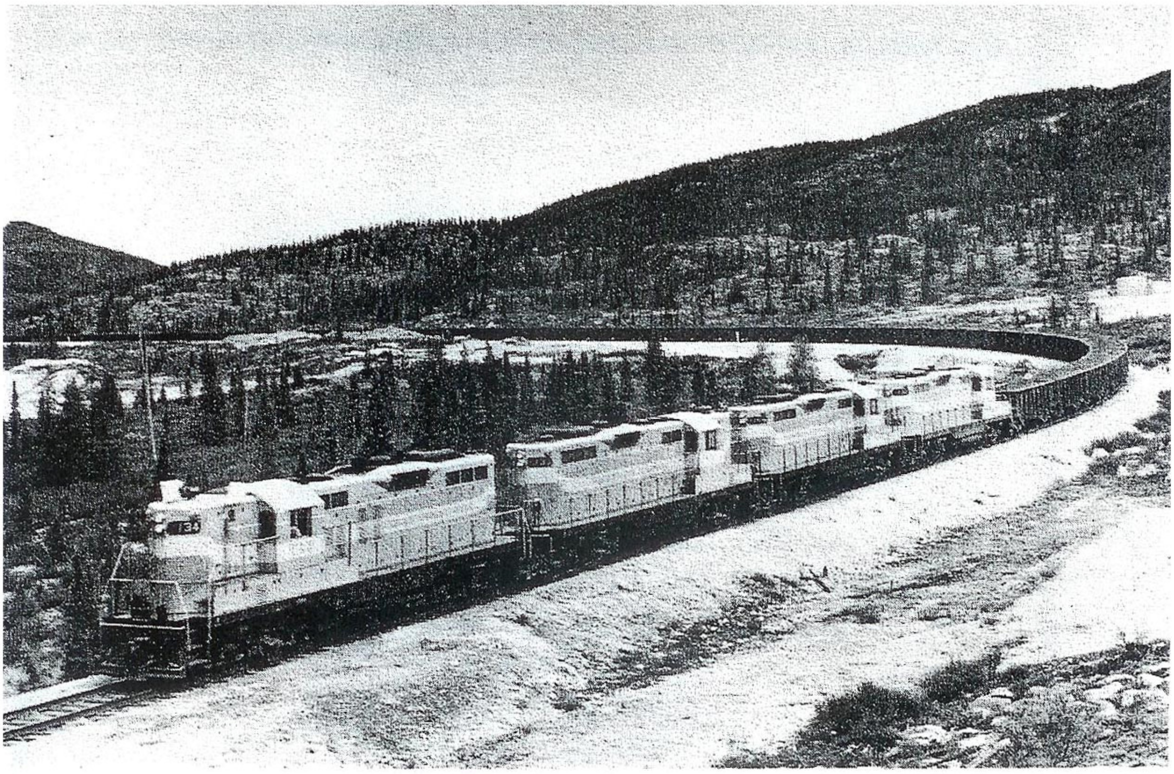
Two Point Four Pounds per Ton and The Railway Revolution

A Ramble through the History of Railway Mechanics

Doug Landau - 2003

Transcribed by Chris Newman from a photocopy of the original – July 2013



The Power of the Railway - Sixteen Thousand Tons On The Move

Prologue

Over the last two hundred years or so mankind has witnessed countless inventions. Some might think too many. Refrigerators, lawn mowers, washing machines, bicycles, gramophones and the like have all made their contribution. Perhaps the most civilising of all inventions were the WC and a main drainage system. Together they transformed the health of nations. But none of these, in themselves, could or did transform the very fabric of society. The revolution that might be dubbed the "Modern Age" was delivered by rail.

The railway was more than just an invention, it was a whole system. Like the Internet revolution now unfolding, it was, in essence, a communication system.

The Earliest Railways

The beginnings of the railway are obscure. The first recorded mention was in *Cosmographioe Universalis* by Sebastian Munster published in 1550. It described a narrow gauge railway with wooden tracks at a mine in Leberthal in the Alsace district of N.E. France. In 1556 an illustration of rail trucks appeared in *De Ria Metalica* by George Bauer. Such railways, with flanged wooden wheels, quickly became widespread in the mining districts of Europe at this time. Before the end of the sixteenth century the first mining railways had arrived in England. Iron rails first appeared in Cumberland in 1738, Coalbrookdale in 1767, and Sheffield in 1776. These early iron rails were sometimes of the plate or 'L' shaped variety, used in association with unflanged wheels. The first public goods line, the Surrey Iron Tramway opened in 1803, was of this type. After some initial popularity, by 1825 the plate rail system was in serious decline in favour of the edge rail and flanged wheel.

The Power of the Railway

There are two orders of mechanical invention: static and dynamic. The designer of the former, such as a bridge or mast, encounters the problem of strength as a primary concern. Dynamic devices introduce two additional design problems, power and control. From the outset the inherent guiding properties of the rails resolved the problem of control. The development of points, like the railway itself, another anonymous invention, introduced some vital flexibility into the basic control system. The decision to use flanged wheels rather than flanged track was another important design decision taken very early on. These first railways did nothing to increase the available power; that was still confined to man, horse, donkey or winch. What it did do was significantly reduce the power required to move a load. Even at its simplest, with crude wooden wheels on wooden rails, loads many times greater could be pushed or pulled compared to dirt tracks or cobbled roads. The basic vehicle technology at this early stage was long established, what was novel was the flange, the rail and the points.

By the time the world's first public goods line, the Surrey Iron Tramway, was opened in 1803, this tractive efficiency would have improved still further. The importance of this cannot be over emphasised because the mechanical motive power which was imminent was heavy, cumbersome, and low in power. A good way to visualise the significance of rail is to compare the lumbering road traction engine to the fleetness of foot of even quite early locomotives.

The First Trunk Railways

By the time of the opening of the first passenger-carrying railways such as the Stockton and Darlington in 1826 and the Liverpool and Manchester in 1829, the basic rolling resistance was about 3.5 lbs/ton, not so very far away from the figure of two point four pounds per ton achieved in the modern railway era. In other words a force could move load over nine hundred times greater. The importance of this, even if only two-thirds as good in 1830, was that even in the infancy of its early development, the steam locomotive could haul prodigious loads.

