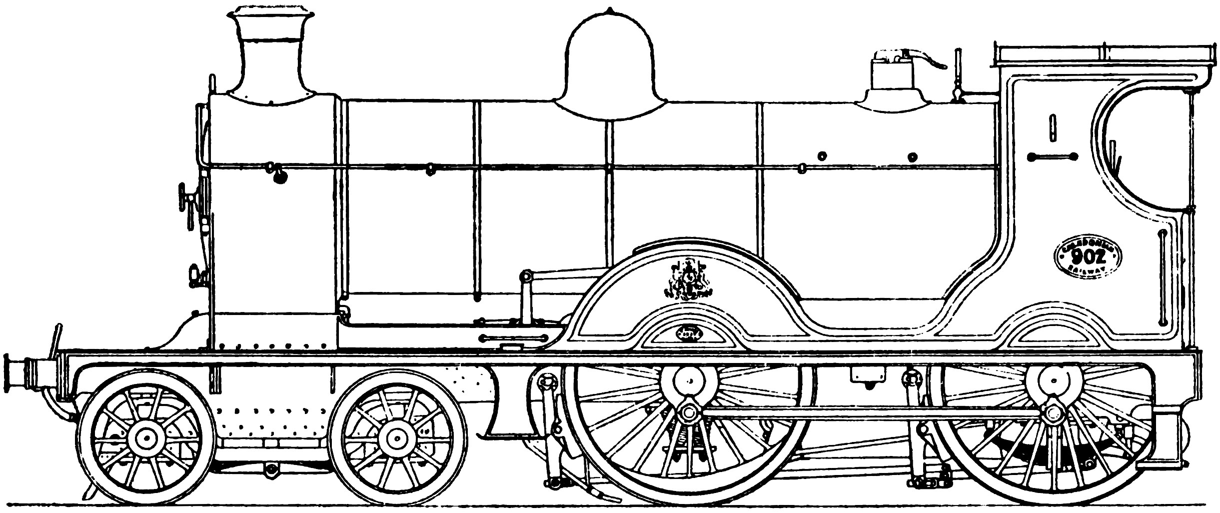

SOME OBSERVATIONS REGARDING LOCOMOTIVE PERFORMANCE

ADRIAN TESTER

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Steam locomotive testing and performance is a very wide topic – far too wide to be given justice in a twenty-minute talk – nevertheless hopefully by considering a couple of items – a peep at specific consumption characteristics and a method for comparing locomotive power – there may be something of interest.

Probably the most common locomotive performance measurement quoted is the specific coal consumption but this may take one or other of two forms – pounds per indicated horsepower per hour or pounds per drawbar horsepower per hour. Of these, specific drawbar fuel consumption is popular amongst locomotive enthusiasts however, it was not necessarily as revealing a factor as we might at first assume.

By way of example, let us consider the following table, which has been taken from *Nigel Gresley: Locomotive Engineer* by F A Brown, wherein an ex-L&NER class 'V2' 2-6-2 was contrasted with an ex-GWR 'King' class 4-6-0.

		'V2'	'King'
Load	tons	762	781
Average speed Badminton – Steventon	mph	64.6	68.5
Coal		Blidworth	Markham
Calorific value	BTU/lb	12,600	14,510
Specific coal consumption	lbs/dhp/hr	3.07	3.00
Boiler efficiency	per cent	69.6	63.0

Comparing the engines simply in terms of their specific coal consumption reveals that the 'King' used less coal, so it would appear to be the more efficient. But, from the information presented we may see that the 'V2' was given coal having a lower calorific value, so it would almost certainly have consumed more – would that have made it more, or less, efficient?

We may take this coal difference into account if we instead compare the engines in terms of the mechanical equivalent of heat.

James Prescott Joule demonstrated that 778 ft-lbs is the equivalent of one BTU or British Thermal Unit – the quantity of heat necessary to raise one pound of water one degree Fahrenheit. From this and knowing 33,000 ft-lbs per minute is equal to one horsepower we may establish that 2,545 BTU per hour is the thermal equivalent of one horsepower, and thereby we may compare the two locomotives in terms of their drawbar thermal efficiencies:-

For the 2-6-2

$$\frac{1 \times 2545 \times 100}{12{,}600 \times 3.07} = 6.58\ \%$$

and for the King

$$\frac{1 \times 2545 \times 100}{14{,}510 \times 3.0} = 5.85\ \%$$

Whence we discover the 'V2' was actually one-eighth more efficient than the 'King' – but this is not the conclusion that would have been drawn simply from comparing them on the basic specific fuel consumption figures. The moral is that such a simple comparison as specific fuel consumption is only possible when the coal was the same in the competing engines – but even then this is not necessarily sufficient.

In the defence of their champion, Swindon men could point out that their engine was hauling a heavier train more over it was running faster – for there were further factors that influenced the specific fuel consumption.

The lower diagram appearing in figure 1 is an example of a typical plot of a modern locomotive's coal consumption against drawbar horsepower for a range of different speeds. Immediately it may be seen that each individual speed curve follows a '**U**' or '**V**' shaped profile commencing at infinity for a light engine – since no drawbar power was being produced therefore all of the coal it consumed was used simply to propel itself. As the power increased so the consumption fell since proportionally more of the greater quantity of coal was being used in hauling the train as opposed to that consumed in driving the engine –

which remains sensibly the same. Finally the curve rose as the engine in effect became 'overloaded' and lost efficiency. From these curves we must also surmise that simple tabular comparisons of specific coal consumption between different locomotives can also be very misleading, despite the coal being the same, unless conditions of loading, speed, route etc, were identical.

