of a known quantity of fuel.

Understanding the process more intimately required rather more, and analysis of the boiler exhaust gases was crucial to this. The procedure most commonly used in the days of steam was the Orsat system. By determining the proportions of CO2, CO and free oxygen it was possible to work out the excess air provided (20-25% was the ideal) and the degree of incomplete combustion as evidenced by the CO (typically absent or present in very small quantities).

Working from the smokebox gas temperatures it was possible to closely calculate the boiler transmission efficiency, and from this, given the known evaporation, the amount of "dry coal fully burned". It was universally found that as combustion rates were stepped up, the amount of "dry coal fully burned" increasingly diminished. The ratio coal fully burned to coal fired was defined as the Grate Efficiency.

Thus Boiler η = Transmission η x Grate η

In comparison, monitoring electric traction energy is not only cheap, it is inherently more accurate, based as it is on a fixed mathematical relationship between voltage current, and power factor, measurements which are not subject to the manifold calibration and accuracy challenges that faced the locomotive test engineer.

Constant Steam Rate Testing

This technique was pioneered by Sam Ell on the Great Western, and latterly the Western Region, in the early post war years. The cornerstone of this technique was Ell's assertion that "Blastpipe pressure was a function of steam rate independent of speed and cut-off". Thus, holding the steam rate constant, using the blast pipe pressure as the control, eliminated many of the problems associated with variable speed testing, and enabled test trains to fit in with normal traffic. When subject to checks and speed restrictions were involved, the steam rate was held against the brake forces. Unfortunately it later emerged that this relationship did not obtain throughout the speed range, and much test data required adjustment as a consequence..

It had long been evident that the heavier the train, the higher the drawbar efficiency. This was because a smaller proportion of the work done was devoted to moving the locomotive. Ell formalised this concept as the "Trailing Gross Weight Ratio" (TGWR), which was a useful tool in predicting drawbar traction efficiency.

$$\text{TGWR} = \frac{\text{Weight of Trailing load}}{\text{Gross Train Weight}}$$

This concept, regarding work done moving the locomotive as nugatory, penalises the efficiency figures. Multiple unit stock escapes this penalty for the most part, the point of measurement being the horsepower delivered at the rail.

Diesel Traction

The emergence of diesel traction significantly simplified test procedures. The main components, the prime movers, generators and traction motors were all amenable to bench testing, enabling traction characteristics to be closely predicted. After a flush of testing in the late 1950s and early 1960s, dynamometer cars tests for traction units became increasingly rare. The last traction unit performance tests using a dynamamometer car, were for a Class 85 electric in 1977. Tests to determine new rolling stock performance and behaviour continued until 1981.

The Current Transformer

The CT is old technology, dating back to 1885. Notwithstanding its cheap, compact construction and inherent accuracy, the routine metering of electric trains as part of the standard fit-out appears to be a relatively recent development, which is surprising given the low cost in providing it.

In association with a voltage transformer and some simple metering, monitoring the energy consumption of individual trains on a daily basis is a practical and economic proposition. Here 'energy' consumption should be used advisedly, since the movement of trains is only the final part of the act, the gross energy footprints on the supply side are somewhat larger.

Curiously, given the ease with which electric traction can be monitored, precious little test data has been published, it's something of a desert. The article, "Power Consumption by 390s" by Virgin Driver in Milepost 30/II in October 2009 was therefore something of a revelation. It makes is possible to compare the energy consumption of railway traction down the years from the days of steam to 25KV electric traction. Rival transport modes can also be compared.

Part II – Testing Revelations

Shovelfuls Per Mile or Minute

Shovelfuls per mile never quite went away as a basis for measurement. As late as the early 1950s observations were made on the down Royal Scot as part of the research into the preparation of a BR firing manual, "Good Firemanship".

Table 1 **London Midland Region**
Firing Rates on the *Down Royal Scot*
Euston - Carlisle
8P Locomotives. Early 1950s

Run	1	2	3	4	5	6	7	8
Shovelfuls	1,084	1,031	998	1,116	937	866	1,109	940
Minutes	326	323	335	326	325	319	326	327
Shovelfuls/Minute	3.3	3.2	3.0	3.4	2.9	2.7	3.4	2.9
Coal Fired Tons #	4.96	4.72	4.57	5.11	4.29	3.96	5.07	4.30
Coal lb/hr	2,045	1,963	1,832	2,105	1,773	1,670	2,092	1,768
Firing Rate Mean Deviation	1.05	0.87	0.87	1.15	0.80	0.71	0.92	1.10

Estimated; coal assumed at 10.25 Lb/shovelful

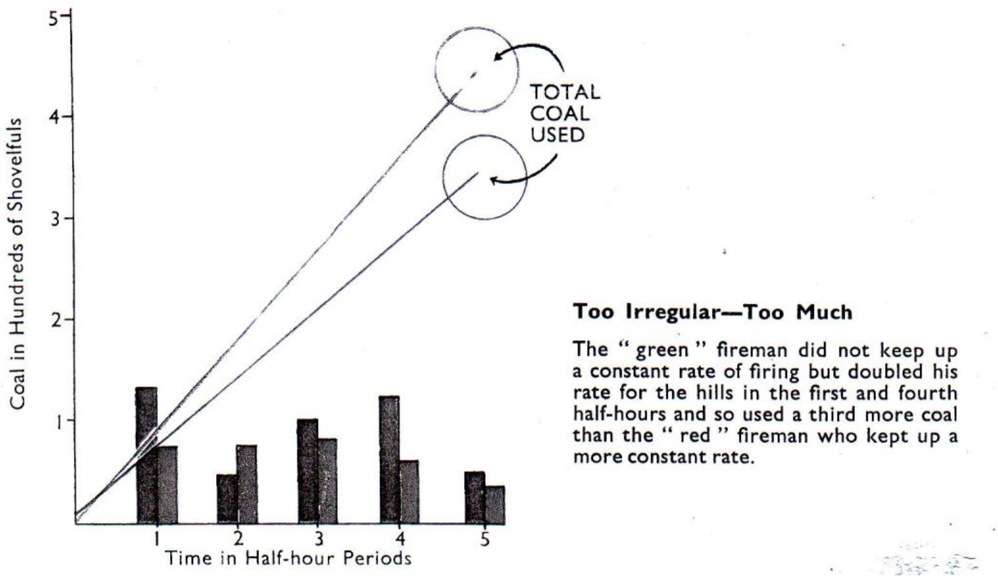


Figure 5 - The case for restrained firing from the BR booklet *Good Firemanship*

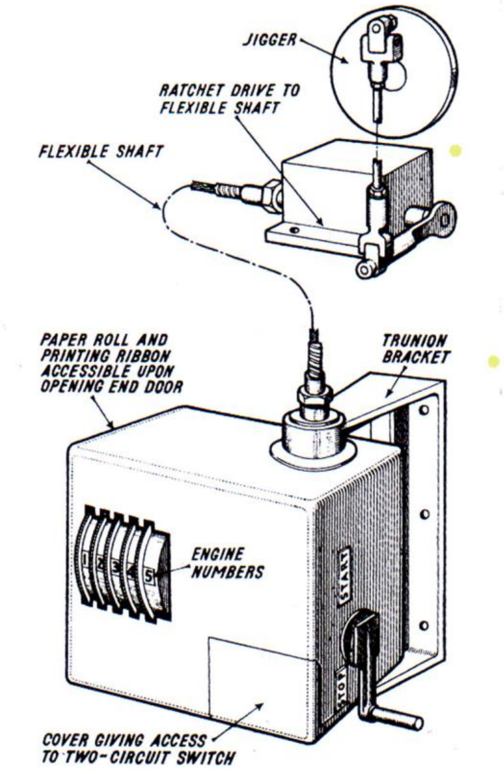
In the original report (of which I only have abstracts), the firing rates were broken down into 12 sections Euston – Carlisle. The highest firing rate recorded was 6.6 shovelfuls per minute Tebay - Shap Summit, equivalent to 4,060 Lb/hr (Run 4). This was also the run with the highest coal consumption. The most economic run (6), was also the fastest; no coal was fired between Tebay and Shap summit. It was concluded that economy was achieved by the 'controlled firing' technique, which could be summarised as "little and often".

