# Why Did BR Give Up On Steam ?

## – And Could It Have Been Avoided

Part 4 – Shunters

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7th October 2023

# Objective

- This presentation seeks to answer two questions:

1. What were the reasons given at the time for the perceived superiority of diesel over steam traction ?
2. Would it have been possible for different designs of steam locomotive to the BR Standards actually built to have addressed these perceived weaknesses ?
3. Part 4 focusses on shunting locomotives

# Contents – Part 4

# Requirements For Steam to Compete With Diesel

- Less Old Fashioned
- Cleaner
  - ➔ Less Pollution
  - ➔ Better combustion (with lower quality coal)
- Less Manual Labour
  - Cleaning/Servicing
  - Firing
  - ➔ machine washing, stoker firing & reduced service reqmts
- Higher Low Speed Performance
    - ➔ Better Acceleration & Hill Climbing
    - ➔ consistent higher power outputs (Kiefer Rule) ➔ mech. firing
    - ➔ better use of locomotive weight for adhesion
- Reduced OPEX
  - Reduce Fuel costs to Diesel levels ➔ Higher Efficiency
- Higher Availability/Utilisation ➔ match diesels
  - Increased Operating Range w/o refuelling/water/ash removal
  - Reduced terminal time (turn, water, coal, ash)
  - Reduced servicing
  - Increased major repair intervals

# Shunting vs. Main Line Loco Design

- Even Riddles & Cox accepted D.E. superior to traditional steam for shunting
  - ➔ Need to do something different for steam to compete
- (Much) lower max speeds
  - ➔ (much) less max power required
- Matching diesel low speed performance critical
  - ➔ tractive effort
  - ➔ adhesive weight
- Matching diesel availability (& hence utilisation) equally important
  - ➔ maximise operational endurance between refuel/water stops
  - ➔ minimise routine maintenance requirements
- Arguably a more difficult technical challenge than main line locos

# Water Troughs

# Water Troughs

- In October 1937 the northbound Coronation had had to make an unscheduled stop at Newcastle due to taking insufficient water at Wiske Moor Troughs to reach Lucker Troughs, 98 miles further north.
- The north and southbound Coronations crossed at Wiske Moor. Both locos took water. Speed was 70 mph.
- Loco inspectors were put on both locos to ensure the max amount of water was picked up
- The firemen were unable to manually raise the scoop because of the high speed.
- Water overflowing from the northbound loco tender hit the southbound loco, breaking the spectacle glass, a piece of which hit and killed the loco inspector on the southbound loco.

- Photo shows an A4 being tested on Wiske Moor troughs after the accident
- Wiske Moor Troughs were 623 yards long – 18 seconds at 70 mph
- Fireman had to manually lower scoop once loco over troughs
- Not surprising actual water pick-up was variable

# Water Troughs (2)

| Pre-Grouping Water Troughs | |
|---|---|
| GC | 2 |
| GE | 2 |
| GN | 4 |
| GSW | 1 |
| GW | 11 |
| GW/LNW | 1 |
| LNW | 16 |
| LNW/LY | 1 |
| LY | 9 |
| MR | 5 |
| NE | 2 |
| Total | 54 |

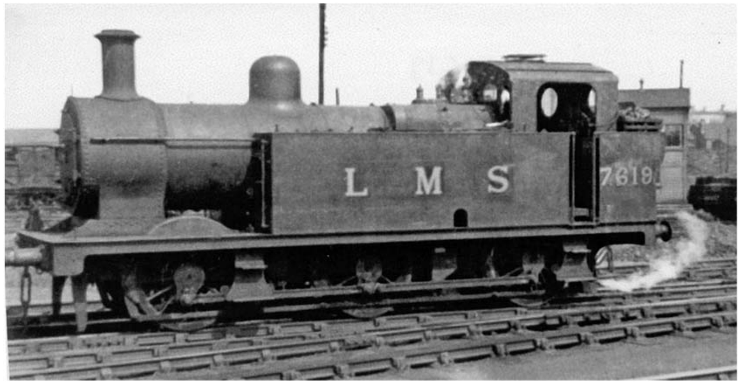
| ECML Water Troughs | | | |
|---|---|---|---|
| | | Miles From KX | Miles From Previous |
| 1 | Langley | 26 | 26 |
| 2 | Werrington | 80 | 54 |
| 3 | Muskham | 121 | 41 |
| 4 | Scrooby | 146 | 25 |
| 5 | Wiske Moor | 220 | 74 |
| 6 | Lucker | 318 | 98 |
| | Edinburgh | 391 | 73 |