Figure 2 shews the equivalent indicated horsepower curves for the same locomotive. Compared to the drawbar set, the indicated curves are seen to be largely reversed. For example, the highest specific coal consumption curves occurred at the *highest* speeds in the case of the drawbar values but in the case of the indicated characteristics they appear at the *lowest* speeds. The reason for this inversion was the increasing power the engine absorbed in propelling itself. Incidentally, this latter influence, in the form of the power-to-weight ratio of the engine, determined if the drawbar profiles referred to earlier, assumed a '**U**' or '**V**' shape, essentially, the higher this ratio, the flatter the shape of the characteristic.

Since the specific steam consumption quantifies the amount of steam needed to generate one horsepower for one hour, then as with the case with the fuel version, there were two forms one based on indicated horsepower and the other on drawbar horsepower. As the former includes the work done by the engine in driving itself it assumes a smaller value, than when expressed in terms of the drawbar power because then only the work done in hauling the train is considered. Thus, comparing the upper and lower diagrams of figure 1 reveals the differences between the water and coal drawbar characteristics. The water characteristic curve is roughly similar, but there is no corresponding rise in steam consumption at high powers displayed by the coal curve.

In some respects there is greater variation in shape between the indicated coal and water characteristic curves, for at low power outputs the coal consumption was at a minimum before rising as more power was demanded of the engine. In the case of the steam consumption curves (full open regulator) at the lowest power outputs the specific rate was little influenced by the speed of the locomotive. In this situation much of the 'consumption' was in fact leakage, throttling and other losses.

Of the two formats, basing the specific steam consumption on the indicated horsepower was the more revealing, but in either case, the lower the specific consumption the better since it implies the steam was being used more efficiently. However it should be appreciated, that although these figures represent a 'relative' rather than truly definitive value on the 'goodness' of the design, nevertheless they represent a useful yardstick, as to how efficiently the engine was using the steam it was provided and so in turn a measure of how good the steam circuit was from the mains steam pipe in the boiler to the chimney cap. For the magnitude of the power output at any point was determined simply by the steam rate divided by the specific steam consumption:-

steam rate ÷ specific steam consumption = horsepower

i.e. lb/hr ÷ lb/horsepower/hour = horsepower

Comparing locomotive performance on a specific consumption basis is not made any easier when we reflect that the magnitude and profile of the coal rate curves was also influenced by the boiler efficiency for the latter quantified the fraction of the heat present in the fuel that was transferred into steam and thus made available to the engine. Obviously the higher the value of the boiler efficiency the better since that meant less fuel was needed for the same steam output. Unfortunately obtaining truly accurate values for the boiler efficiency was far from easy and could only really be obtained either with the locomotive on the rollers of a testing station or else under strictly controlled road tests such as those conducted on the Continent and later on the Great Western.

More frequently in locomotive tests, boiler efficiency was approximated in a cruder form referred to as the evaporation. This, as its name implies, was simply the total quantity of water consumed divided by the total quantity of coal used in the same period. Normally it was expressed in pound per pound, although I suppose to be strictly accurate, it should be expressed as a simple ratio.

This simple concept, deceives how difficult it was in practice to obtain accurate values for the evaporation, although admittedly not as difficult as determining boiler efficiency. Secondly, being a simple ratio, it commonly ignored the influence that superheat and higher boiler pressure had. The former more than the latter, but both had the effect of increasing the heat content of the steam, so that even if the overall thermal efficiency of say two boilers was identical, the one having a superheater would, for example return a lower evaporation.

At this point we should consider the fundamental relationship describing the evaporation – a plot of true evaporation against firing rate approximates to half a parabola – a test station derived example appears as figure 3. Due to its strongly curved characteristic, the value of the evaporation, revealed by the 'gradient' or 'steepness' of the curve at any point was far from constant changing quite considerably over the total firing range of the locomotive. Short 'contour lines' recording evaporation rates are present on the diagram, from which it may be seen that at the lowest firing rates it assumed its maximum value before falling as more coal was fired, albeit the *quantity* of steam generated increased. Finally, it assumed a minimum value at the maximum possible firing rate for the boiler.

In order to allow for the effects that different steam pressures and temperatures had, when determining the efficiency as well as when comparing boilers having different operating parameters, it became the practice to derive the results initially from the equivalent evaporation, which was simply the total heat taken up by the boiler at selected firing rates divided by the latent heat of steam under atmospheric pressure (i.e. 970.4 BTU/lb) thereby giving rise to what was commonly referred to as 'evaporation from and at 212°F'.

Since specific steam consumption *and* boiler efficiency together determine the specific coal consumption – let us look at another comparison. The following figures have been taken from Mr E S Cox's paper ***'A Modern Locomotive History – Ten Years' Development on the LMS'*** wherein they were presented as a vindication of the benefits of large-lap valves. In this trial, which although not of the standard achieved on the Continent with constant speed tests or the Great Western's constant steaming rate methods, they are nevertheless truly reflective of the locomotives' performances in service. Furthermore, they represent an eminently fair comparison since the engines, including their boilers, were very similar in design while they hauled similar weight trains over the same road at nominally identical speeds to the same schedule whilst burning the same coal and experiencing similar weather conditions.