There is no reference to the makeup of the fire at Euston. By repute some trains set forth with enormous fires, requiring no more coal until Bletchley or even later. It looks as if the firemen on these test runs were on their best behaviour, it being apparent that such long intervals were not indulged. The average firing interval was 7 minutes, the minimum 4.7 and the maximum 18.9

Pounds Per Mile

Pounds of coal per mile, and pounds per ton mile were simple measures of great utility, remained current until the last days of steam, when the economics of steam verses diesel was argued out in the railway press of the 1950s and 60s. PPM was the MPG of the railway industry.

In the 1930s the LMS introduced coal weighing equipment as part of their motive power depot modernisation programme. Ever keen statisticians, railway management was now able to monitor monitor performance and progress to a degree not previously possible.



Mechanism for recording engine number and amount of coal delivered

Figure 6 – LMS coal logging apparatus

Table 2 **LMS Passenger Working 1929 – 1936**									% Change 1929 - 36
Year	1929	1930	1931	1932	1933	1934	1935	1936	
Coal; Lbs/Mile	53.0	51.6	51.3	51.2	51.5	51.5	51.5	52.1	-1.75%
Engine miles per day	94.6	95.2	99.5	102.8	106.8	110.5	115.6	118.1	24.9%

The reduction in coal consumption seems to have halted in 1932, but the improvement in engine miles per day was to some extent attributable to accelerated train services, so there appears to be some evidence here of “improving the breed”. By the end of 1936 Stanier’s modernisation programme was in full cry, with 858 locomotives to his design in service.

Pounds per ton mile was also a cheap but effective way of comparing different design features, always provided the same train services were being worked, and a number of locomotives were involved in the sample. Below is a good example comparing piston valves and slide valves.

Midland 2P 4-4-0 Saturated - Comparative Tests 1910[1]						Table 3
Coal	**Trips**	**Coal cwt**	**Miles**	**Ton Miles**	**Lb/Mile**	**Lb/ton mile**
Piston Valves	19	914.85	3,179.75	762,689	32.6	0.134
Slide Valves	17	788.25	2,809.25	653,262	31.4	0.135
Water	**Trips**	**Coal cwt**	**ton miles**	**Gallons**	**Lb/Lb Coal**	**Lb/ton mile**
Piston Valves	14	670.88	562,155	60,930	8.1	1.08
Slide Valves	7	338.68	270,872	30,030	7.9	1.11

From a practical standpoint these results can be considered identical. 3 slide valve engines and 4 piston valve engines were involved in these tests.

Boiler Performance

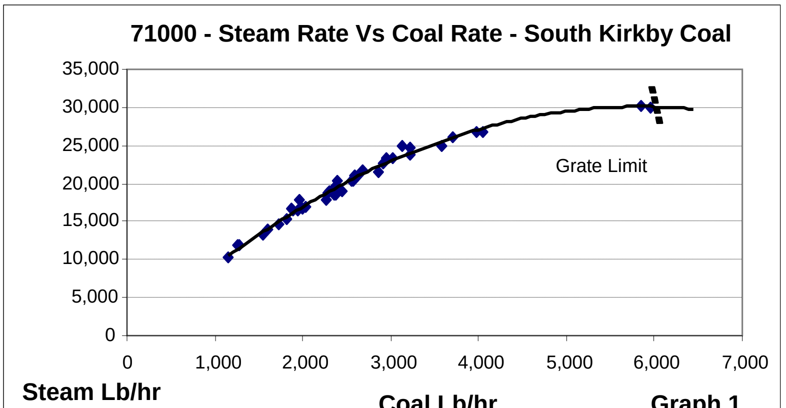
The heat transmission efficiency, $B_T\eta$, for a well proportioned locomotive boiler of the Stephenson type was pretty good, typically around 85% at low combustion rates, only falling by 5 or 6% at maximum output. The grate efficiency, $B_G\eta$, which is defined as the percentage of coal fully burned, is another matter. At very low combustion rates 100% grate efficiency is possible, but spark loss increasingly erodes efficiency as the output is stepped up, and in the worst cases it may fall to 60%. The overall efficiency is primarily a function of these two factors, radiation losses amounting to no more than 2%.

The maximum output could be limited in two ways, first the 'Front End Limit' which is a function of the draughting efficiency, and occurs when the available excess air falls to a point where complete combustion is no longer possible. 20% excess air is usually regarded as the desirable minimum, but examples of only 15% being sufficient are on record. The BR standards were intentionally designed to be front end limited to avoid "uneconomic combustion rates". The later emergence of some double chimneys was in response to declining fuel standards.

The second limit was the 'Grate Limit', which could only be reached in the absence of a 'Front End Limit', and occurs when steam production ceases to increase, the parabolic steam rate curve having reached its apogee. It can be shown this point occurs when the boiler efficiency falls to half the notional efficiency at zero output, or:

At grate limit $\Delta W_f + \Delta B\eta = 0$

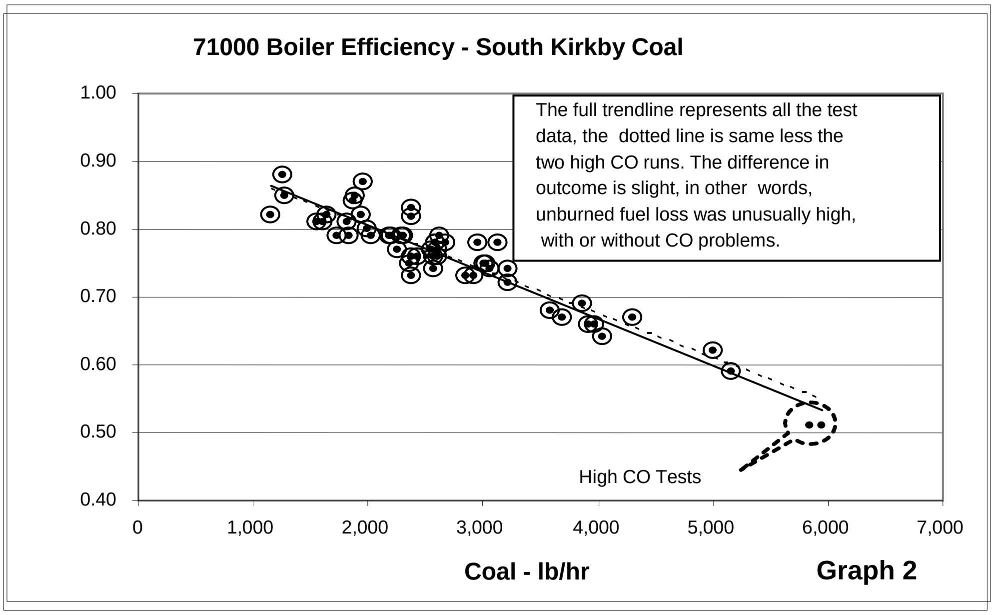
(ΔW_f = increase weight fired, $\Delta B\eta$ = change in boiler efficiency, a negative value.)



Graph 1

71000 was relatively rare case of a locomotive prematurely reaching the grate limit as a result of over draughting, giving rise to excessive spark loss (Graph 1). Forget suggestions that the damper area was inadequate, such a deficiency would have imposed a front end limit' long before the grate limit was reached. As now running 71000 is fitted with exactly the same ashpan arrangement as obtained when tested at Swindon.