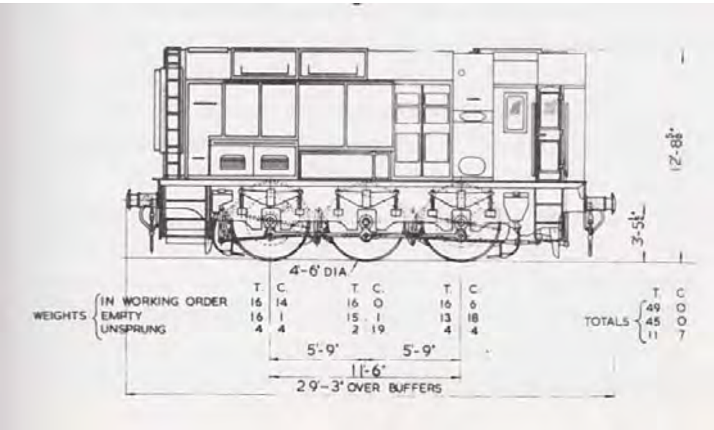
| ECML LNER Pacifics Water Balance | | |
|---|---|---|
| Water Required | | |
| gal/mile | Distance (miles) | gal |
| 50 | 400 | 20,000 |
| Water Supplied | | |
| Boiler | | 3,000 |
| Tender Tank | | 5,000 |
| Pickup /Trough | | 2,000 |
| ntrough | 6 | |
| Total Pickup | | 12,000 |
| Total Supply | | 20,000 |

- At 2000 gal pickup/trough, LNER Pacific operation was on the limit
- Higher power locos would need more water
  - Bigger tenders/longer troughs/more troughs/automated pickup
  - Or condensing