A Performance Comparison Between a LMS Standard Class 7 0-8-0 and
an ex-LNWR 'G2' 0-8-0 - Toton – Brent

		LMS 0-8-0	LNWR 0-8-0
Average weight of train	tons	900	940
Average running speed	mph	17.3	17.6
'Average' drawbar power (from coal consumption.)		333	346
Coal:- Pounds per mile		53.9	79.0
Pounds per ton mile including engine		.055	.076
Pounds per drawbar horsepower hour		2.8	4.02
Average per □ft of grate area per hour	lbs	39.4	59.0
Water:- Gallons per mile		46.1	50.0
Pounds per drawbar horsepower hour		24.0	25.4
Pounds per pound of coal		8.57	6.32

The specific coal consumption reveals a thirty per cent saving in favour of the new LMS Standard Class 7 0-8-0 fitted with large-lap valves over the ex-L&NWR 'G2' class 0-8-0. This economy has been put forward as proof of its superiority over the short-lap version fitted to the older engine.

However, if we inspect the specific steam consumption, we see the economy in favour of the large-lap engine was a mere five per cent or so – a difference as likely explained by its higher working pressure, tighter six-ring piston valves than specifically due to the possession of 1½ ins laps. The evaporation is seen to be 35 per cent higher in the new engine, and that is the overwhelming reason for the economy in coal it returned. Had instead, both boilers returned the same efficiencies, then the following specific coal consumptions would have been obtained:-

	LMS 0-8-0 lbs/dhp/hr	LNWR 0-8-0 lbs/dhp/hr
Both boilers having the efficiency of the 'G2' boiler	3.80	4.02
Both boilers having the efficiency of the G7¾S boiler	2.80	2.96

I suspect that the evaporation figures obtained for the Standard Class 7 0-8-0 are incorrect – this certainly appears to be the case if they are compared to the equivalent figures obtained from other locomotives used on this duty and route – both superheated *and* saturated.

Be that as it may, what these tests do however is to lend considerable support as to why the LMS was reluctant to fit large-lap valves to certain of its classes, a saving of 5 per cent in specific steam consumption would have been completely swallowed up in the increased maintenance costs that the longer travel created. Thus, the 'Austin Seven' class 0-8-0 was destined to be out-lived by its short-lap precursor even though the latter engines also suffered from 'undersized' axleboxes. Incidentally, some of the technical reasons for this lack of economy and thus why the LMS, having built large numbers of replacement locomotives under its 'scrap and build policy' it did not recoup the fuel savings it hoped, are explored in my book *An Introduction to Large-Lap Valves and Their Use on the LMS*.

The second moral is that, when making comparisons between different locomotives, even when engaged on the same duties over the same road etc, we must consider *all* of the factors influencing the magnitude of the specific coal consumption, for otherwise erroneous conclusions may still be drawn.

Turning now to the second part of this talk, it is an interesting exercise to compare different locomotives. When the chosen subjects have been the subjects of scientific testing then with certain reservations the process is straightforward. For most locomotives we are lucky if we are able to obtain a few indicator diagrams – how are we to proceed then?

Soon after its formation, the LMS conducted a number of locomotive comparison tests and one such trial, which might have some bearing this afternoon, was that concerning the

Caledonian Railway 'Pickersgill' 4-4-0 tested on a 300-ton train between Carlisle and Leeds and back – November 1924. For whatever reasons, although the engine and its crew made a game attempt, the performance was disappointing in terms of economy and power. In view of this, opinion has been expressed that a superheated 'Dunalastair' IV would have put up a superior performance. I do not know if this would have been so in economic terms but it is possible to gain an insight into its possible mechanical performance. To do this, we must determine the variation in power output with speed characteristics for the respective engines and then comparing the results.

A common way, when a sufficiently large number of horsepower values were available was to plot them on a graph before drawing a fair curve through their midst. Such an exercise was performed by Edward Poultney in respect of Caledonian Railway 'Breadnalbane' 4-4-0 Nº 772 in *British Express Locomotive Development 1898-1948*. The results apply to one journey made from Glasgow to Carlisle on 23rd February 1898, when a number of indicator diagrams were taken. Writing six years later, John McIntosh stated that when undertaking tests on the Glasgow-Carlisle road, indicator cards were taken every minute and I believe this was the case here. Mr Poultney drew two curves one represents the 'all-out' maximum performance of the engine and the other 'mean' power – quite whatever that implies. He referred to the cut-offs varying between 30 and 38 per cent combined with different regulator openings. These curves appear in figure 4 wherein it will be seen the maximum power output was 1,019 horsepower at 31 per cent cut-off and 52 miles per hour. Given a large enough number of horsepower values and a knowledgeable steam locomotives engineer, it is possible to obtain good results by this method, however, in inexperienced hands it is very easy for the draughtsman to become over optimistic.

It would appear the source for Mr Poultney's curves was a diagram that appeared in *The Engineer* 23rd December 1898 – the relevant portion of this chart appears as figure 4b. In it, the horsepower, mean effective pressure and speed appear as continuous traces. Notwithstanding the large number of indicator diagrams used, to produce a continuous record in this manner from what in effect comprised a series of discrete snapshots was fraught with difficulty, and if it was to be even reasonably accurate, demanded a large number of check calculations, necessary to allow for the effects of inertia, gravity and acceleration on the train. If they are ignored, then some peculiar values can result. Mr Nock tabulated some figures he extracted from *The Engineer* diagram - these appeared on page 44 of his book *'The Caledonian Dunalastairs'* and for convenience are repeated in the following table, however, the opportunity has been taken to introduce an additional column recording the 'engine constant'.