It appears that on a couple of road tests, experiments were made with a thicker fire in an attempt to cut down spark loss (Graph 2). Notwithstanding adequate excess air, complete combustion was no longer achieved and significant CO was produced, more than offsetting the reduction in spark loss, overall resulting in a slight reduction in boiler efficiency. On all other tests with South Kirkby coal, the gas analysis was free of CO.



The Steam Performance Envelope

It was not until post WWII that a full performance envelope of the steam locomotive was produced, largely as a result of Sam Ell's pioneering work on controlled road test procedures at constant steam rates.

In 1949, the new Peppercorn A1 and A2 pacifics were subjected to a series on dynamometer tests between Kings Cross and Leeds. 'Darlington Report E2', May 1949, produced with commendable speed, was completed about 3 weeks after the final test run.

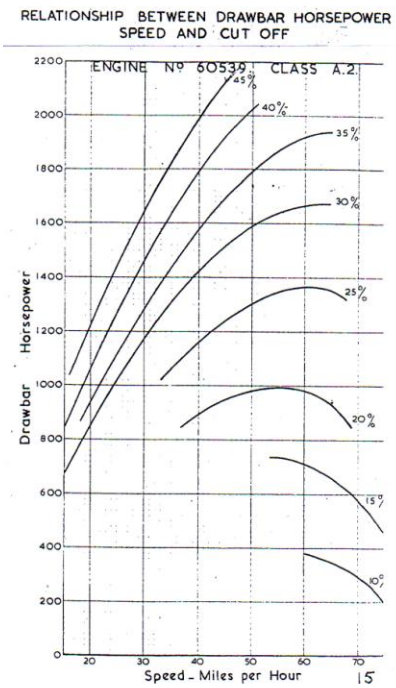
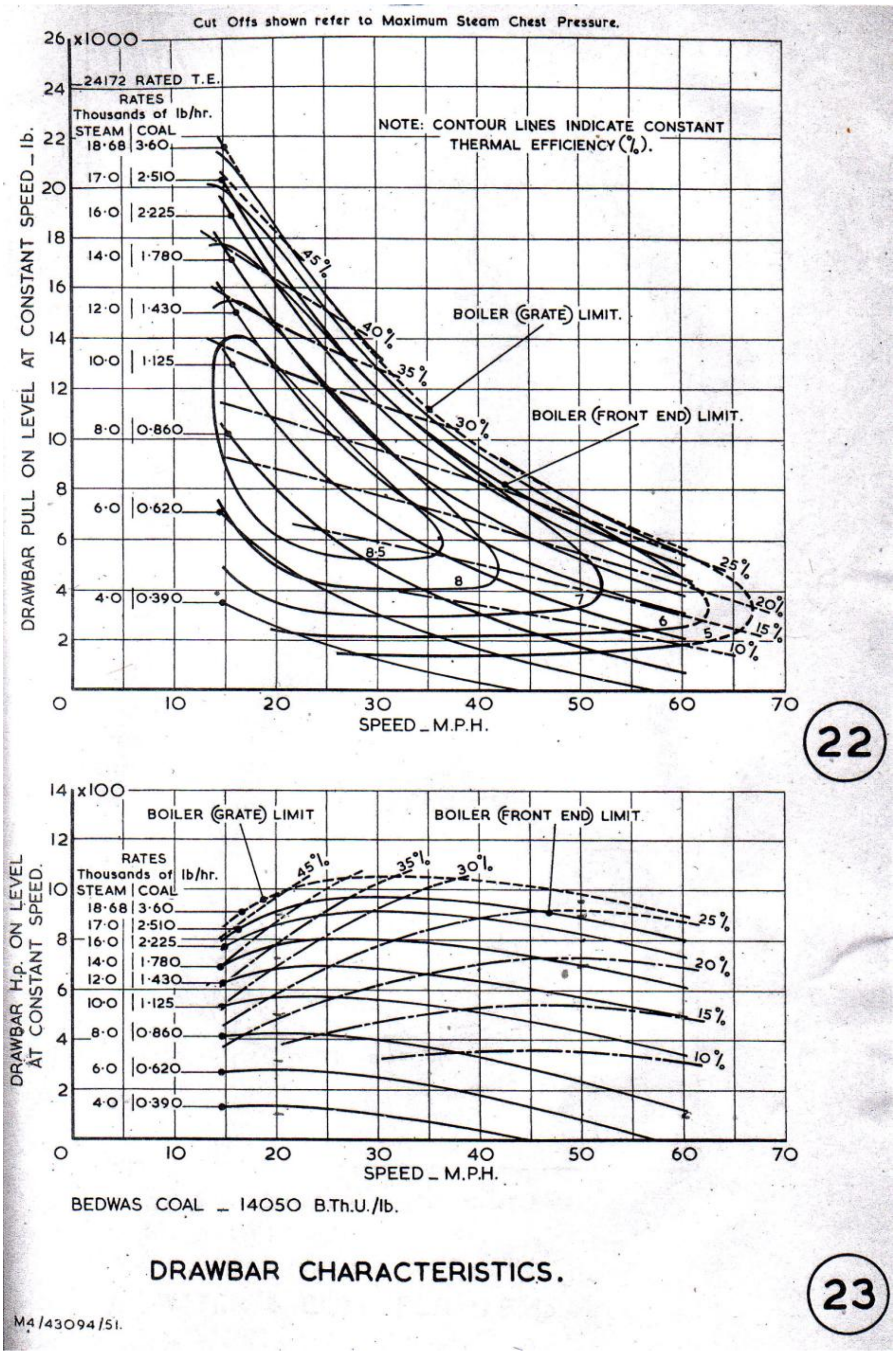


Figure 7 - Drawbar Horsepower Curves – A2 Pacific 60532

The A2 DBHP Vs Cut-off and Speed curves (Fig. 7), as published in Darlington Report E2, 1949. Boiler pressure throughout the tests was in the 223–235 Lb range, so the curves do not represent the full potential, which as maximum pressure could increases by 6 or 7%.

Based on performances of 60532 *Blue Peter* in preservation, the curves shown appear to have been pretty accurate, and the same could be said, based on the performances of 60132 *Tornado*, for the equivalent curves in the report for the A1, but the information in the report is very limited. There is nothing here as to the coal and steam rates involved. It's rather like a map before the advent of contour lines, but that's how things were after 50 years or so of dynamometer car tests. Things were soon about to change.

In 1951 British Railways published Test Bulletin No. 1, covering the performance and efficiency tests with exhaust steam injector for Western Region Modified Hall Class 4-6-0 number 7916. Two key diagrams, 'Drawbar Characteristics' and 'Cylinder Characteristics" encapsulated the complete performance envelope of a Stephenson type steam locomotive in a way not previously seen.



Figures 8 & 9 Typical BR Test Bulletin Drawbar Tractive Effort and Drawbar Horsepower Plots – LM Class 4 2-6-0

The examples shown here are for LMS Class 4 2-6-0 43094 (Test Bulletin 3, 1951). Note the significant changes on the information provided compared to previous standards, notably a series of curves expressing power output as a function of constant coal and steam rates. These curves could be considered analogous the fixed throttle positions of diesel traction. Note the contour lines for overall thermal efficiency plotted on the drawbar tractive effort curves. These tables could be described as the "Brochure Performance", something a salesman selling locomotives might use to good effect. These curves come with one significant proviso; the power and efficiency curves relate to "at constant speed on level track", which renders them, in effect, a false prospectus. From these tables other useful relationships could be determined, such as pounds of coal per drawbar horsepower hour, and specific steam consumption per indicated horsepower hour, water consumption, etc.