# Previous Solutions

# Traditional Steam Shunting Loco vs D.E.

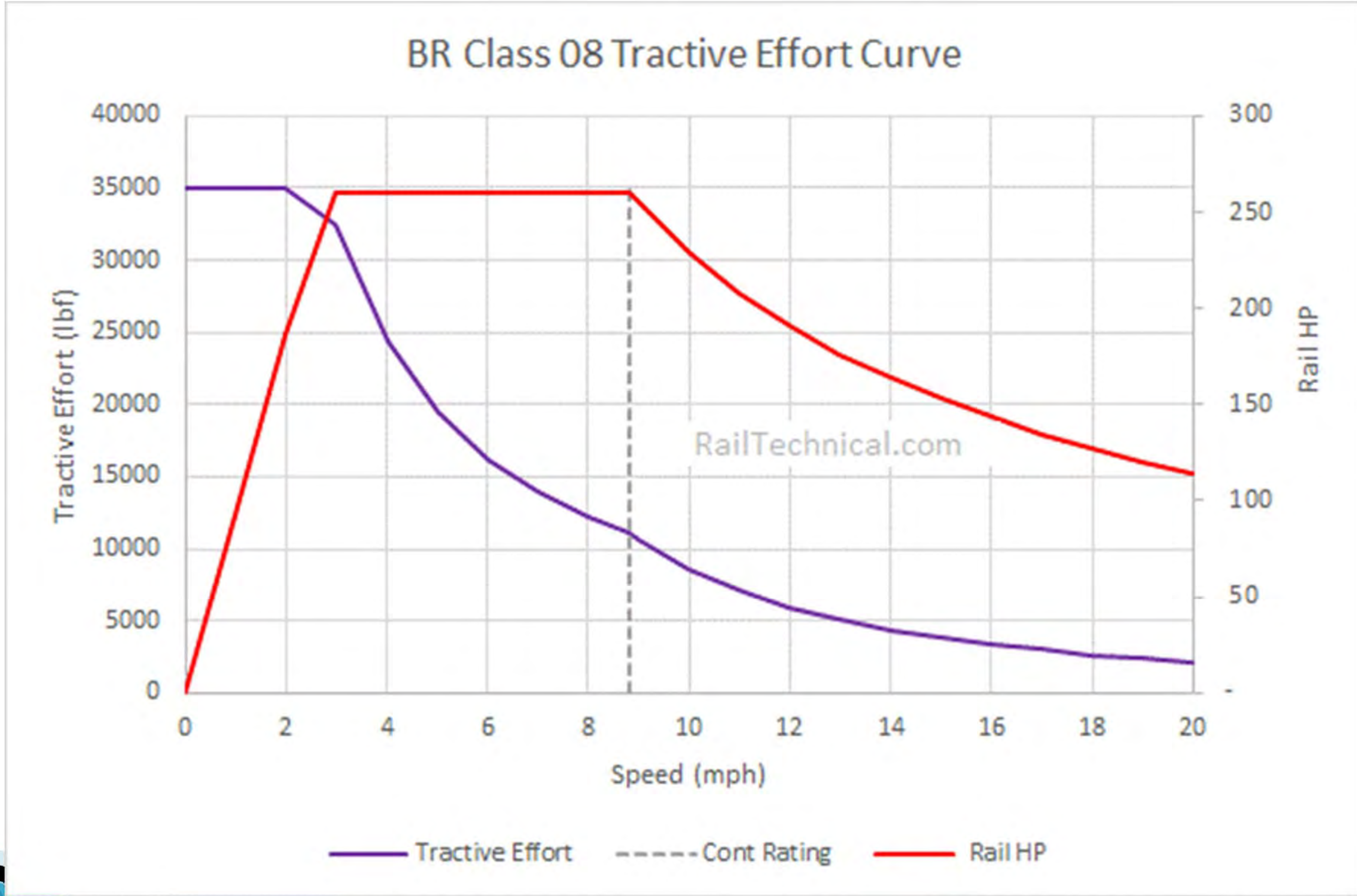



| | 3FT | Class 08 | |
|---|---|---|---|
| Loco Max power | 480 | 350 | hp |
| Loco Max Weight | 50 | 49 | T |
| Adhesive Weight | 50-42.3 | 49-46.5 | T |
| Starting T.E. | 20,835 | 35,000 | Lbf |
| Starting Mu | 0.189 | 0.319 | |
| Empty Tanks & Bunker | 0.223 | 0.336 | |
| Max Speed | | 20 | mph |
| Fuel | 2.3 | 2.5 | T |
| Water | 5.4 | | T |

| | Fuel Capacity | Energy Density | Energy Input | Thermal Efficiency | Energy Output |
|---|---|---|---|---|---|
| | litres or t | MJ/L or GJ/t | GJ | % | GJ |
| Class 08 | 3040 | 38 | 115 | 24 | 28 |
| Steam | 10.3 | 30 | 308 | 9 | 28 |