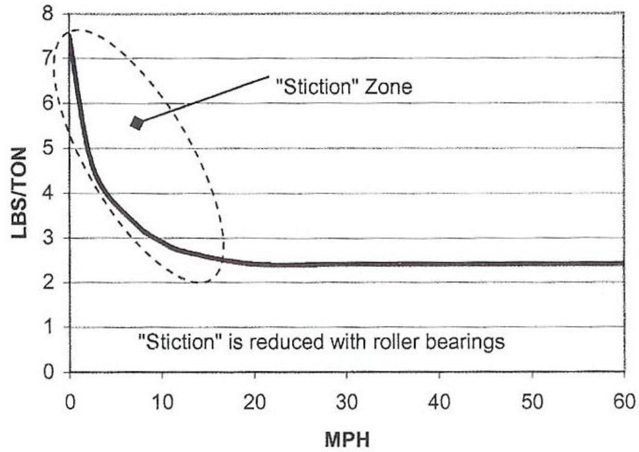


Figure 1 Basic Rolling Resistance - BR Stock

Note the stiction zone before things get moving, but even at worst, the force/resistance ratio is over 250. Once on the move other resistive forces will come into play, namely track resistance and aerodynamic drag. These will be considered later.

The low tractive force requirements were important to the early economic development of the railways. It held in check the capital investment in motive power required to move useful loads.

From the late 1830s onwards trunk railway lines began to appear thick and fast, the first being the Grand Junction Railway in 1837 and later that year the London & Birmingham Railway which was completed in 1838. It has been said that the early railways can be dated by their ruling gradients. There is perhaps some truth in this as long as the topography was not too severe to make gentle grades too costly to achieve.

Table 1 Gravity Horsepower on Inclines

Year	Railway	Ruling Grade		Lbs/ton	Gravity HP/100 tons	
					Up at 50 mph	Down at 60 mph
1837	London & Birmingham	1 in 330	16 ft/mile	6.8	91	-107
1850	Great Northern	1 in 178	30ft/mile	12.6	168	-201
1868	Midland London Extension	1 in 120	44ft mile	18.7	249	-299
1845	Sheffield, Aston & Manchester	1 in 100	53ft mile	22.4	299	-359

The first three listed all faced the same problem of crossing the Chiltern Hills north of London. The increasing ruling grades reflect the growing confidence in locomotive power. But as the last example listed shows (out of chronological order) that where hard economics intervened, easy gradients were often ruled out from the earliest days. Another example of this is on the London & Birmingham listed above; they could do no better than 1 in 70 for the first mile out of Euston to the top of Camden Bank. As a consequence in the early years trains were rope-hauled up the bank until 1844.

Throughout this period the technology of the permanent way made considerable strides. The earliest metal "fish-bellied" rails were made of cast iron; these were quite short in length. In about 1825 wrought iron rails about 15ft long came into use. Although these were a definite improvement, they were relatively soft and had fairly short lives. The first rolled steel rails were introduced by the Midland Railway in 1857and quickly became the universal practice. All these changes brought about some reduction in the resistance of trains.

By 1867 most of the major trunk routes were in place. Table 2 gives a snapshot of railway intercity scheduled speeds at that time.

Table 2 Some Intercity Speeds from London - 1867

Name of Town	Miles	Hrs: Min.	MPH
Great Western			
Reading	36	0:44	49.1
Oxford	63½	1:23	45.9
Birmingham	129¼	3:00	43.1
Exeter	193¾	5:00	38.8
Penzance	328	11:48	27.8
North Western			
Rugby	82¾	2:0	41.4
Holyhead	264	6:40	39.6
Edinburgh	400	10:30	38.1
Glasgow	405¼	10:42	37.9
Birmingham	113	3:00	37.7
Manchester	188½	5:00	37.7
Inverness	613¼	18:05	33.9
Great Northern			
Peterborough	76½	1:37	47.2
Manchester	201	4:45	42.1
York	191	4:40	40.9
Newcastle	275	6:55	39.8
Edinburgh	399½	10:30	38.0
Great Eastern			
Colchester	51¼	1:15	41.0
Cambridge	57⅓	1:30	38.2
Midland			
Leicester	99	2:10	45.7
Leeds	201	4:45	42.3
Manchester	182	5:05	35.8
South Eastern			
Dover	88	1:55	45.9
Ramsgate	97	2:50	34.2

End to end speeds approaching, or at times even exceeding 40 mph, meant that journey times previously measured in days were now being measured in hours. Even today, given present traffic conditions, it might not always be that easy to match some of these times, city centre to city centre. Up to the advent of the trunk railway, long distance travel inland had been wholly reliant on the horse-drawn stage coach of about 15 seat capacity. This was from around 1650 onwards. Travel was, at best, limited to 70 or 80 miles a day.

From about 1750, a network of Tar-Macadam "Turnpike" roads were developed between principal cities. Turnpike means barrier, a point where tolls are collected (shades of things to come?) By 1775 a little over 100 miles/day could be covered, but with overnight stays in coaching inns, the very best overall journey times averaged little more than 5 mph. Travel was an expensive business, the cost of which was dramatically reduced with the coming of the railway. Some early comparative tests showed that a horse working on the stage coaches would typically achieve a little over 5 ton miles a day. The figure for a horse working a railway was nearly 200 ton miles a day.

Freight

A similar revolution in the movement of goods was also brought about by the railway. Few canals of any significance were built in the second half of the 19th century. Before the railways, even the largest of horse teams can only rarely have moved tonnages in double figures, whereas loads were now being measured in hundreds of tons. In 1852 freight traffic in the UK overtook passenger traffic as the main source of revenue.

The Rise in Speed

Up to the end of the nineteenth century there was little further progress in intercity speeds, but demand and train loads steadily increased. The famed "Railway Races to the North" in 1895 showed the potential, always provided a high power weight ratio could be achieved. End to end average speeds as high as 67 mph were achieved. Early in the 20th century one or two mile a minute schedules started to appear, but it was in the 1930s that the steam-operated railway reached its zenith world-wide. In Britain, by the summer of 1939, over 12,000 miles per day were being covered at schedules of 60 mph or more, the fastest being 71.9 mph. In the USA in 1940 no less than 81,391 miles were run daily, although the first diesel electrics were by then in service. The fastest steam schedule was operated by the Chicago, Milwaukee, St. Paul & Pacific Railroad at 81 mph start-to-stop over the 78.3 miles from Sparta to Portage. Sustained 100 mph running was routine. In the post-war period steam in Britain never quite recovered to pre-war levels. By 1958 the 60 mph figure was no more than 8,890 miles per day.