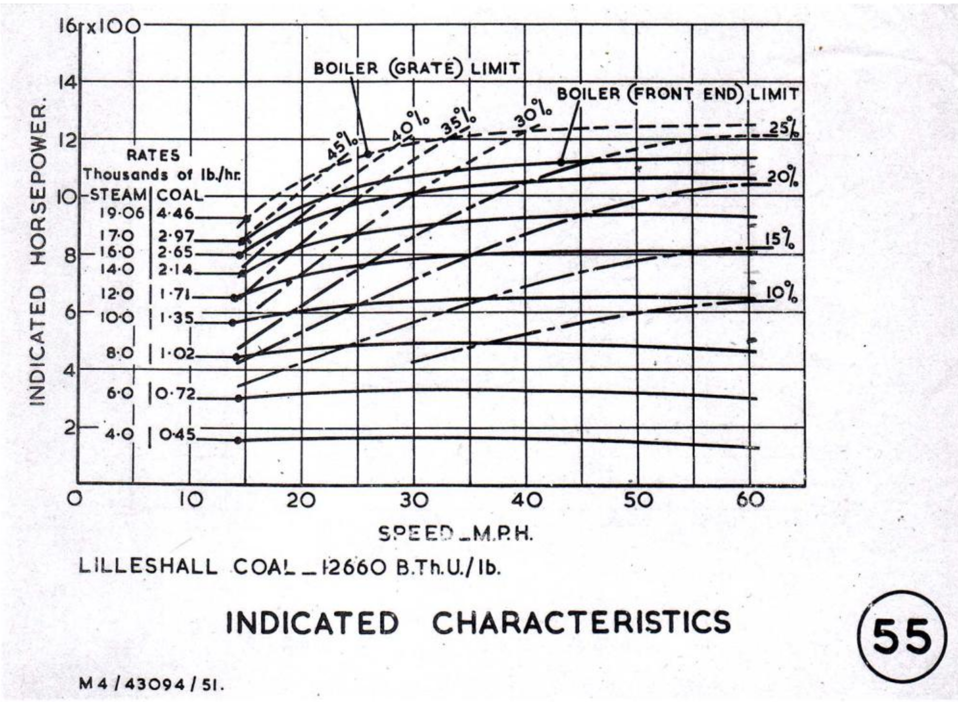
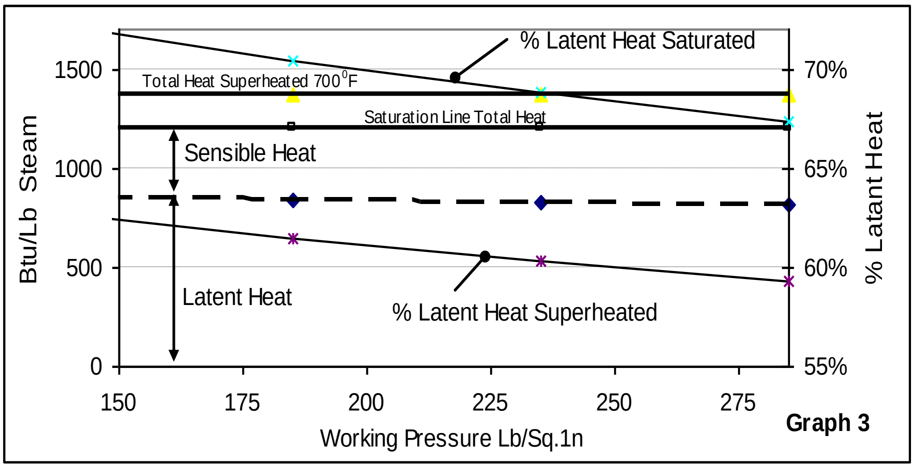


Figure 10 - Typical BR Test Bulletin Indicated Horsepower presentation

Overall Efficiency

At best, the maximum drawbar efficiency ($B_D\eta$) of the BR Standard locomotives approached 9%, which to lay minds likely had every appearance of incompetent design, notwithstanding nearly 150 years of development. The earliest steam locomotives were no better than 3%. The problem was more fundamental, rooted in the inescapable mathematics of the steam tables. Only the sensible heat and superheat possessed a potential for useful work, it came at a cost (Graph 3).



Producing steam was akin to joining a club with a very expensive, continuous, non refundable membership fee. That fee is 'the latent heat of evaporation'; the energy involved transforming water into steam. Even in condensing cycles this energy produces no useful work, excepting where some industrial process requiring relatively low grade heat can be tagged onto the system.

The percentage of latent heat involved in the thermal cycle was very high, especially in saturated applications at modest boiler pressure (Graph 3). Inevitably, the low thermal efficiency of the steam locomotive, was written into the steam tables.

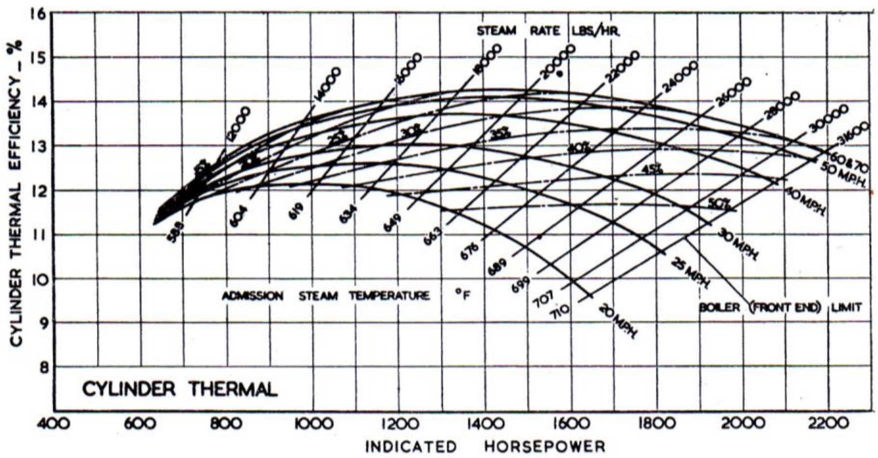


Figure 11 - A typical map of Cylinder Efficiency-Rugby Test Plant

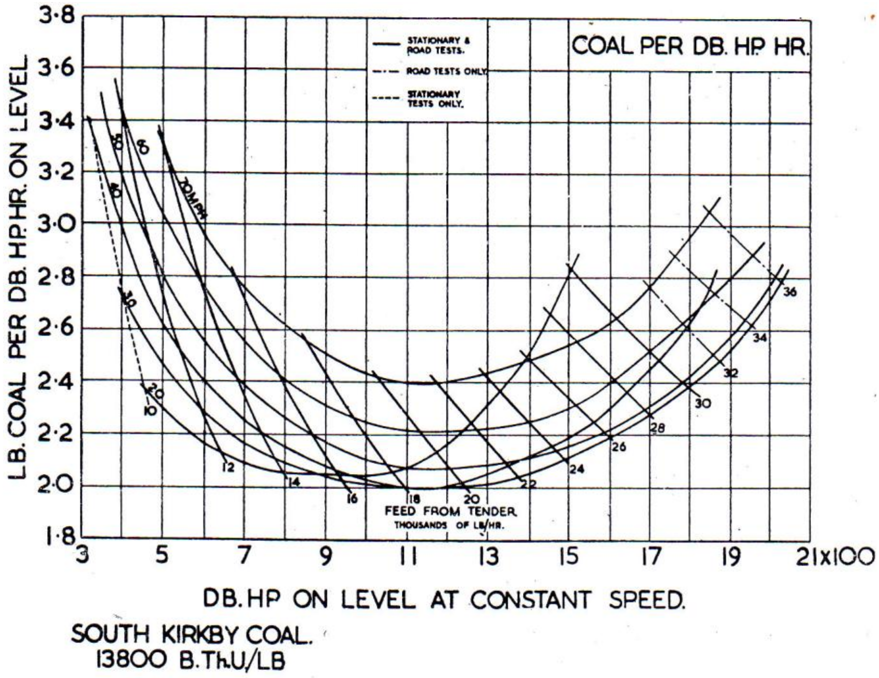


Figure - 12 Coal Consumption per DBHP Curves

Actual Performance in Traffic

The 1948 Locomotive Exchanges, probably the most comprehensive series of locomotive trials in the history of railways, were fortunately the subject of a comprehensive official report. Table 4 below, summaries the net traction efficiencies, for the Kings Cross – Leeds service. This was fairly typical of the series as a whole, with schedules of 45-47 mph, 450-500 ton loads, and the sometimes all too frequent delays en route that were typical of the period. Each locomotive, worked two trains in each direction. The visiting drivers were given familiarisation runs before the test runs.