Now the indicated horsepower of a locomotive is obtained from the formula:-

$$\text{Indicated horsepower} = \frac{Pm \times L \times A \times N}{33{,}000}$$

where:-

Pm = mean effective pressure
L = cylinder stroke (ft)
A = area of one piston (sq. ins)
N = Nº of working strokes per minute

Inspection of this formula reveals it comprises two variables, mean effective pressure and number of working strokes, and two items determined simply by the physical dimensions of the engine. Thus it is possible, for any given engine, to simplify the calculation so that it reduces to the product of a constant, the mean effective pressure and the speed, so, taking Nº 772 as an example, 6ft – 6ins wheels, 19ins × 26ins cylinders.

Hence:-

$$= \frac{Pm \times 26 \times 19^2 \times \pi \times 2 \times 2 \times 5280 \times mph}{12 \times 4 \times \pi \times 6\frac{1}{2} \times 60 \times 33{,}000}$$

which reduces to:-

$$\text{indicated horsepower} = .32089 \times Pm \times mph$$

Comparing this constant of .32089 with those values appearing in the table demonstrates the difficulty of reconciling the instantaneous values of horsepower, speed and mean effective pressure into a continuous record and thus is indicative some of the errors present in the chart.

Caledonian Railway – Express Engine 'Breadnalbane' 4-4-0 Nº 772

Location	Speed	Regulator opening	Cut-off per cent	Boiler pressure lbs/sq in	Mean effective pressure lbs/sq in	Indicated horsepower	Value of the engine constant
Rutherglen Junction	50	Full	31	180	65	1,020	.3138
Newton	40	Full	31	177	71	870	.306
Uddington	58	Full	31	167	47	660	.242
Before Motherwell	40	Full	31	180	75	900	.300
Flemington	30	Full	31	180	78	770	.329
Garriongill Junction	27	Full	38	180	90	950	.391
Law Junction	31	Full	38	180	90	950	.3409
Braidwood	26	Full	38	170	73	850	.4478

Engine constant obtained by back calculation from indicated horsepower ÷ (mean effective pressure × speed)

Not long after these test results had appeared in *The Engineer* Professor Dalby analyzed some indicator diagrams obtained from Professor Goss' work conducted on the stationary testing station erected at Purdue University. He found that the mean effective pressure recorded on a series of cards taken at constant cut-off, fell lineally with increase in speed. From this relationship it was possible to derive a parabolic curve that closely replicated the indicated horsepower capacity of the engine. More importantly, this accurate method was very simple to apply – avoiding the difficulties and skills associated with drawing parabolic curves by eye – all that it requires is a reasonable number of indicator cards be available, ideally for a spread of cut-offs.

LMS built Compound Nº1065 was tested the following February hauling 300 tons on what was the direct equivalent of the train hauled by Caledonian engine Nº 124 (LMS Nº 14466). A summary of the regulator and cut-off position has survived for the Compound's runs and these suggest that on the easier sections it was run in notch 6 with later cut-offs, notches 7 and 8, used on the steeper portions. Another table, reproduced in part below, recorded the indicated horsepowers and mean effective pressures obtained from Nº1065 running in notch 6, which was the equivalent of 67 per cent cut-off in the HP cylinder and 55 per cent in the LP ones.

LMS Railway – Compound 4-4-0 Nº 1065

Speed mph	Indicated horsepower			Mean effective pressure lb/sq ins	
	HP	LP	Total	HP	LP
38.4	417	244	902	71.2	34.3
40.6	481	266	1013	78.3	35.4
48.6	464	284	1032	63.15	31.5
43.8	426	261	948	64.2	32.1
33.6	376	232	840	73.9	37.2

The mean effective pressure values figures have been plotted in the diagram 5a from which two curves were developed – the upper one for the high pressure cylinder and the lower for the low pressure cylinders. Calculate the engine constants, for the HP and LP cylinders, remembering there was only one of the former and two of the latter, then for a selection of speeds multiply them with the appropriate mean effective pressure derived from the initial curve. From these curves, we may establish the corresponding horsepower curves, these appear in the diagram 5b with the upper horsepower curve representing the combined total from all three cylinders present in the locomotive.

Nº 1065, although LMS built, had been fitted with liners so its cylinders were reduced to the former Midland dimensions of 19ins dia. HP cylinder and 21ins for the LP cylinders – the valve settings for either cylinder diameters remained the same having been decided from some tests conducted on Nº 1011 in 1923. Two sample horsepower values obtained from this latter engine running in notch 6 appear in O S Nock's *The Midland Compounds* on page 60. As Nº 1011 was fitted with 7ft driving wheels, if we reduce the speeds associated with these power outputs in the ratio 6¾:7 or .9643 we will approximate to the running conditions of Nº 1065, whence:-

883 horsepower at 36.6 mph becomes 883 horsepower at 35.29 mph
and 969 horsepower at 43.3 mph becomes 969 horsepower at 41.75 mph

This pair of 'spot' horsepower values, with their speeds adjusted for wheel diameter, appears in figure 5b, indicated by triangles, and serve to demonstrate further how effective this simple technique is.

Since a selection of indicator cards taken from a superheated 'Dunalastair IV' Nº 139 appear in O S Nock's *The Caledonian Dunalastairs* page 74 it is possible to repeat this same exercise for that engine running in notch 3 or a cut off of 32 per cent. The relevant curve of mean effective pressure against speed appears in figure 5c. It will be seen that for both locomotives the curves describing the fall in mean effective pressure with speed are subject to some scatter, hence the need for several cards in each cut-off. This is normal and appears primarily due to errors is ascertaining the speed of the locomotive when the cards were taken.