# Class 08 Power Curve



# Diesel Power Curve Characteristics

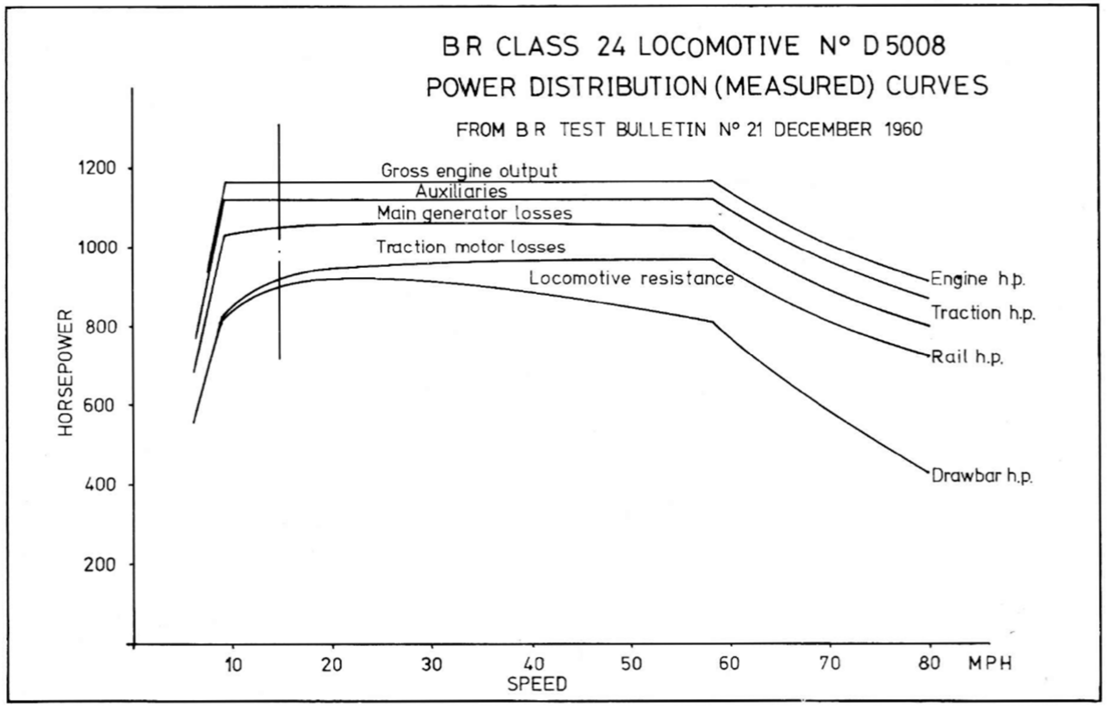
- Quoted HP is Engine SHP
- RHP is SHP – Aux  & Transmission Losses
- RHP is approx. 80% of shaft hp

For the Class 56 the losses are:

- Ancillaries 3.2% (104hp)
- Generator Efficiency 93.3% (211 hp)
- TM Efficiency 92% (235hp)
- i.e. 17% loss from SHP to RHP

- Diesel Loco resistance curve similar  to Steam

- RHP is therefore most analagous to Steam IHP
  - Wardale used 4% difference IHP to RHP in 5AT FDCs




Thanks to steve@railtechnical.com for the diesel info

# R.E. 1951 Report – Operating Benefits of D.E. Shunters

- One man operation
- Better low speed performance
- Improved visibility (but worse audibility)
- Continuous availability, 24 hours/day for up to 16 days
  - UK practice 6 day week, 7th day inspection/servicing/maintenance
  - LMS/LNER experience DE shunter availability 86%-93%
  - Trad. steam has coal for 24 hours only, also needs fire cleaning & water several times/day
- More intensive operation possible with D.E. shunters (no breaks reqd for water etc.) ➔ fewer D.E. shunting locos reqd
- 52 350hp D.E. shunters taken over from Big 4, further 162 ordered by time of R.E Report
- Under BR, 369 new 0-6-0T steam shunters were built

# Comparative Shunting Engine Costs

| | 3F Tank | | 350 hp Diesel | | 3ATT |
|---|---|---|---|---|---|
| | R.E Rpt | Single Manned | R.E Rpt | No CAPEX Reduction | Target |
| CAPEX (£) | 6,200 | | 21,000 | | 6,200 |
| | d./mile | | d./mile | | d./mile |
| Interest on CAPEX | 15.51 | | 23.91 | 52.53 | 15.51 |
| Renewal | 7.85 | | 27.51 | | 7.85 |
| Repairs incl. admin | 42.79 | | 34.75 | | 42.79 |
| Running Expenses | | | | | |
| Wages & NI | 132.54 | 53.72 | 53.72 | | 53.72 |
| Fuel | 94.78 | | 26.26 | | 47.39 |
| Water, lubricants, misc | 15.02 | | 4.19 | | 7.51 |
| Total OPEX | 307.7 | 228.88 | 181.04 | 209.66 | 174.77 |

- Target 3ATT fuel & water ½ of 3F
- 3ATT single manned
- Target 3ATT CAPEX & OPEX both lower than DE