Table 4	
1948 Exchanges Kings Cross - Leeds	
Coal/ DBHP Hr and Drawbar Traction Efficiency(Dη)	
King	3.39 Lb 5.5%
Duchess	3.04 Lb 6.1%
Merchant Navy	3.73 Lb 4.9%
Rebuilt Scot	3.26 Lb 5.7%
A4	2.92 Lb 6.4%
Averages	**3.27 Lb 5.7%**

None of the locomotives achieved a drawbar efficiency approaching 9%, all falling short of "brochure" performance levels, why? The performance levels derived from the test plant and dynamometer car road tests represented an artificial, steady state, constant speed scenario, aloof to the realities of a locomotive in traffic. The shortfall on "brochure performance" ($B_{DB}\eta$) can be attributed to two factors.

1. The Trailing Gross Weight Ratio (TGWR)
2. Contingent losses - Σ_L

All locomotive hauled trains, be they steam, diesel or electric, are affected in some degree by both of these factors. Multiple unit stock, is not affected by the TGWR, since in this circumstance its value is unity, and power is measured at the rail rather than the drawbar.

The "Brochure Drawbar Performance" ($B_{DB}\eta$) is on the basis of drawbar performance at constant speed on level track, and is analogous to the equivalent drawbar horsepower (EDBHP), whereas it is the actual drawbar horsepower (DBHP), is measured in traffic, which under most circumstances differs from EDBHP since an element of locomotive power is either absorbed or released by positive or negative gravitational effects; +/- acceleration, and +/- gradients. The ratio between DBHP and EDBHP, is an approximate function of the TGWR (route topography, speed restrictions and schedules introduce the variability). he EDBHP is therefore a more representative measure as to what degree the "brochure performance" ($B_{DB}\eta$) has been achieved. Below are some examples of how this works out in practice.

Table 5 **TGWR DBHP/EDBHP - Traction Operating Ratio** — **Some Estimated Outputs**

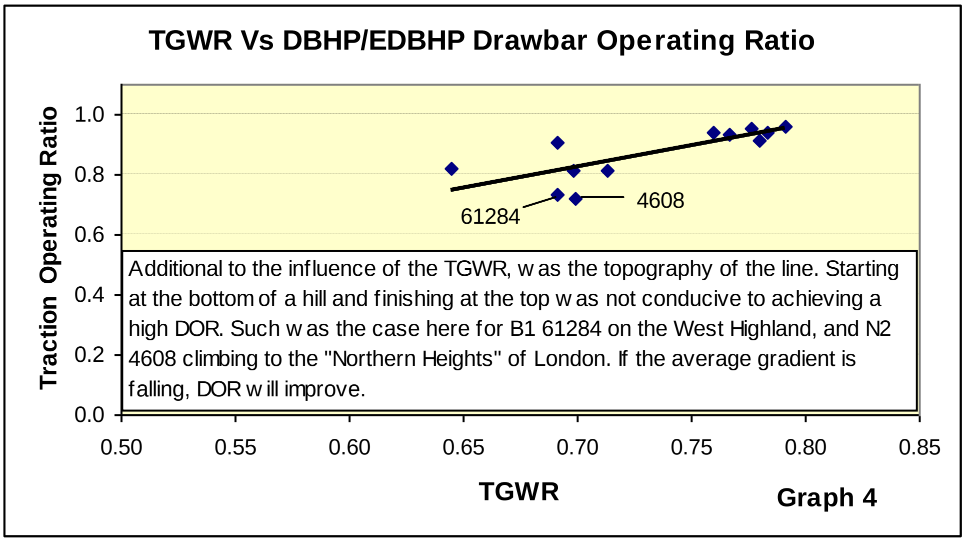
Run	Loco	Route	Gross Tons	Train Tons	DBHPHRs	EDBHPHRs	TGWR	DOR #
1	46224	Euston - Rugby	525	685	1372	1465	0.77	0.94
2	70035	Ipswich - Norwich	325	470	536	592	0.69	0.91
3	10000	Peterborough - Grantham	410	575	477	588	0.71	0.81
4	8860	Kings X - Welwyn Gdn C	220	315	162	200	0.70	0.81
5	61284	Tulloch - Corrour	275	398	236	321	0.69	0.74
6	865	Waterloo - Southampton	505	645	1106	1175	0.78	0.94
7	30931	Tonbridge - Ashford	390	500	388	425	0.78	0.91
8	34006	Exeter - Bristol	475	612	683	717	0.78	0.95
9	45253	Exeter - Bristol	475	600	587	611	0.79	0.96
10	222	York - Leeds	200	310	147	179	0.65	0.82
11	4608	Finsbury Pk - East Finchley	160	229	51	71	0.70	0.72
12	35029	Salisbury - Sidmouth Jcn	475	625	1048	1114	0.76	0.94
	# DOR = DBHP hrs / EDBHP hrs							

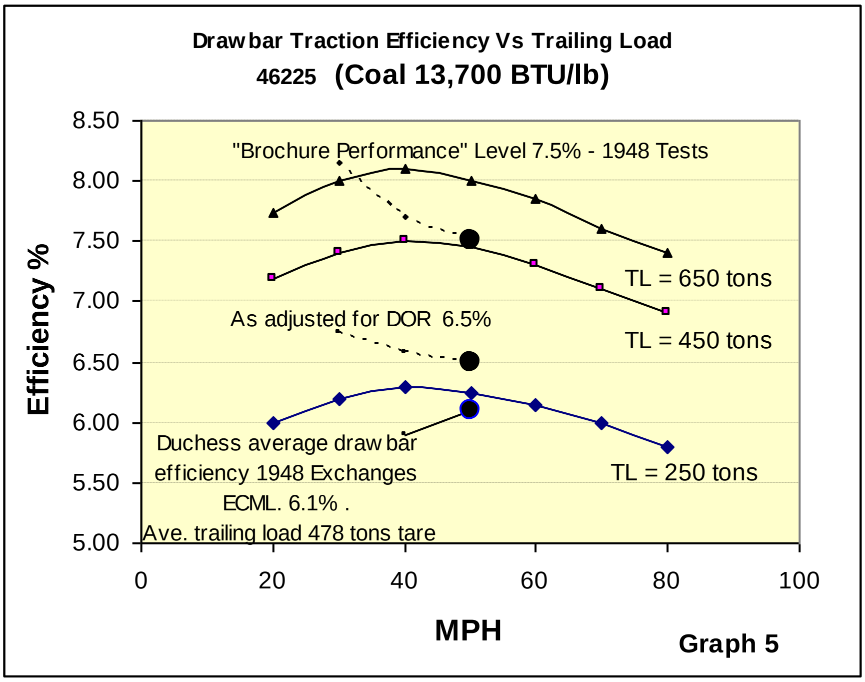
The ratio between DBHPhrs and EDBHPhrs is defined here as the Drawbar Operating Ratio (DOR).

DOR = DBHPhrs/EDBHPhrs

It will be seen from Graph 4, that low TGWRs and challenging gradient profiles, could make serious inroads into DOR achieved.