Caledonian Railway – Express Engine 'Dunalastair IV' 4-4-0 Nº 139

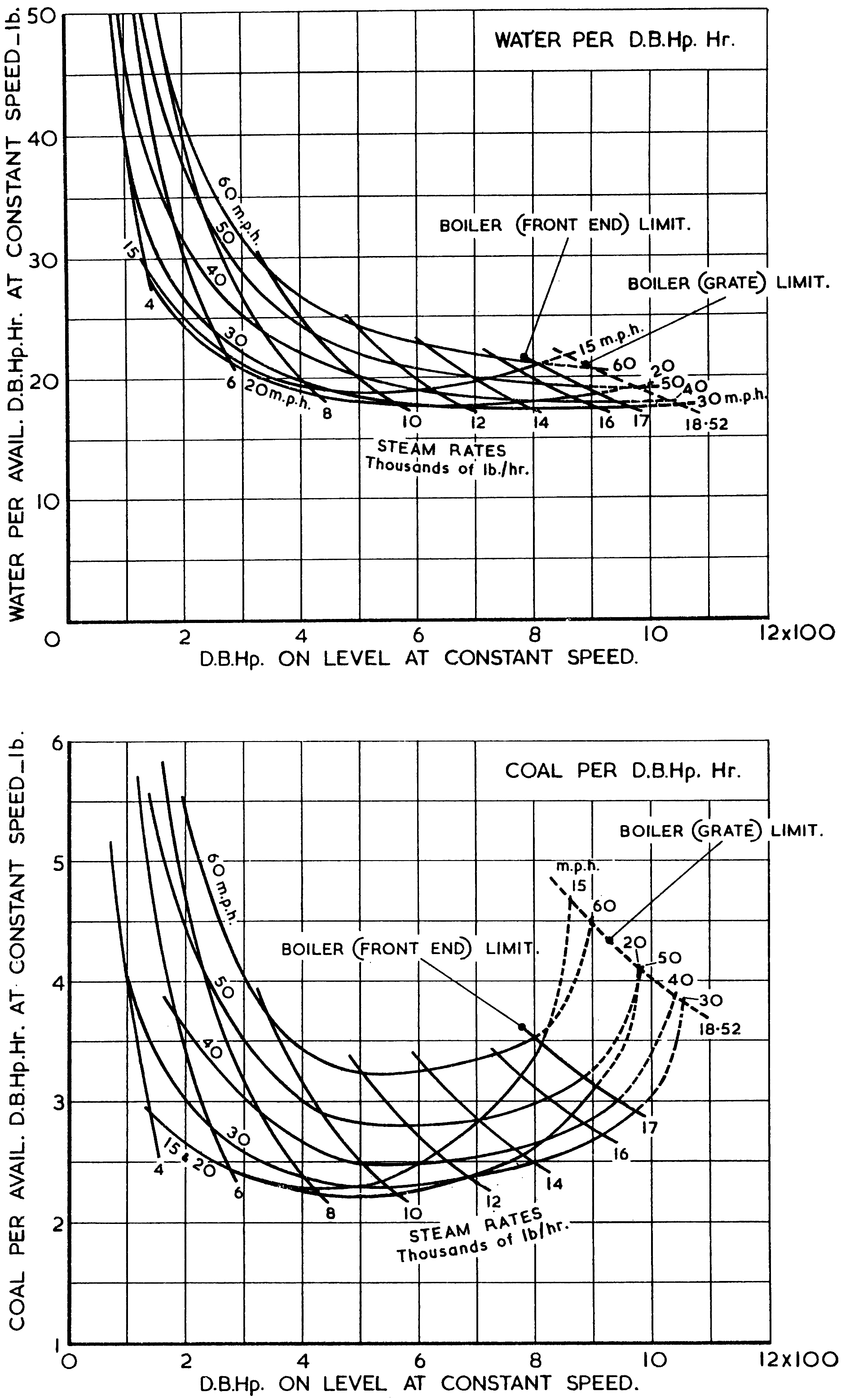
Speed mph	Indicated horsepower	Mean effective pressure lbs/sq in	Value of the engine constant
32½	888	77	.3548
42	904	61	.3528
30¾	836	77	.3531
26	684	74	.3555
23¼	654	81	.3473
21½	636	84	.3521
21½	636	84	.3521
26	720	78	.3550

Having established the alignment of this curve – it is usually better to draw it by eye rather than using any regression method such as least squares, as the points are not necessarily all of equal accuracy – the smooth predicted curve of indicated horsepower against speed may again be derived as per the Compound

Comparing the two locomotives records that at similar speeds, the Compound could produce slightly more horsepower running in a HP cut-off of 67 per cent cut-off (which approximated to 27½ per cent in a simple), so for a Caledonian Dunalastair IV to have produced the same power as a Compound would have necessitated it running in a later cut-off than notch 3 or 32 per cent, assuming that the boiler was capable of generating sufficient steam. This performance would however almost certainly, have been obtained at the cost of a significantly lower boiler efficiency due to the presence of a smaller grate area.