The coming of the diesel electric, and the WCML electrification in the 1960s, brought about a huge advance in intercity average speeds. The commercial introduction of the HST 125 diesel electrics in 1976 brought about a further speed fillip, and booked averages of over 90 mph appeared for the first time.

Table 3 British Railway Train Speeds 1939 – 2000: Weekday Mileage								
Schedule	**Year**							
	1939		**1958**		**1968**		**1976**	**2000**
	Miles	Number	Miles	Number	Miles	Number		
58 mph	18,717	203	15,193	172			Publication of comparative data ceased in 1970	
60 mph	12,916	116	8,980	103	60,009	1,369		
62 mph	4,580	33	1,628	240	52,527	940		
64 mph	1,829	11	901	10	44,876	808		
65 mph	1,606	9	654	7	37,019	724		
70 mph	730	4	-	-	20,678	239		
75 mph	-	-	-	-	10,782	113		
80 mph	-	-	-	-	1,787	14		
90 mph	-	-	-		-	-		
Fastest	71.9		67.8		81.9		95.7	113.6

The completion of the ECML electrification in 1991 brings the advance in speed in the second half of 20th century almost up to date. By 1992 no less than one hundred and nineteen 100 mph booking had appeared in the ECML timetable. Whilst overseas railways could claim the fastest trains, the average standard of speed provided by British Railways was unmatched.

There will long be speculation as to how far steam might have progressed had its development continued, but to some extent the form of motive power was only of secondary importance. The most significant factor behind the speed revolution was the steadily increasing power weight ratio of the train. This was mainly achieved by more powerful traction units, but train weights have also tended to reduce. The 16, 17 or even 20 coach trains from the days of steam became a thing of the past, although in recent times 20 coach formations have appeared on the Eurostar.

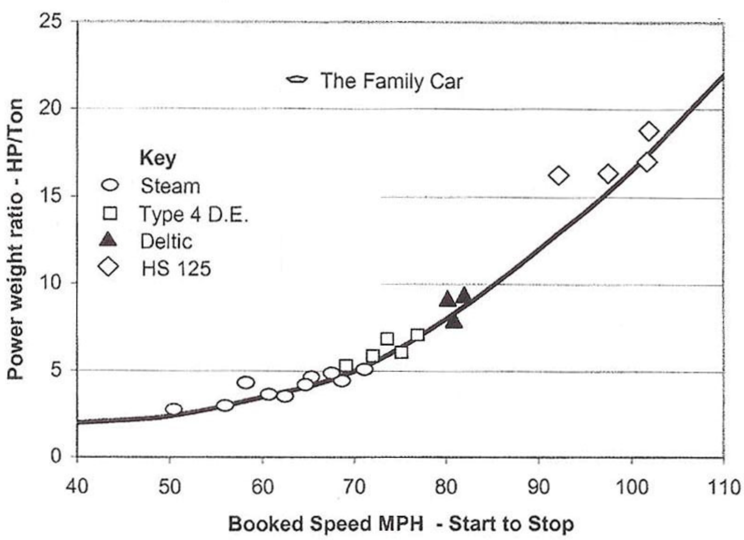


Fig 2 - Speed vs. Power Weight Ratios – the General Trend, UK Practice

The scatter in the diagram reflects the varying topographies of the routes involved. What is striking from Figure 2 is that on the railway, a little horsepower goes a very long way. Note that the family car, of about one ton weight, at 60 mph requires power in the order of 5 to 1 compared to rail.

To some extent this advantage to rail is eroded by the generally more massive engineering of railway rolling stock compared to road vehicles, but in most operating circumstances a significant operating advantage in energy usage remains with the train. This is detailed further below.

The Mechanics of the Train

The essential mechanics of the train are well-established; three principal components are involved.

1	**Mass**	Acceleration & braking, generally taken as 7 or 8% more than gross weight to allow for the rotating masses.
2	**Gravity**	The affect of gradients.
3	**Traction**	Friction, track resistance, aerodynamic drag and ancillaries.

Only Item 3, traction, can be directly influenced by design, but if this reduces weight, elements 1 & 2 will be beneficially affected.

For locomotive-hauled passenger rolling stock the resistance formulae listed below are typical:

Jointed Track $R = 2.4 + V/20 + V^2/1100$ lbs/ton

Welded Track $R = 2.4 + V/26 + V^2/1100$ lbs/ton

Strictly speaking, the three elements of the formula are no more than a simplified mathematical convenience to solve the experimental results. But they do, nevertheless, approximate to the following elements:

1st Term	Basic journal friction and wheel rolling resistance.
2nd Term	Track resistance, i.e. track deflection, flange friction, miscellaneous ride losses and joint transition where present. Curvature is not covered in this general formula; it is seldom of much significance on mainline work.
3rd Term	Aerodynamic Drag. Although there is no logical relationship between weight and drag (wetted area, displacement and form drag are the key factors), it is convenient for the engineer to express aerodynamic drag in this form, based on the experimental results.

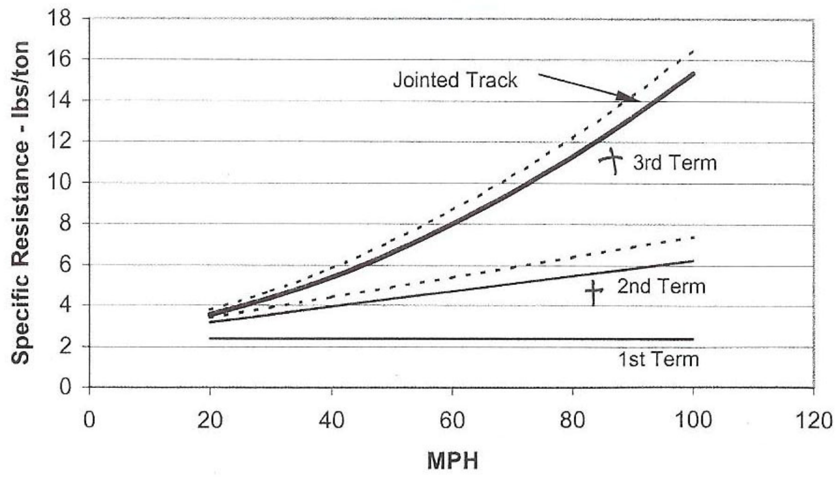


Fig 3 - Specific Resistance – Loco-hauled Passenger Stock

These formulae show close compliance when tested against actual results with predictable motive power units such as diesel electrics. The traction horsepower per ton on welded track at 60 mph is as low as 1.3 hp/ton. The total savings attributable to welded track with a 400 ton trailing load is shown in Table 4.