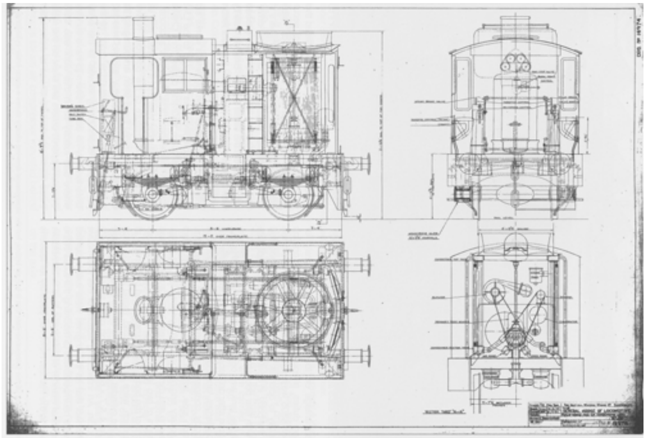
# SR Class Z

Holcroft shunter design criteria:
- 100% Adhesion
- 3 cylinders – maximise usable T.E.
- Small grate – minimize stand-by losses
- No superheater – intermittent duties

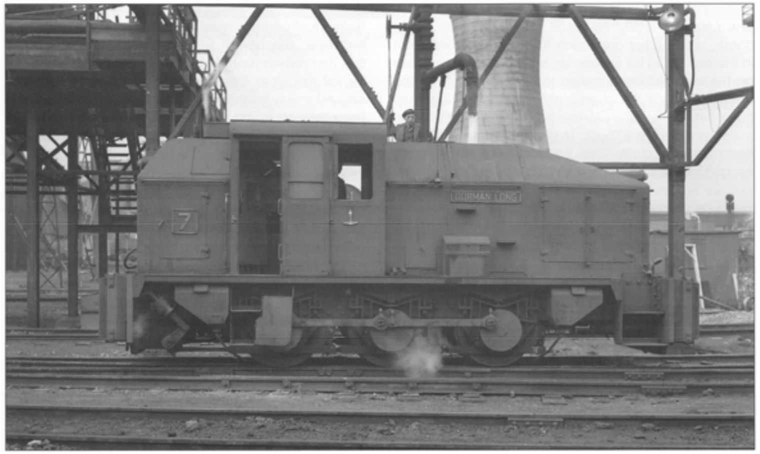

| SR Class | Wheel Arrgt | N Cyl | Coal | Water | Total weight | Adhesive Weight (t) | | Grate Area | Max Axle Load | Tractive Effort | Mu | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | t | gall | t | Full | Empty | ft2 | t | lbf | Full | Empty |
| Z | 0-8-0T | 3 | 3.0 | 1500 | 72 | 72 | 62.3 | 18.6 | 18.0 | 29,376 | 0.182 | 0.210 |
| G16 | 4-8-0T | 2 | 3.5 | 2000 | 95 | 73 | 60.6 | 27 | 18.3 | 33,391 | 0.204 | 0.246 |
| H16 | 4-6-2T | 2 | 3.5 | 2000 | 96 | 60 | 60 | 27 | 20.0 | 28,200 | 0.210 | 0.210 |

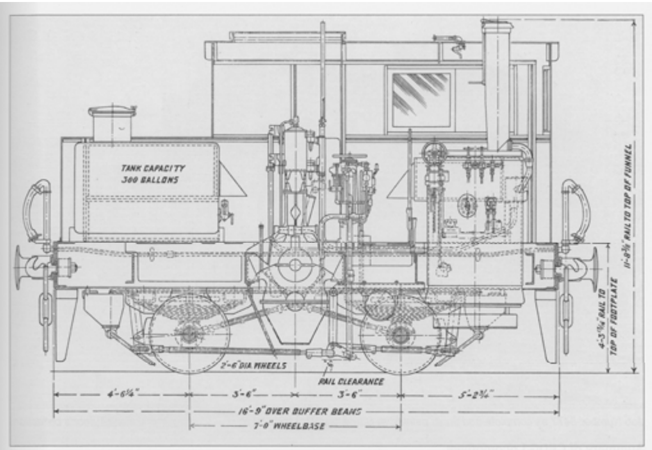
# Sentinel Shunters – 100/200 hp


Job Number 8477 as complete and finish painted at Shrewsbury for the LNER. (Author's collection)