Typical Drawbar Characteristics

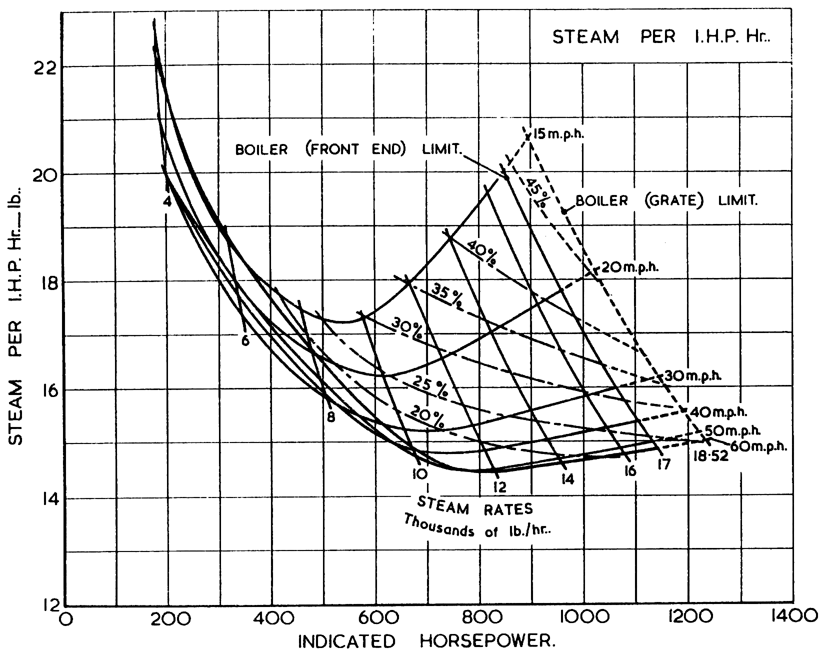
Fig 1



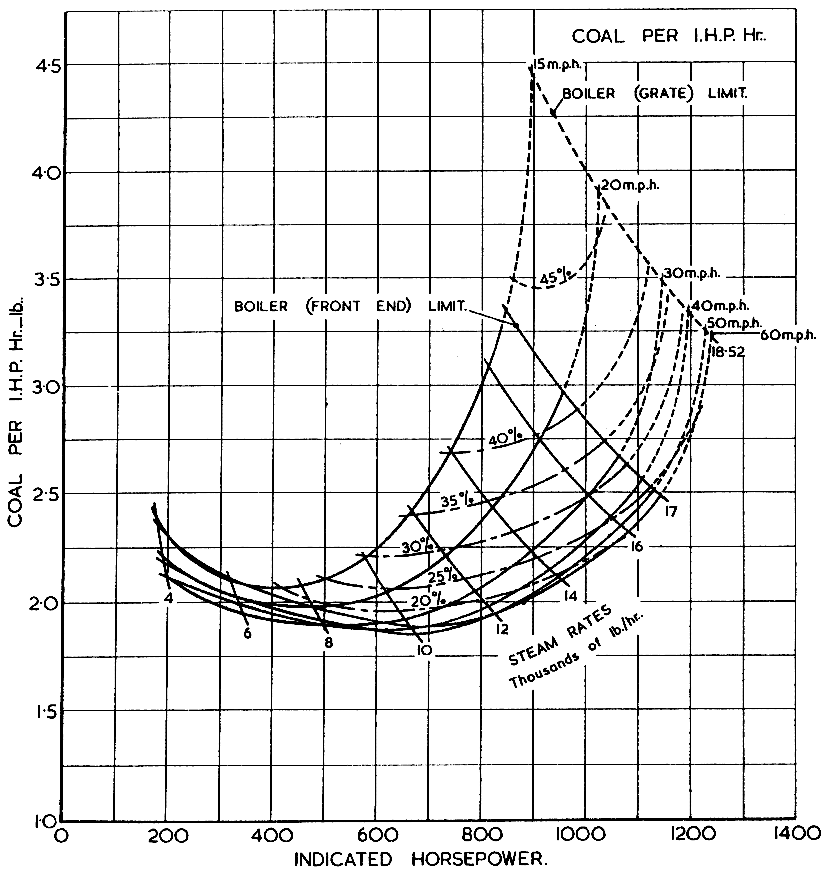
Drawbar horsepower curves for LMS/BR Class 4 2-6-0 - Blidworth Coal (12,560 BTU/lb)