Table 4 Welded Track Power Savings # 400 ton Loco hauled train					
Speed (mph)	60	70	80	90	100
Power Saving (hp)	72	98	128	162	200
# Savings shown include reduced locomotive resistance & losses					

Road v Rail Economics

The high specific power requirements for road vehicles shown in Figure 2 will be noted. The ratio is about 5 to 1 in favour of rail, but to some extent the comparison shown is misleading since it is based on weight in terms of horsepower/ton. Rail loses some of its inherent advantage on account of higher weights per passenger seat. The crucial comparison therefore, is the energy required per seat mile, and here the load factor achieved will be significant. Some comparative figures are shown in Table 5 & Figure 4 below.

Table 5 Horsepower-Hours/100 Passenger Miles @ 70 mph on Level						
Formation		**Passenger Load Factor**				
		0.2	**0.4**	**0.6**	**0.8**	**1**
Rail	8 Cars + D.E. Loco	25	12	8	6	5
	11 Cars + D.E. Loco	21	10	7	5	4
Road	5 Seat Small saloon	36	18	12	9	7
	5 Seat Medium Saloon	50	25	17	13	10
	60 Seat Coach	26	14	9	7	6
Horsepower-Hours for rail include acceleration from rest, negligible for road vehicles.						

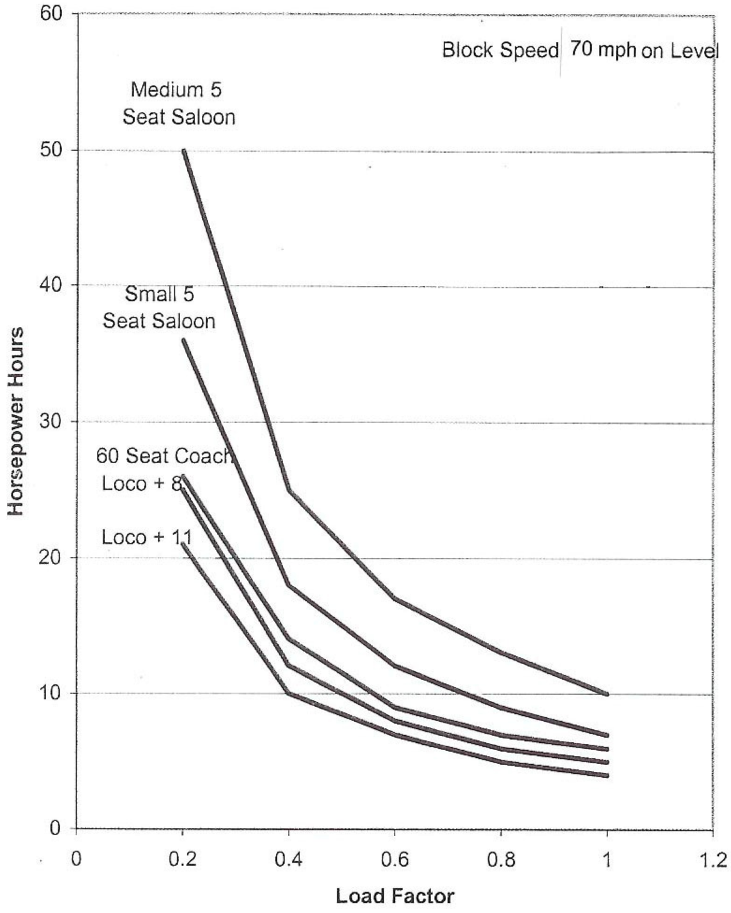


Fig 4 – Horsepower-Hours/100 Passenger Miles

It will be seen that the modern road coach gives rail a close run in energy efficiency. Energy efficiency is only one factor affecting the overall economics of road and rail; there are many elements involved and the pros and cons will long be argued.

Acceleration & Braking

Like many things in life, the low rolling resistance of steel on steel, is something of a double edged sword. This limits the adhesion factor (the ratio of adhesion weight to tractive effort) putting rail at a disadvantage to road in regard to acceleration and braking, an old rule of thumb being that adhesion factors much lower than 4 would be troublesome in unfavourable conditions. On roads an adhesion factor as high as unity is attainable.

In the days before the advent of SI Units when measurements were more readily comprehensible *(sic)*, the acceleration of a free-falling object was expressed as 32.2 ft/sec^2. What wasn't always taught was that this closely approximated to 22 mph/sec. Thus a force of 224 lbs applied to a mass of 1 ton will produce an acceleration of 2.2 mph/sec. It makes acceleration calculations mental arithmetic a practical proposition.

Where all or most of the wheels in a train are powered, as on multiple units, an initial acceleration force of 500lbs/ton (0.22g) is possible, producing an initial acceleration of 5mph/sec. With a heavy locomotive-hauled train, or when starting on a gradient, the initial acceleration may be reduced to a fraction of this figure. These adhesion factor limitations coincidentally prevent trains reaching acceleration rates that could discomfort standing passengers.

The adhesion limit assumed for braking is more conservative than for traction. This situation obtains because wheel locking is potentially a more serious problem than wheel slip. The maximum force is usually assumed at 0.15G, producing a deceleration of 3.3 mph/sec. Some typical braking distances are shown in Table 6.

Table 6 - Typical Braking Distances in Feet - Level Track

Speed MPH	10	20	40	60	80	100
Vacuum	200	320	775	1,775	3,600	6,100
Standard Air	150	280	670	1,550	3,250	5,600
Electro-Pneumatic	110	250	640	1,390	2,725	4,850
Saloon Car	15	40	120	250	405	610

From 100mph to rest requires 1.15 miles for vacuum, 1.05 miles for air, and 0.92 miles for electro-pneumatic with simultaneous direct application.

The Speed Trap

One of the problems arising from ever faster train schedules is the increasing difficulty of recovering time lost through delays. This is clearly brought out in Table 7 below.

Table 7 - Time Recovery of 5 Minutes Delay over a 60 mile section

Booked Speed MPH	Booked Time Minutes	Recovery Speed MPH	Recovery Power Index Schedule = 100
50	72	54	116
60	60	65.5	121
70	51.5	78	127
80	45	90	133
90	40	103	138
100	36	116	144

The recovery power index shown assumes level track, so in some circumstances may be under or over-stated. It is unlikely that the reserves of power required will always be available, and speed limits may also inhibit the scope for recovery. The faster the schedule, the bigger the problem. It is perhaps in deference to this problem that "on time" in Britain is now defined as within 10 minutes of booked time. In the days of steam the criteria was within one minute of booked time.