Even when an adjustment is made for DOR, as in Table 5, a shortfall the theoretical brochure performance remains, for example, the Duchess performance in the 1948 exchanges improves drawbar efficiency from 6.1% to 6.5% (a DOR of 0.94 assumed) whereas according test report R13 a figure in the order of 7.5% is to be expected (Graph 5); why the difference?





Contingent Losses in Traffic

The answer is item 2, contingent losses, these again affect all forms of traction to some degree, but the list of potential losses with steam is significantly longer.

The contingent losses (Σ_{CL}) can assumed as the “missing quantity” after the drawbar traction operating ratio (DOR) has been allowed for.

$$\Sigma_{CL}\% = B_{DB}\eta - \frac{D\eta}{DOR} = 7.5 - \frac{6.1}{0.94} = 1.0\% \text{ (as for 46236, 1948 Exchanges).}$$

The figure of 1% is the actual contingent loss in drawbar efficiency; it represents a 15% reduction in overall efficiency. Such a degree of contingent losses are typical, and to some extent are an unavoidable characteristic of locomotive hauled operation.

These losses introduce another acronym, DTOR (Drawbar Traffic Operating Ratio) which covers both the drawbar operating (DOR) losses and the various contingent losses Σ_{CL}.

$$DTOR = \frac{\text{Actual Drawbar } \eta}{B_{DB}\eta}$$

In the case of the Duchess in the Locomotive Exchanges works this out at

$$DTOR = \frac{6.1}{7.5} = 81\%$$

In other words the actual efficiency in traffic falls nearly 20% short of brochure performance, of which about a quarter is attributable to the inherent TGWR losses of locomotive hauled stock, the remainder including a mixture of avoidable, and unavoidable in traffic operating losses.

Table 6 Potential Contingent Losses Affecting Traction Efficiency In Traffic

		Steam	Diesel	Electric
Standby losses at station and signal stops, and when coasting		Blower in use, losses high if blowing off occurs	Prime mover idling losses circa 5% of maximum output	Transformer magnetising losses circa 1%. AC systems only
Variable speed operation outside optimum performance enevelope		Efficiency poor at low speeds	Moderately affected	Marginally affected
Poor Driving Technique		All traction forms potentially affected up to 10 - 15%		
Blowing Off		Not always avoidable	Not Applicable	Not Applicable
Cylinder Cocks		Operate when starting		
Continous Blowdown		Not all locos fitted #		
Cylinder Relief Valves		Rarely operate		
Valve and Piston Leakage		Maintenance sensitive		
Train Heating	Steam	Seasonal, 4-5%	Independent Boiler	
	Electric	Not applicable	Parasitic, 4-7%	Added Load 4-7%
# Rendered inoperative for 1948 Exchanges, and BR performance and efficiency tests				

Diesel Traction

Analysis by pounds per mile or per trip, remained a useful measure of performance. This was especially the case when it came to general comparisons between steam and diesel. From this simple comparison it was shown that diesel efficiency was superior to steam by a factor of almost 4 (Table 7).

Table 7

Steam Loco	Diesel Loco	Service	Fuel Lb		Fuel Ratio Diesel/Steam	
			Steam	Diesel	Actual	CV Adjusted
B1	Brush 1250 HP	Liverpool St - Norwich 50 mph	8,876	1,438	16%	23%
BR7			8,453		17%	24%
BR7	EE Type 4	Lverpool St - Norwich 48.3 mph, 409 t	9,413	1,910	20%	29%
A3	EE Type 4	Kings X - Newcastle 60.3 mph, 313 t	10,970	1,830	17%	24%
A3	EE Type 4	Kings X - Newcastle 53.5 mph, 451 t	13,837	2,385	17%	24%
Gas Oil assumed at 19,600 BTU/Lb, coal at 12,6000 BTU/Lb (Blidworth)			Averages		18%	25%

For a while, full efficiency trials were conducted for a number of types, and performance and efficiency test bulletins were published for the English Electric 1000 BHP Type1, the Brush 1250 BHP type 2, and the English electric 3,300 BHP Deltic. Because of the high predictability of performance, tests on the stationary test plant were not necessary.

The test results for the Deltic (Table 8) reveal a drawbar efficiency of around 22%, nearly four times the value typically achieved by steam. There is insufficient information in the bulletin to determine the drawbar operating ratio (DOR), but the overall traffic operation ratio (DTOR) can be determined. The "Brochure Performance" listed has been calculated by the author, which in this instance was reduced by 12 – 14% on a DTOR basis. The Deltic packed its punch into a much lower weight (106 tons), than the Type 4 diesels (120-130t), and thus enjoyed a higher TGWR for a given trailing load.

Table 8 **Prototype Deltic Test Results on S & C**

Item	Carlisle - Skipton	Skipton - Carlisle
Miles	82.9	82.9
Under Power	57.9	47.9
Minutes	91	86
Under Power	64	50
Drifting/Brakes	27	36
Average MPH	54.6	57.9
Under Power	54.3	57.5
Average DBHP	1943	1743
Average DBTE tons	5.99	5.08
Fuel Pounds	1,183	876
Lb/DBHP.hr	0.571	0.602
Lb/mile	14.29	10.58
Lb/Ton-mile	0.02	0.01
BTU/DBHP.hr #	11,152	11,757
Drawbar η	22.8%	21.6%
Brochure Lb/DBHP.hr	0.51	0.52
Brochure BTU/DBHP.hr	9,863	10,097
Brochure η	25.8%	25.2%
Trailing Load - tons	642	642
TGWR	0.86	0.86
DTOR	0.88	0.86
# Fuel at 19,530 BTU/Lb		

Here the DTOR averages 87%, a 13% loss of Brochure η when in traffic

Electric Traction

Little attention seems to have been given to testing electric traction from the efficiency standpoint, there seems to have been a general assumption of higher efficiency. Perhaps part of the problem being that the fuel was consumed at remote power stations operating at varying degrees of efficiency. In early electrification schemes these were sometimes owned by the railway companies, but in the modern era, the interest was more localised; the KWHR readings at the lineside substations, which captured total traffic demands, rather than a relationship to work actually done.

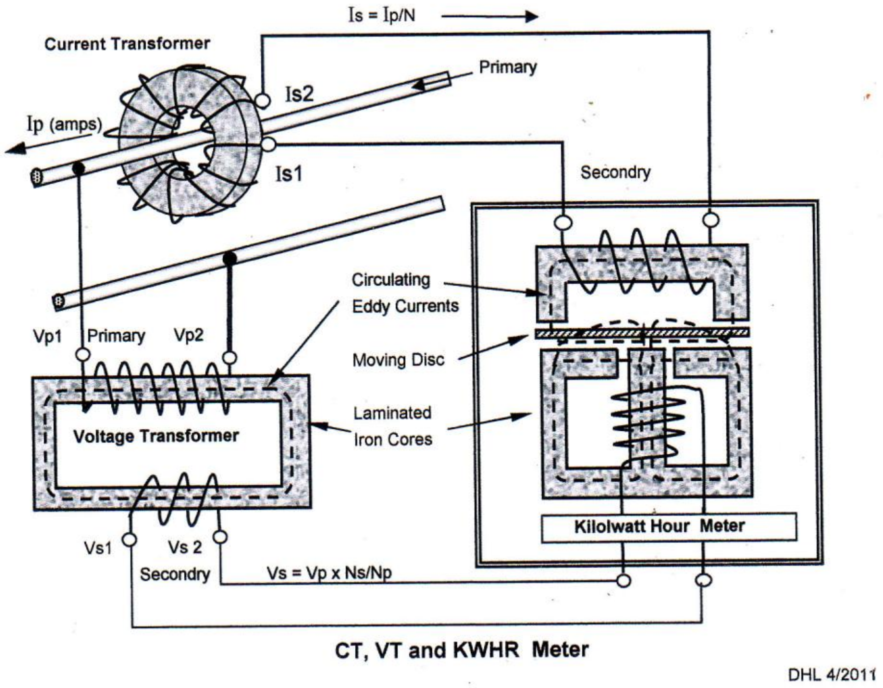


Figure 13 - The Simple Metering Set-Up for Electric Traction (Single Phase)

It was therefore something of a revelation when the article "Power Consumption by Class 390s on the WCML" by Virgin Driver appeared in Milepost 30/II in October 2009 (Table 9).