Typical Indicated Characteristics

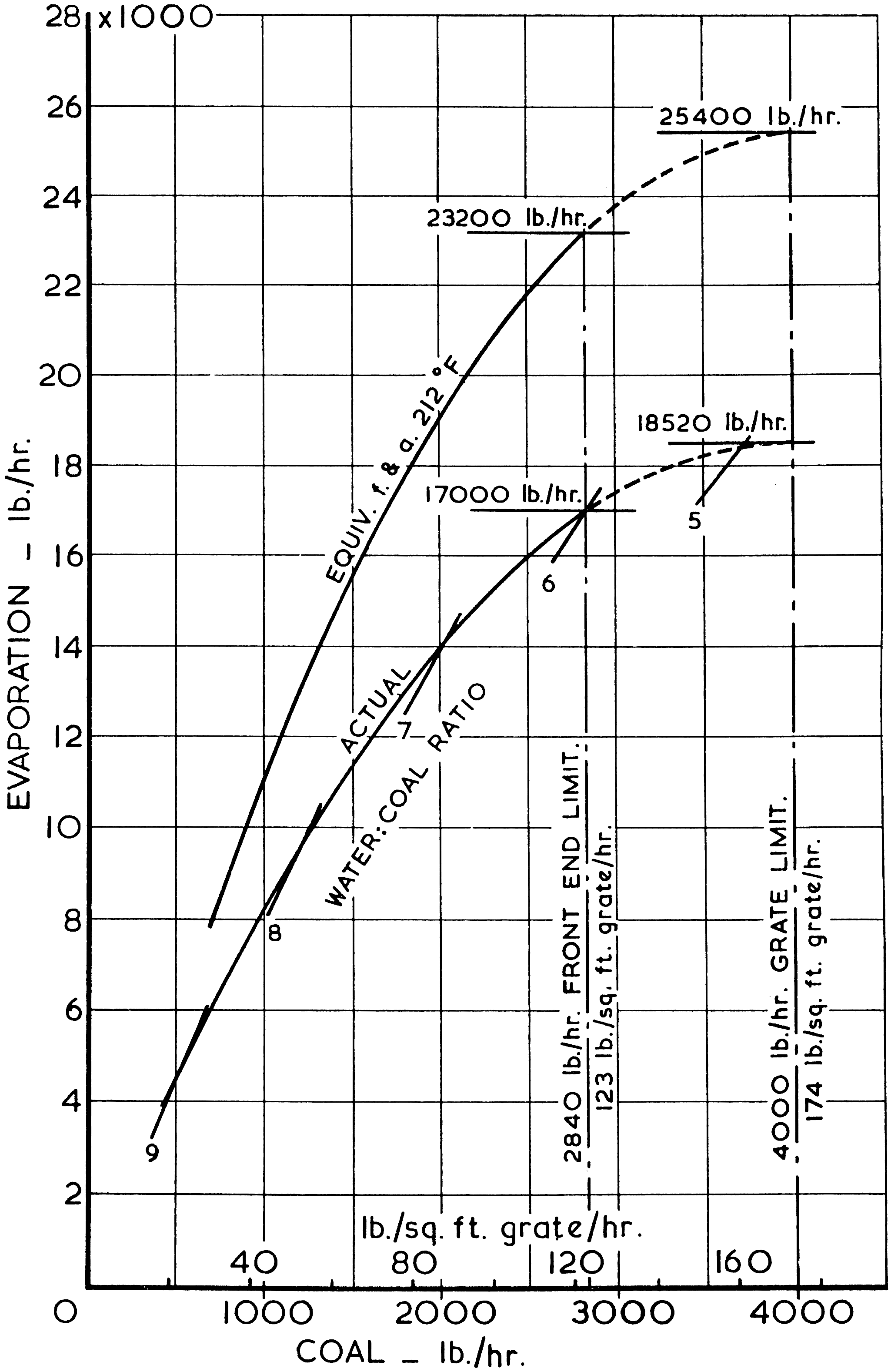
Fig 2



Cut Offs shown refer to Maximum Steam Chest Pressure.



Indicated horsepower curves for LMS/BR Class 4 2-6-0 - Blidworth Coal (12,560 BTU/lb)



Evaporation curves for LMS/BR Class 4 2-6-0 - Blidworth Coal (12,560 BTU/lb)

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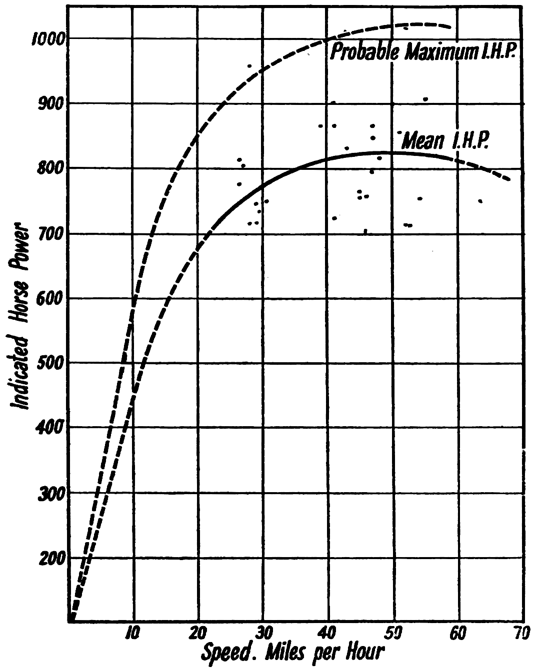
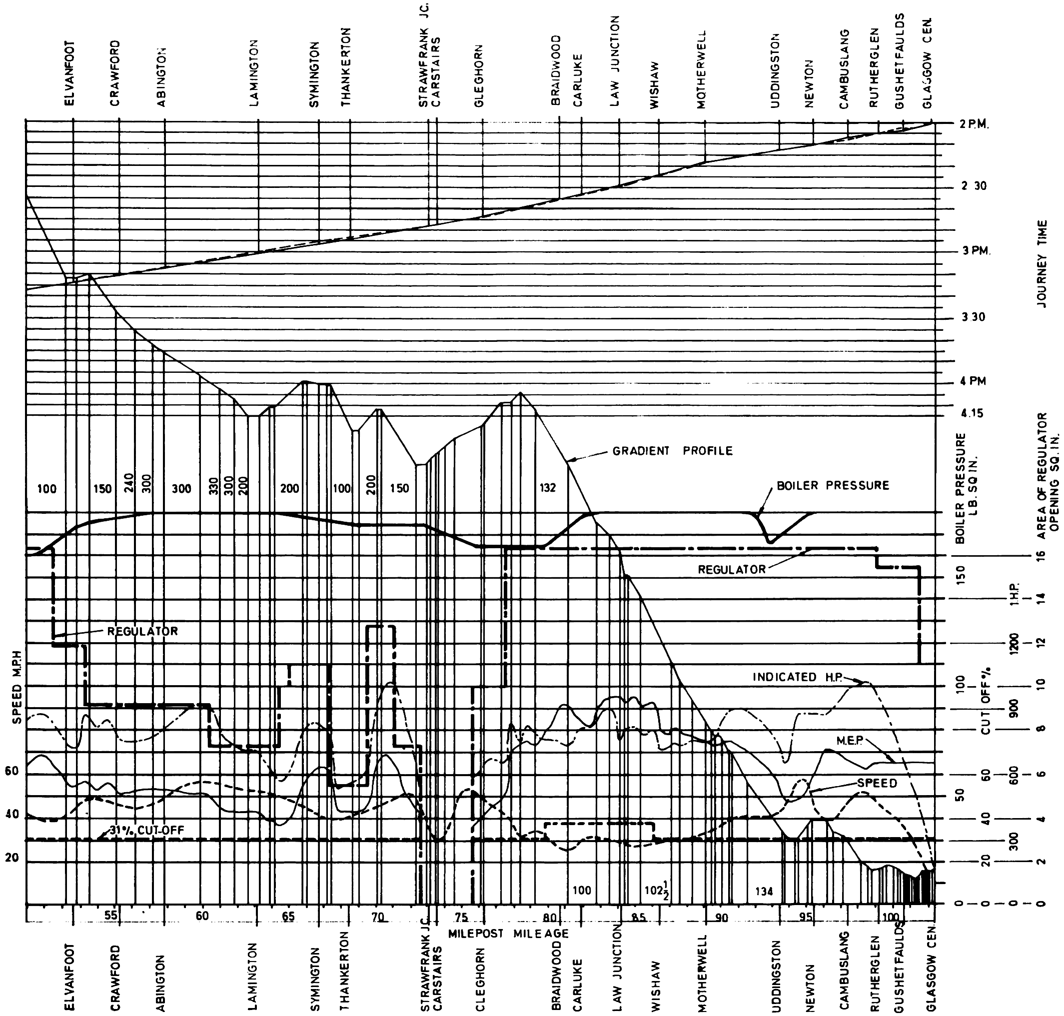
Horsepower Curves for Caledonian Railway Breadnalbane 4-4-0