The High Speed Railway

One answer to the speed trap problem, and an effective one at that, is the dedicated high speed railway. This eliminates many of the operational problems associated with the conventional railway. In addition, the new lines this almost inevitably involves provide the opportunity to engineer the track and signalling to an altogether higher standard than in past times. This has led to some spectacular train operating speeds. This trend is international. Additionally, the track, signalling and rolling stock of many long-established lines, is being upgraded in the quest for speed.

This trend, involving both dedicated lines and upgraded routes, is shown in Table 8.

Table 8 - The World's Fastest Trains			
Country	**Route**	**Miles**	**MPH**
Japan	Hiroshima - Kokura	119	162.6
France	Valence TGV - Avignon TGV	80.6	161.1
International	Brussells Midi - Valence TGV	516.4	150.4
Spain	Madrid Atocha - Sevilla	292.3	129.9
Germany	Stendel - Wolfsburg	47.3	118.3
UK	York - Stevenage	160.9	113.6
Sweden	Skovde - Sodertalje	172.1	107.5
USA	Baltimore - Wilmington	68.4	103.5
Italy	Rome - Florence	162.1	102.6
Finland	Salo - Karjaa	33	94.24
China	Guangzou - Shenzen	86.3	94.17

Future projects plan to push speed still further. The proposed Beijing - Shanghai line is to be aligned for 350 km/hr (217 mph) (The French TGV operates at up to 320 km/hr, 200 mph). The limits of the flanged wheel may now be coming into view. he Japanese MAGLEV Project plans for 500 km/hr (310 mph).

Motive Power

A crucial factor in the success of the early railways was the intrinsically low traction resistance. A little power went a long way. This was just as well because the early steam locomotives only converted about 2 or 3% of the fuel energy consumed into useful work at the drawbar. By the time of steam's passing from the everyday scene, this figure had risen to 9.5% at best and overall probably averaged 6-7% on mainline service in Britain.

To a great extent this low efficiency was the inevitable outcome (rather than poor or inept design) of the non-condensing thermal cycle adopted for the classic Stephensonian steam locomotive. This point is seldom emphasised. The inescapable problem, even for condensing cycles (unless supercritical pressure is adopted) is that of the *Latent Heat of Evaporation*. It might well be dubbed the *Lost* or *Nugatory* heat.

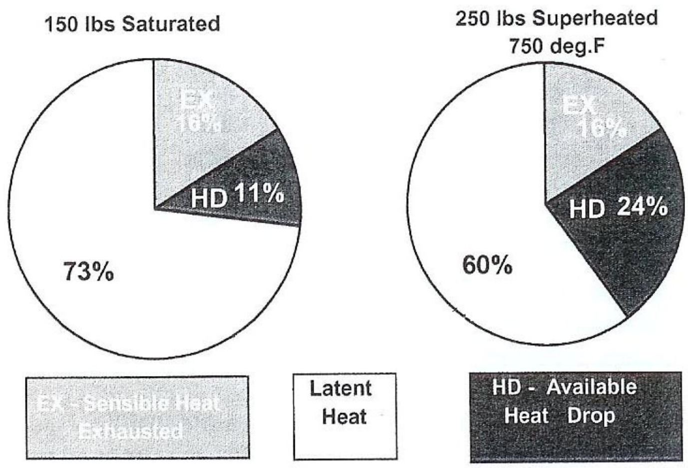


Figure 5 - The Latent Heat Problem

In its final development, the maximum cylinder efficiencies attained were about 14%. The Rankine efficiency, i.e. the ratio to what was theoretically obtainable, approached 70%. Higher values were obtained, notably in France, with compound locomotives.

Some of the sensible heat in the exhaust could be recovered for feed water heating. This took two forms; the feed water heater and the exhaust steam injector. Although the feedwater heater was more efficient, it involved a feed-water pump and some other complications, and this seems to have mitigated against its widespread adoption. The exhaust steam injector was widely adopted in Britain and in controlled tests economies of up to 6% in water and 9% in coal were achieved.

The Boiler

If the cylinders were the muscles of the locomotive, the boiler was its heart. A key point here is that the steam locomotive is an external combustion engine. This solved to a large extent what might otherwise have been a serious problem, that is: matching power output to demand. The boiler, with its ability to meet short-term overloads, provided a cushion when a locomotive lived beyond its means. For many poorly draughted locomotives it could almost become a way of life.

There are close parallels in the theory of power regulation adopted by the steam locomotive and the petrol-driven internal combustion engine. The traditional locomotive blastpipe and chimney and the carburettor were both ejectors working on the Bernoulli principle.

There was a subtle difference. In the petrol internal combustion engine, burning more fuel developed more power; in the steam locomotive it was the act of meeting the demand for more power that burned more fuel.

The conventional steam locomotive boiler was relatively efficient, with efficiencies at low combustion rates as high as 85%. The problem was that to cope with power demands, combustion rates unthinkable on stationary land boilers, were routinely demanded to meet the power requirements. Whereas on a land boiler the specific combustion rate might be limited to 30lbs.sq.ft/hr, steam locomotives sometimes operated at four or even five times this combustion rate. It makes little economic sense to operate such combustion rates as a matter of course, and rates of 80 to 100 lbs/sq.ft/hr were more typical. At such a rate boiler efficiency would be in the order of 70 to 65%.

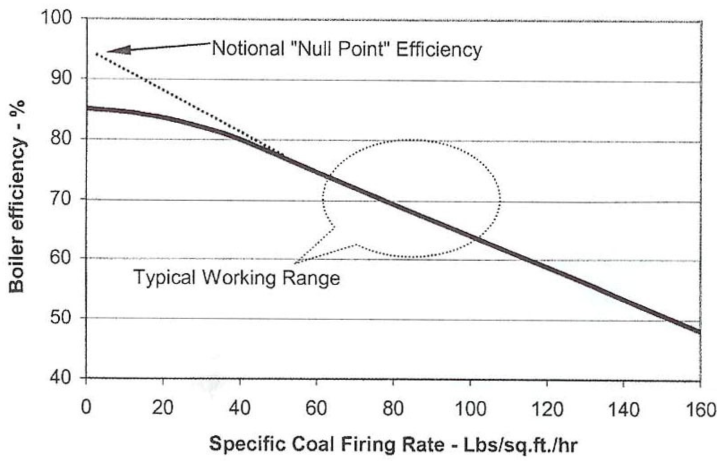


Figure 6 – A Typical Boiler Efficiency Curve

Boiler Limits

Maximum boiler output could be limited in three ways, either of which could occur first:

Front End Limit: This was a draughting limitation, when the available excess air fell below about 20% and complete combustion could no longer be achieved. If this occurred prematurely the locomotive concerned would be deemed a poor steamer. It could also be set by the designer at a value that would provide adequate steam, while at the same time avoiding "uneconomic" combustion rates. The BR Standard locomotives were designed on this basis.