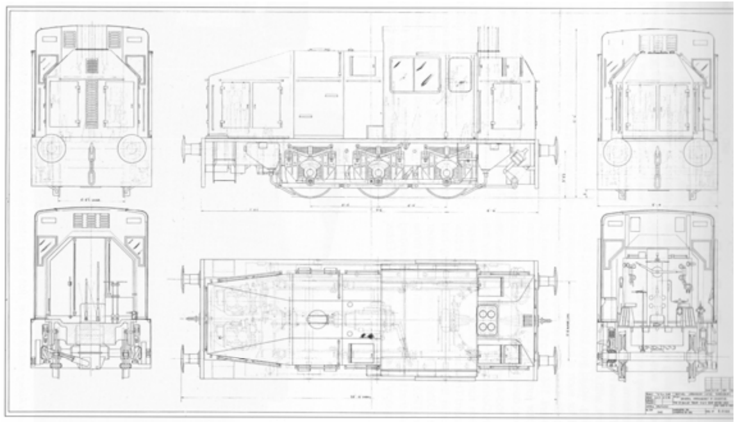
General Arrangement drawing of Job Number 8805





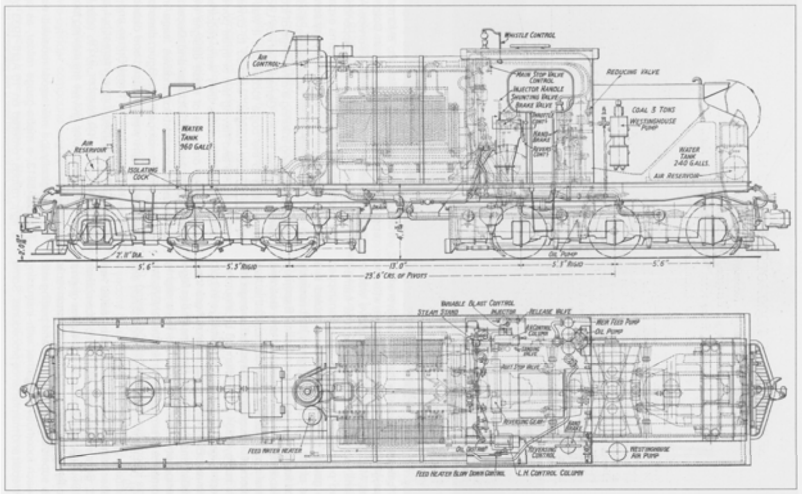

A side elevation of the CEDG locomotive.


Job Number 8805 as built at Shrewsbury with two side mounted condensers. (Author's collection)



General Arrangement for X49 as original built.