Fig 4

(a) Variation in Indicated Horsepower with Speed - CR Saturated Breadnalbane 4-4-0 No. 772 - 1898

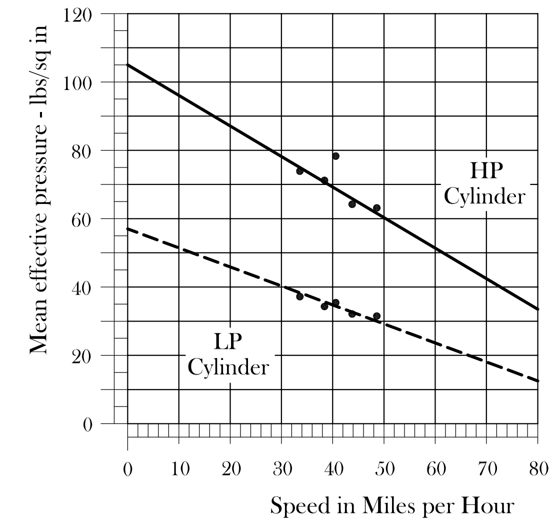


(b) Performance Curves Derived from Test Run Between Glasgow and Carlisle by Caledonian Railway Saturated Breadnalbane 4-4-0 No. 772 - 1898

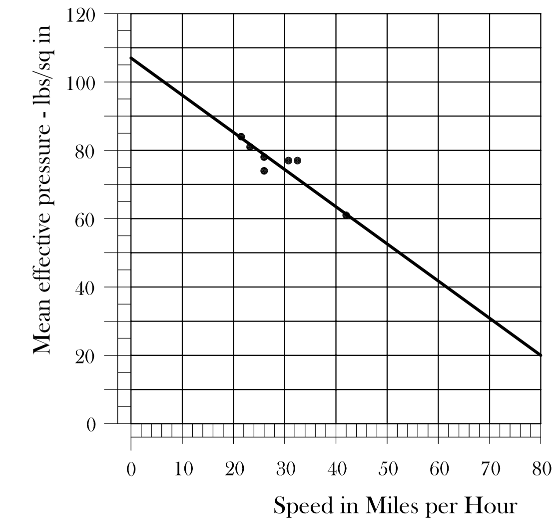


Variation in Mean Effective Pressure & Indicated Horsepower with Speed - LMS Compound & CR Dunalastair IV Fig 5

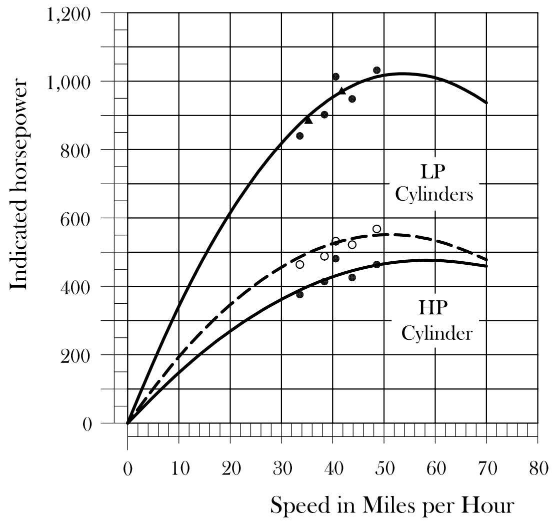
(a) Fall in MEP with Speed - LMS Compound - cut-offs 67% HP, 55% LP



(c) Fall in MEP with Speed - CR Superheated Dunalastair IV - cut-off 32%



(b) Variation in IHP with Speed - LMS Compound - cut-offs 67% HP, 55% LP



(d) Variation in IHP with Speed - CR Superheated Dunalastair IV - cut-off 32%