Discharge Limit: This is also sometimes described as the 'Front End Limit', but it is quite different to the condition described above. It occurs when the steam exhaust velocity reaches the speed of sound. At this point theory has it that the pressure/draught relationship breaks down. Curiously however, there are recorded instances of this limit being exceeded without apparent distress. It does however involve very high back pressures upwards of 14 Ibs/sq.in., and was definitely something best avoided.

Grate Limit: This is the point where stepping up the combustion rate produces no additional steam. It occurs when the incremental fall in boiler efficiency is greater than the firing rate increment. It always occurs at exactly half the notional "Null Point" efficiency shown in Figure 6.

The grate area was therefore a primary indicator of a locomotive's power potential. The typical maximum steam rate of 'front end' limited boilers was about 700 lbs of steam per hour per square foot of grate area. Locomotives without this limitation such as some fitted with double chimneys, could achieve over 1000Ibs of steam an hour per square foot, but not very economically.

Traction Characteristics

The mathematical relationship between power, speed and tractive effort affects all forms of motive power. Generally speaking the available power cannot be fully exploited at low speeds. Adhesion is a governing factor here but there are others. For example 2000 drawbar horsepower at 50 mph represents a force of 15,000 Ibs, something a large Pacific locomotive could readily produce. To develop such power at 5 mph would involve a drawbar force of 150,000 Ibs, or about four times the likely rated nominal tractive effort. Even if adhesion was not a factor, the cylinders would need to be impracticably large, or the wheels impossibly small, to achieve such power at low speed. The steam locomotive was unique in that maximum torque was developed at zero speed, but the extended speed range over which it operated and adhesion considerations limited the extent to which this could be exploited.

In the 1950s economic steam rates were usually defined as where traction efficiency was within 2% of the maximum. On the larger locomotives there was a significant reserve of power over this rate.

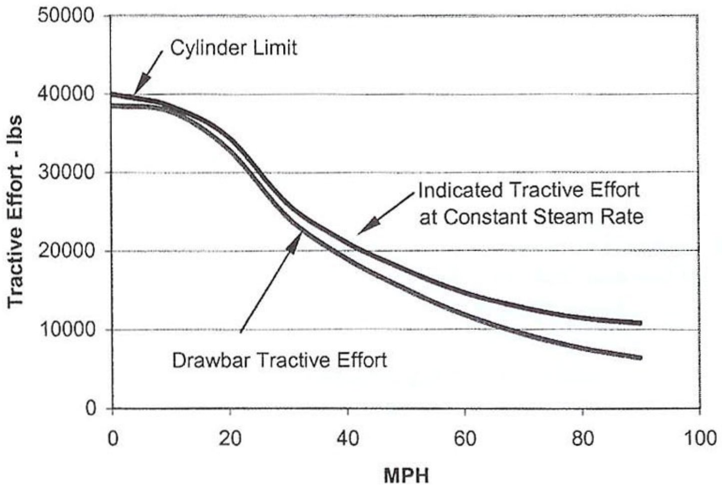


Figure 7 – Typical Steam Locomotive Traction Characteristics

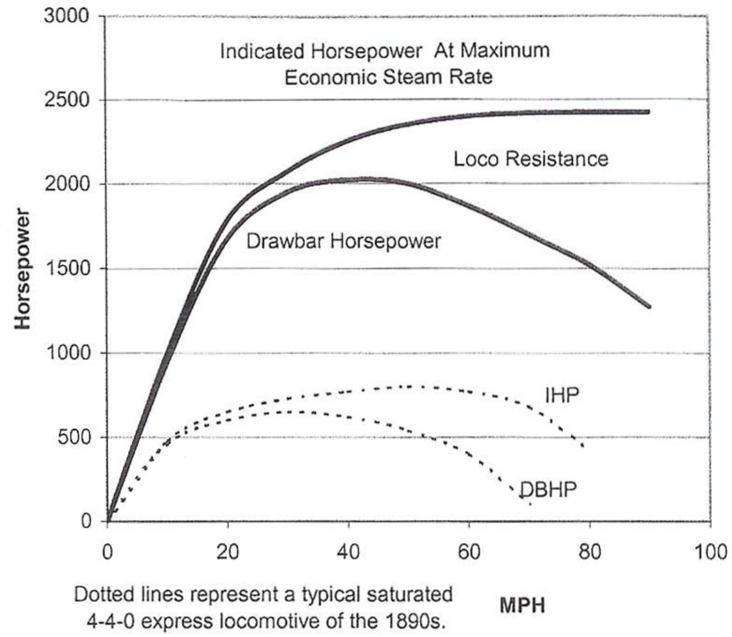


Figure 8 – The Steam Locomotive – Typical Power Characteristics
Modern Practice – Superheated – Long Travel Valves

Diesel Traction

Among other things, diesel traction brought about significant advantages in thermal efficiency, and eventually in power weight ratios. Another important advance was that a much higher proportion of the weight, often 100%, was available for traction adhesion. Starting from prime mover efficiencies that in some instances approached 40%, peak drawbar efficiencies in the order of 30% were realised.

Maximum efficiency is attained at full output, quite the reverse of the marked decline in efficiency associated with the steam locomotive under such conditions. All without any resort whatever to strenuous physical effort, stoker fired locomotives excepted.