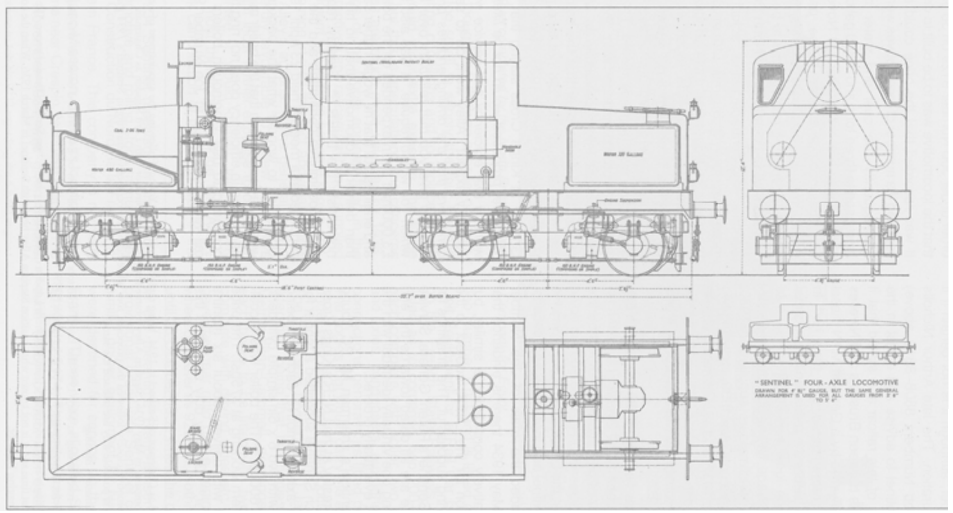
# Sentinel Locos – 600 hp



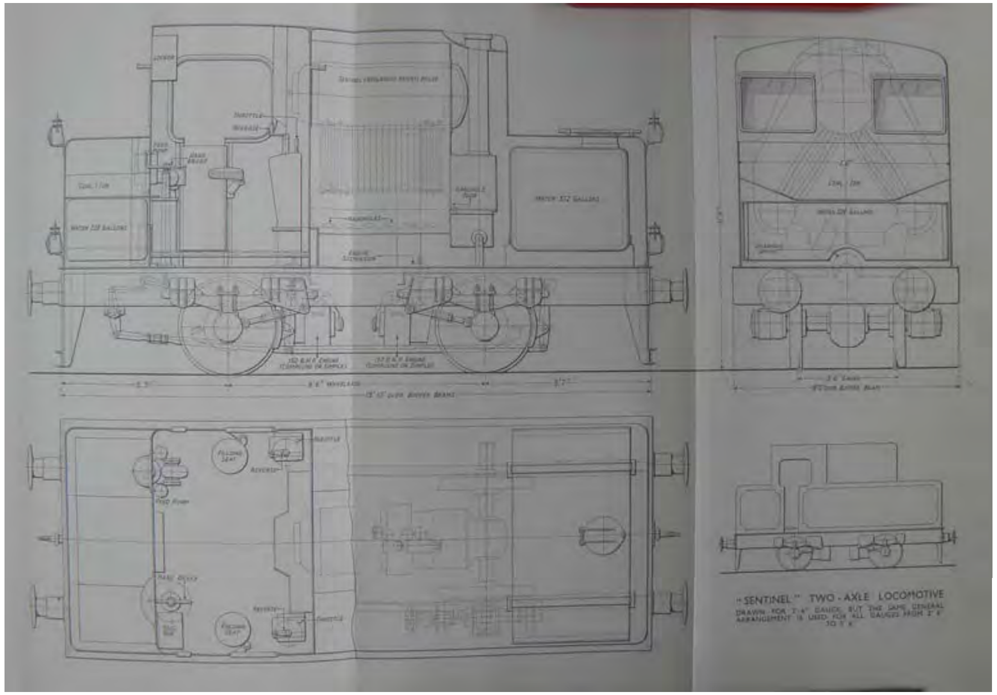
Elevation and plan of the Columbian locomotives from Sentinel drawing 15907. This drawing has an 'R' prefix, indicating it had been redrawn to a higher standard with additional details added, something that was usually done for publication purposes.

Job Number 8808 on trial in Belgium near Champlon 1934. (Author's collection)