Table 9	**Class 390 Energy Performance - Rated 5,100 KW, 6,840 HP, Tare Weight 458 tons, 9 cars, 145 seats 1st, 294 Std**				
Service	Stops	Route Miles	Runs	Average KWHR	KWHR/mile
Euston - Manchester via Stoke	3	186.5	13	3,285	17.61
Euston - Manchester via Stoke	3	186.5	7	3,430	18.39
Euston - Manchester via Crewe	3	188.6	3	3,507	18.59
Sample Bookings				Average KWHR/mile	18.0
Euston - Nuneaton: $59^{1}/_{2}$ minutes, 97.8 mph				Average Net KWHR/ton mile	0.039
Nuneaton - Stoke: $32^{1}/_{2}$ minutes, 89.4 mph				Average Net HPHR/ton mile	0.053

Given the train schedules compared to 1948, the average power demand of 0.05 HPHrs/ton mile is remarkably low, the average demand on steam in the 1948 exchanges was 0.029 DBHPHrs/ton mile, or 0.021 DBHPHrs/ton mile if the loco weight is included. These numbers are not strictly comparable because the Class 390 figure also covers, additional to the traction requirements, losses, and the power for lighting, heating, air conditioning, etc. They nevertheless clearly demonstrate that the quest for speed has been achieved without a disproportionate increase in energy demands. "Net" figures per ton mile ignore the weight of passengers.

As multiple units such concepts as TGWR and drawbar horsepower no longer apply to the Class 390s, and the overall energy demands reflect power station efficiency and transmission losses (Table 10)..

Table 10 **UK Power Average Energy Mix**		
Source	Contribution	Thermal η
CCGT	39%	48%
Coal	32%	37%
Nuclear	22%	37%
Channel Link	2%	37%
Wind	2.5%	90%
Other	2%	90%
	Average η	43.5%
N. Grid Transmission Losses		2%
Lineside Substation Losses		5%
Catenary Losses		2%
Net Supply Efficiency		**40%**

The energy mix shown in Table 10 is based on a 125 day record taken the NETA website, efficiencies shown are assumed averages based on typical values. The supply efficiency at the overhead pick up is a small improvement on the best prime mover efficiencies available for diesel traction, which typically stand at 35-36%. The subsequent losses are less than half those obtaining for diesel traction. The supply mix and overall efficiency varies from day to day.

-

Table 11 **Equivalent Passenger Miles per Gallon**					
Transport Mode	Seating	Tons Gross	Lb/ton.mile	Ton.miles/Gal.	EPMPG
Rail					
Steam	483	488	0.068	108	108/27
Diesel	483	488	0.019	399	394/98
Class 390	439	487	0.016	461	415/104
Road					
Saloon Car – 60mpg	4	1.25	0.099	75	240/60
Range Rover – 30 mpg	5	2.6	0.095	78	150/37
Minibus – 33 mpg	15	3.6	0.062	119	495/124
Single Deck Bus 12 mpg	48	9.0	0.070	106	576/144
Notes 1. Lb/ton mile based on calorific values as for diesel or petroleum fuel source- 19,600 BTU/Lb, 7.39 Lb/gallon					
2. Class 390 figures derived from KWHR/ton-mile assuming 40% metered supply efficiency					
3. Ton miles per gallon exclude passenger weight and locomotive weight in the case of locomotive hauled trains. EPMPG figures not effected. Road consumption figures as for quoted “Extra Urban” MPG.					
4. The equivalent passenger miles per gallon (EPMPG) figures are based on 100% & 25% passenger loading.					

It can be seen that steam, on a lb/ton-mile basis, notwithstanding its low thermal efficiency, was superior to motor cars (though not on an EPMPG basis). This should come as no surprise given the inherently low traction resistance of railways. Some comparative tests carried out by Nicholas Wood in the Liverpool area in the1820s, showed that coaching horses, working in a team of four, could achieve 6 or 7 ton-miles per day per horse at an average speed of 10 mph. In contrast, a single horse working on an industrial railway at 3 or 4 mph could achieve almost 200 ton-miles a day. It was a dramatic demonstration of the very low frictional resistance afforded by metal wheels running on metal rails.

In Table 11, energy consumption for various transport modes has been expressed in terms of the equivalent passenger miles per gallon (EMPG). Average load factors will inevitably be somewhat lower than the first figure shown, representing 100% LF., the second, 25% LF , would be more representative of typical averages. Exceptional load factors may occur on commuter services, when standing passengers can raise the load factor to over 150%. The specific EPMPG will only me marginally affected by the load factor, so sensible approximations for any given load factor can be readily determined from Table 11. The Ministry of Transport has estimated that the average private car loading was 1.4 passengers, including the driver, representing load factor averaging around 25%, assuming an equal 5/6 seating mix. In 2007 energy consumption of Class 390 set number 049 was monitored over 20 consecutive weekdays. The energy consumed in non revenue earning service was: empty stock working 2.2%, terminal layovers 2.3% and on depot 6.1%. On this basis the EPMPG at full load shown in Table should be adjusted by a factor of 0.894, yielding a net EPMPG potential of 455. Given the performance level on offer, with some bookings over 90 mph, this a remarkable figure, testimony to the inherently high mechanical efficiency of rail transport, the lower weight advantages of multiple units, and the contribution of regenerative braking, which reduced energy consumption by 16.7%, saving close on £7,000 a month.

Table 12 Tons Per Seat
50 Years of Progress

Train	Coaches	Tons tare	Seats	Coach Tons/Seat	Gross tons/Seat
LMR *Caledonian* 1957	8	264	276	0.96	1.54
Class 390 2007	9	458	439	1.043	1.043

Notwithstanding the massive increase in power/weight ratio, from around 5 HP/ton to 15HP/ton, the gross tonnage per seat fell by 32%, though sadly, despite the provision of air conditioning, passenger comfort, compared to the WCML's premier express of the late 1950s, declined significantly.

Conclusions

Notwithstanding its poor efficiency, the inherent low resistance of rail vehicles enabled steam to compare favourably with road transport on a ton mile basis. It is not without some irony, that testing the low tech steam locomotive presented considerable technical challenges, challenges that 150 years of endeavour, and substantial investment in testing facilities never entirely resolved, whereas testing high tech electric traction has proved simplicity itself. Gone is the need to monitor numerous pressures and temperatures, drawbar pulls and water consumption, take gas samples and weigh bags of coal. Just sit back and let the magnetising currents take their intrinsically accurate readings. In a way things have gone full circle, the determination of traction efficiency is now thought of, just as it was at the time of the Rainhill Trials, in commercial terms rather than the strictly scientific. KWHR per trip has superseded pounds of coal. No one seems to mention horsepower or actual efficiency.

Glossary

$B_{DB}\eta$ Brochure Drawbar Efficiency at constant speed on level track.

$D_B\eta$ Actual Drawbar Efficiency - Drawbar horsepower efficiency as recorded in traffic

DBHP Drawbar Horsepower - As recorded or estimated at drawbar

EDBHP Equivalent Drawbar Horsepower - DBHP adjusted for constant speed on level.