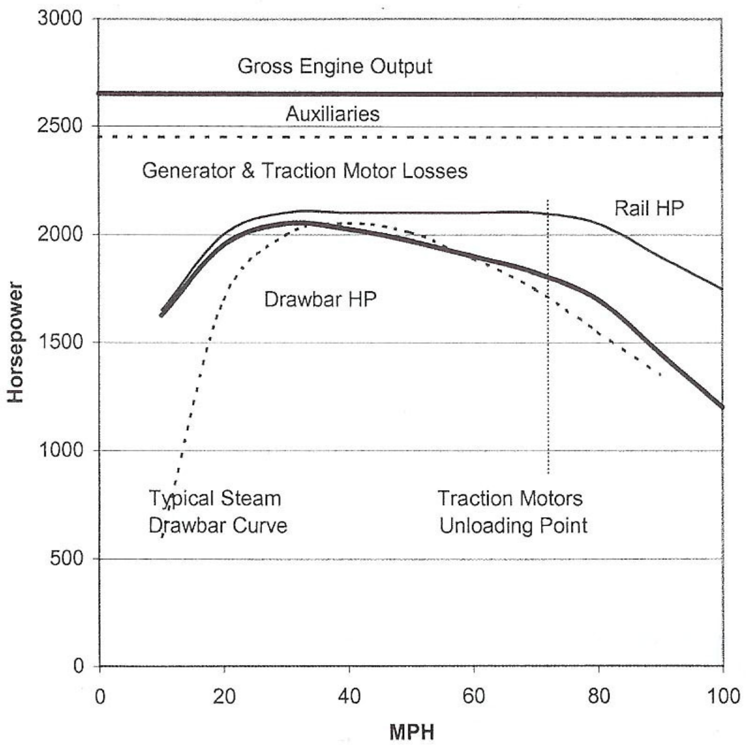


Figure 9 – Typical Diesel-Electric Horsepower Characteristics

In further contrast to steam, there are closely defined limits to the available maximum power, as imposed by the rated prime mover capacity. Thermal limitations of the generator and traction motor windings sometimes incurred an hourly limit at the maximum power rating.

Electric Traction

None other than George Stephenson foretold of "magnetic forces" moving the trains of the future. The DC electric traction motor comes close to having the ideal torque/speed characteristics. Not being locomotives in the strict sense, i.e. not self propelled, (power being drawn from an external source), there is a potential for significant weight savings compared to diesel electrics and steam locomotives. Since power is not limited by an installed prime mover, there is scope for considerable short-term overloads. For example, the Class 90 Electrics, which are continuously rated at 5,000 HP, have short-term rating of 7,680 HP, an increase of 54%. Weighing only 83 tons, this is a peak of 92.5 HP/ton. The equivalent figure for the 3,300 HP Deltic diesel electric, e.g. at the traction motors, was 25 HP/ton. The overload time limits are dictated by the traction motor winding temperatures.

Efficiency-wise, from the thermal standpoint, electric traction is very varied. With cheap hydro-electric power, such as is widely available in Switzerland, water turbine efficiency can be as high as 90%, so after allowing for station auxiliaries and transmission losses over the power distribution network, peak drawbar efficiencies can approach 70%. At the other extreme, if power is supplied from a low-tech thermal station operating at 30% efficiency, drawbar efficiency may be no more than 20%.

Very high utilisation rates can be achieved; there is no need for refuelling movements or stops. Self-evidently maintenance will be lower than those for diesel electrics, but against this must be set the cost of maintaining the power distribution system. Overhead electrification systems are vulnerable to mechanical damage or failure, and the effects of this are sometimes widespread.

Multiple Units

Whether diesel or electric, multiple units introduce a number of operating advantages and reduced weight per passenger seat. There has been a marked increase in power weight ratios in recent years, as shown in Table 9 below. The adhesion weight percentage will be high and may in some instances reach unity.

Table 9 - Multiple Unit Power Weight Ratios

Year	Class	Transmission	Units	Tons	HP	HP/Ton
1957	104	Diesel Mechanical	2	62	600	9.7
1959	303	25kV AC O/H	4	123	828	6.7
1954	421	750V DC 3rd Rail	4	155	1000	6.5
1988	321	25kV AC O/H	4	136.5	1328	9.7
1991	465	750V DC 3rd Rail	4	133.5	1608	12.0
1998	170	Diesel Hydraulic	3	89	1200	13.5

There is an inherent reliability gain compared to locomotive hauled trains since there is some power unit redundancy available. A power unit failure may reduce performance but it will not stop the train. Very high utilisation rates are possible and the actual outcome as often as not, is dictated by traffic demands rather than unit limitations. Seat weights below 0.4 tons/passenger are now commonplace. On a busy commuter train, crowded with standing passengers, it would perhaps be a little dubious to claim a weight of 0.15 tons/passenger constituted an "improvement" in operating efficiency!

HS 125 - Class 43 HST

These units, introduced in 1976, have proved a tremendous operational success. Technically, they are something of a hybrid unit, having some of the characteristics of the multiple unit, the locomotive at each end being an integral part of the train, and in an emergency there is a 50% power redundancy. The UK forerunner for this concept in some respects was the Midland Pullman which was introduced in 1960. It proved to be mediocre, with poor seating capacity and a notoriety for poor riding. Only 5 sets were built, and as a consequence utilisation was very low, with two sets, 40% of the fleet, idle on standby. All were scrapped after just 13 years.

Table 10 - Twin Power Unit Passenger Formations

Year	Class	Formation	Gross Tons	Installed Power	HP/Ton	Max Speed	Seating
1960	Midland Pullman	6	299	2 x 1000 BHP	6.7	90 mph	132
		8	364		5.5		226
1976	HS 125	9	379	2 x 2250 BHP	11.9	125 mph	354
		10	414		10.9		419
		11	448		10		484

Notes
1. The train formation figure includes the two power units.
2. The Midland Pullman power units incorporated some seating.
3. Some HS 125s were upgraded to 2 x 2700 BHP.
4. HS 125 seating figures and tonnages shown are typical only, and will vary with the actual train formation make up.

Fortunately, the *Midland Pullman* experience did not kill the concept. After some teething problems with the 1500 rpm diesel engines, the HS 125s have given enduring service. It has been claimed more than once that they transformed the economics of British Rail's Inter-City services.

The Loading Gauge

Finally, a few thoughts on a somewhat overlooked topic: The Loading Gauge. There are approximately a dozen track gauges in general world-wide use, ranging from 24 inches to 5 feet 6 inches. The situation with loading gauges is much more diverse, there being no fixed relationship between track gauge and loading gauge. Many 3' -6" gauge lines for example, are associated with significantly larger loading gauges than those enjoyed in the UK with its wider 4' - 8½" gauge. The loading gauge is of greater significance than the track gauge, in regard to what the designer can achieve. Some sample loading gauges for the UK, Continental Europe and the USA are set out below.

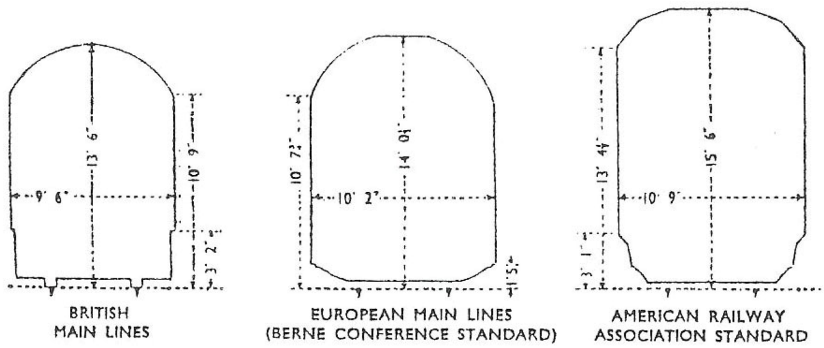


Figure 10 – Typical Loading Gauges

The restricted UK loading gauge perhaps reflects the penalty of being first in the field. In the 1930s, the largest steam locomotives that could be squeezed into the British loading gauge were built; maximum power output was circa 3,300 Indicated Horsepower. In France over 4,000 IHP was recorded and in the USA over 6,000. Curiously, the USA did not fully exploit their loading gauge when it came to diesel electrics, preferring to work a number of units in multiple rather than maximising unit power. On some of the longest freight trains, locomotive(s) were situated half way down the train because the gross train weight involved traction forces beyond the strength of the standard coupling arrangements. A large loading gauge has great advantages in the movement of goods, fewer loads are potentially "out of gauge". There is also considerably more scope when designing such things as double deck trains.

Epilogue

Looking back over the history of railways, it is clear that new thresholds of development have never been far away at any stage. From the perspective of a foothold in the 21st Century it seems this continuing evolution has by no means run its course. Tilting trains and the Channel Tunnel High Speed Rail Link are just two examples in the UK. There are many exciting developments in progress world-wide, and technical innovations will doubtless keep appearing on the horizon.

The set of flangeless driving wheels depicted below were originally manufactured for the Bristol & Exeter Railway 4-2-4 broad gauge locomotive No. 40 built in 1868. Eight-feet ten inches in diameter, this wheelset now stands outside the main entrance to the National Railway Museum at York, exerting a powerful, brooding presence. I regard them as a fine example of modern art. If Henry Moore or Jacob Epstein had been commissioned to make a sculpture symbolising the spirit and boldness of the early railways, they could have done no better than to come up with something just like No. 40's wheelset.

The momentum generated by this boldness of concept continued well into the 20th Century. Let one example suffice. Early in March 1935 the LNER board of directors gave the go ahead for a new streamline train: *The Silver Jubilee*. A little over six months later, on 27th September, the new train, headed by the prototype A4 locomotive, No. 2509 *Silver Link*, was demonstrated in spectacular fashion to the press, reaching speeds of 112.5 mph and averaging 100 mph for 43 miles, and 107.5 mph for 25 miles. No.2509 worked the new service single-handed for the first fortnight, clocking up 5,266 trouble-free miles.

In similar circumstances today, I suspect it might take six months just to form the Health and Safety Committee. No doubt the spirit of enterprise is still out there, but things do seem to have become embedded in a glue of procedure.

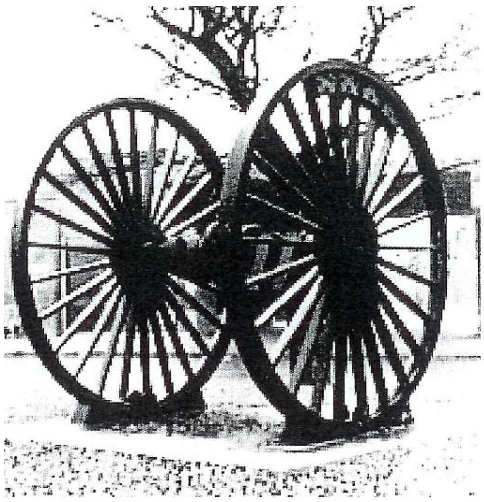


Photo by courtesy of the National Railway Museum

Some Milestones in Railway Engineering to the Year 1936		
1804	Penydaren Tramway Locomotive	Richard Trevithick
1813	*Puffing Billy* geared adhesion locomotive.	Wm Hedley
1825	*Locomotion No .1,* Stockton & Darlington Rly.	George Stephenson
1829	Rainhill Trials - *Stephenson's Rocket,*	Robert Stephenson
1830	*Planet* locomotive - horizontal cylinders	Robert Stephenson
1833	Steam Brake	Robert Stephenson
1839	Steam Superheating	Hawthorn's
1840	Long Travel Valve Gear.	John Gray
1841	Sanding Gear	Robert Stephenson
1844	Radial Valve Gear	E Walschaerts
1848	Steel Rail Coach	W B Adams
1859	Brick Arch & Firehole Deflector Plate	Matthew Kirtley
1859	Live Steam Injector	M Giffard
1860	Water Pick-up Apparatus	John Ramsbottom
1863	First "Cut & Cover" Underground Rly.	Metropolitan Rly.
1871	Compressed Air Brake	Steel & McInnes
1874	Speed Indicators	William Stroudley
1876	Exhaust Steam Injector	Davis & Metcalfe
1878	Automatic Vacuum Brake	Gresham
1879	Electric Locomotive Exhibited Berlin	W. Von Siemens
1878	2 Cylinder Compound Locomotive.	A Mallet
1881	Worlds First Public Electric Rly,	Berlin
1887	First Articulated Rigid Frame Locomotive	A Mallet
1890	Worlds First Underground (Tube) Rly	City & S. London Rly
1897	Boiler Flue Superheating	Wilhelm Schmidt
1905	Circle Line Electrified	Metropolitan Rly.
1906	1st use in England of Schmidt Superheater	George Hughes
1909	Garratt Articulated Locomotive	Beyer Peacock
1911	Direct Drive 1000 BHP Diesel	Klose & Sulzer
1913	Atlas Diesel Eectric Railcar	Sweden
1924	Diesel Hydraulic Loco Tested on LNER	German Built
1924	First Diesel Shunter trials in USA	GEC-Alco-Ingersol
1925	First Diesel Electric Locomotive	Lommonosoff - USSR
1933	The *Flying Hamburger* Diesel Railcar	Germany
1935	The *Silver Jubilee* Streamlined Train	LNER - Sir N Gresley
1935	*Hiawatha* Streamline Train - Steam	U.S.A
1936	*Burlington Zephr* Streamline Diesel Electric	U.S.A