DOR Drawbar Operating Ratio - The ratio of recorded DBHPHrs to EDBHPHrs

DTOR Drawbar Traffic Operating Ratio - The ratio of actual drawbar efficiency to brochure drawbar efficiency

ΣC_L Contingent Losses - Miscellaneous energy operating losses in traffic

$B\eta$ Boiler Efficiency - Usually determined by the equivalent evaporation from and at 212^0F as a percentage of fuel energy supplied.

$B_T\eta$ Boiler Transmission Efficiency - The percentatage of energy (dry coal full burned) absorbed

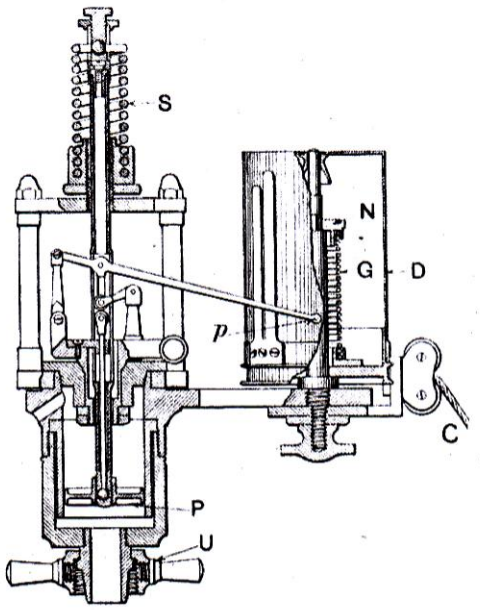
$B_G\eta$ Boiler Grate Efficiency - The percentage of coal fired fully burned.

$B\eta$ Boiler Efficiency can be shown as a function of the Transmission and Grate Efficiencies:

$$B\eta = B_T\eta \times B_G\eta$$

Appendix - Indicating Equipment

Conventional Mechanical Indicators



Key:

C = Cord that attaches to the engine crosshead or connecting rod
G = tensioning spring for the cord and drum
N = Tensioning spring adjustment nut
U = Connecting union with taper faced seating
D = Drum that carries the chart to be marked
P = Marking stylus or pen
S = Pressure spring against which the piston moves
P = Indicator piston

Figure 14 A Typical Spring Type Mechanical Indicator
(Crosby Steam Gauge & Valve Co)

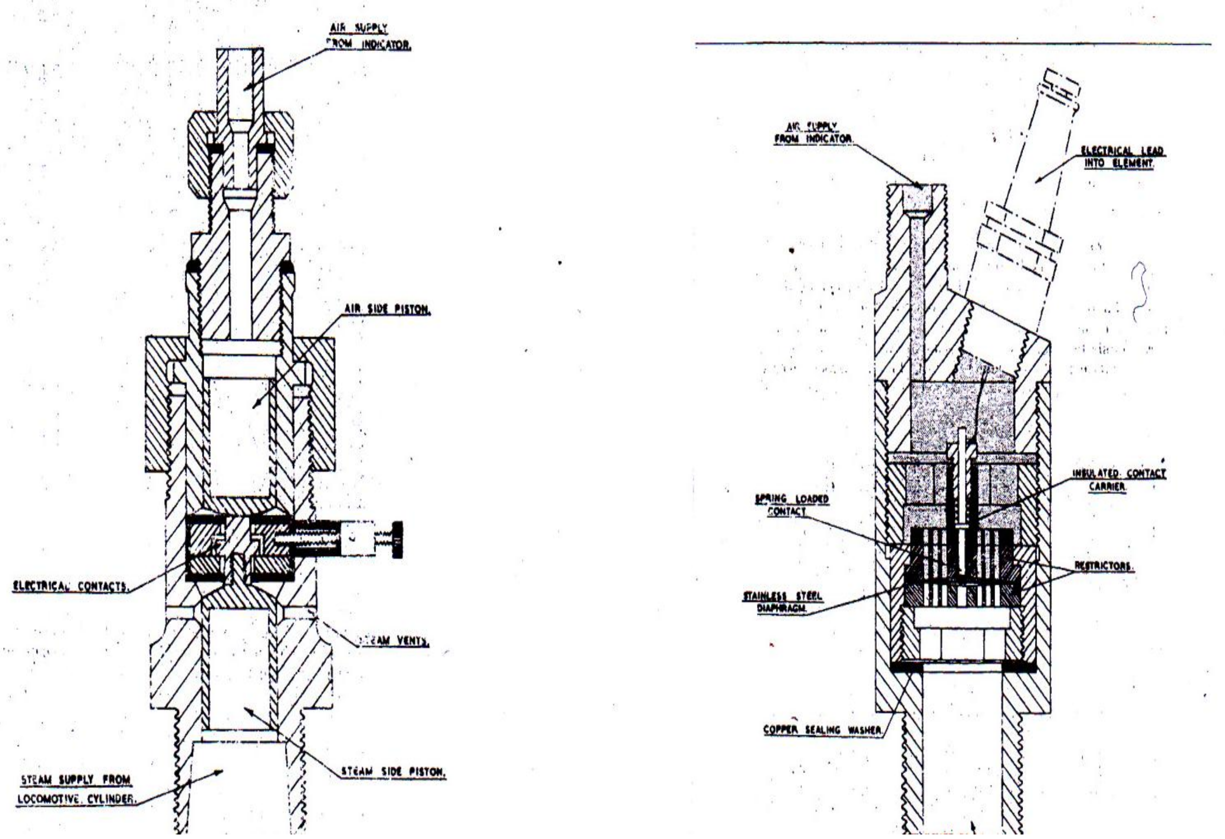
The indicator depicted is typical of latter day instruments still in use in the 1950s. The amplifying arm depicted was a later development, the early indicators that evolved in the 19th century featured simple vertical pen movement, with sometimes no more than one inch vertical maximum displacement, which might represent 200 lb or more. At five thousandths of an inch displacement per pound it would be unrealistic to expect a high degree of accuracy.

Spring were prone to weaken with use, and the amplifying arms could be subject to slight whipping at speed. All these factors, together with potential backlash in the several pin joints, and the inherent inertia and hysteresis effects will tend to exaggerate the diagram area.

I do not know who first coined the term "Indicated Horsepower", but I am tempted to suspect that "indicated" was a euphemism for "approximate".

Diagram areas were either determined by "Simpsons Rule", or by using an area planimeter, a tricky instrument to apply in practice with reliable and consistent results, especially on small areas.

The Farnbro' "Balanced Pressure" Indicator



Derby Pattern | Rugby Pattern

Figure 15 The Farnbro' Indicator

This indicator was originally developed for testing internal combustion engines. Many of the inherent problems associated with the traditional indicators were eliminated, but it's adaption for testing steam locomotives took some time to achieve a satisfactory standard of mechanical reliability, sensitivity and consistency.

The basic operating principle was "balance pressure", whereby the vertical displacement of The indicator arm was driven by a compressed air supply, the pressure was allowed to gradually fall, whenever the air pressure and steam pressure were equal, a high voltage spark punctured a pin hole through the recording paper. The paper was moving forward at a rate relative to the locomotive speed, as the air pressure fell to zero, a complete indicator diagram was traced. This was on radial basis rather than the usual stroke basis. A special machine was provided for converting the diagrams to a stroke base.

The Derby and Rugby versions differed in detail, the former used opposing pistons, and the latter a diaphragm. In both examples, a contact in the high voltage spark generating circuit was broken whenever the opposing pressures of air and steam were equal, thus releasing a spark. The pin from which the spark was released replaced the usual pen.

It was the usual practice at the Rugby test plant to take five or six sets of diagrams with the locomotive running under “steady state” conditions. The diagrams, 8 inches by 12 inches, were significantly larger than the usual steam indicator diagram. This significantly improved the accuracy of area measurement and determination of mean effective pressure.