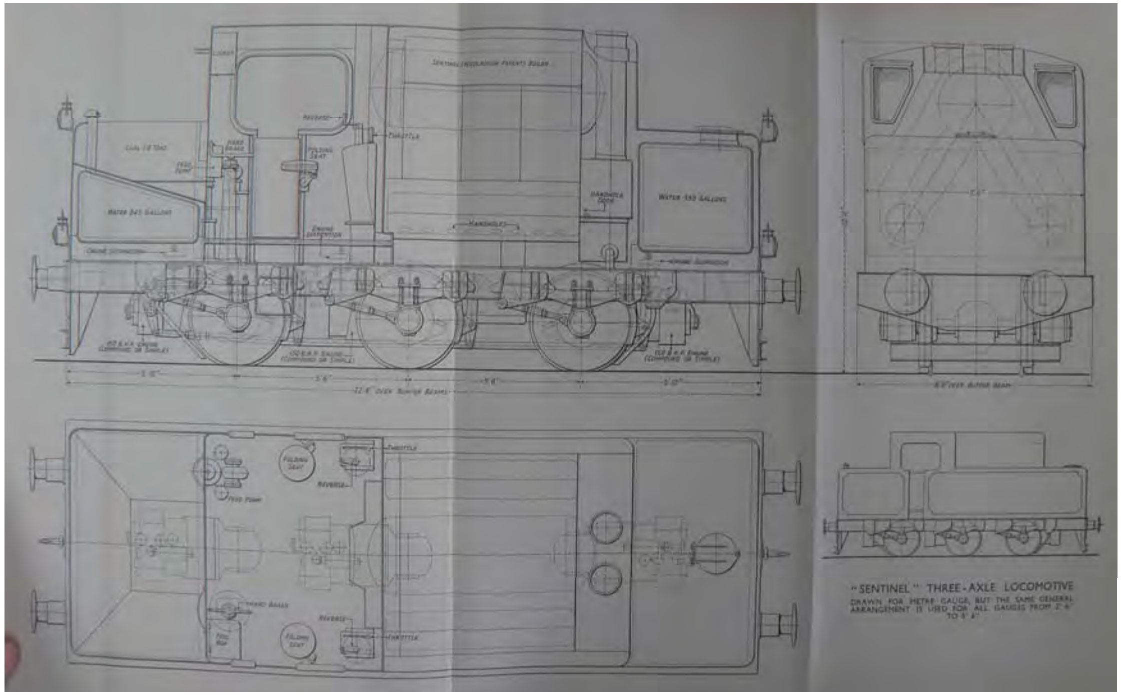
Nigel Gresley, CME of the LNER, was a keen exponent of the Sentinel locomotive and railcar, the LNER being far and away Sentinels biggest customer for rail vehicles. It is therefore appropriate to include a photograph of Mr Gresley ascending the cab of Job Number 8808 during the trials in Belgium: a visit that resulted in the LNER ordering the abortive bogie locomotive to Job Number 9129. On the left William Stanier of the LMSR waits his turn. (Author's collection)



# Sentinel General Service Locos – 1930s

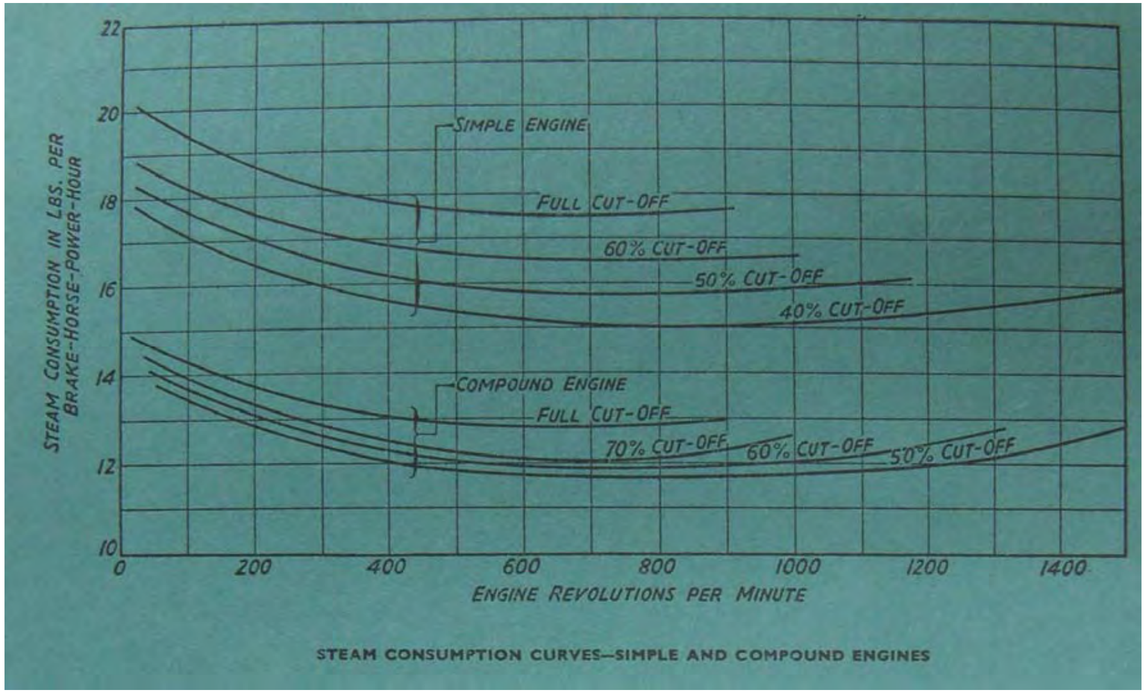


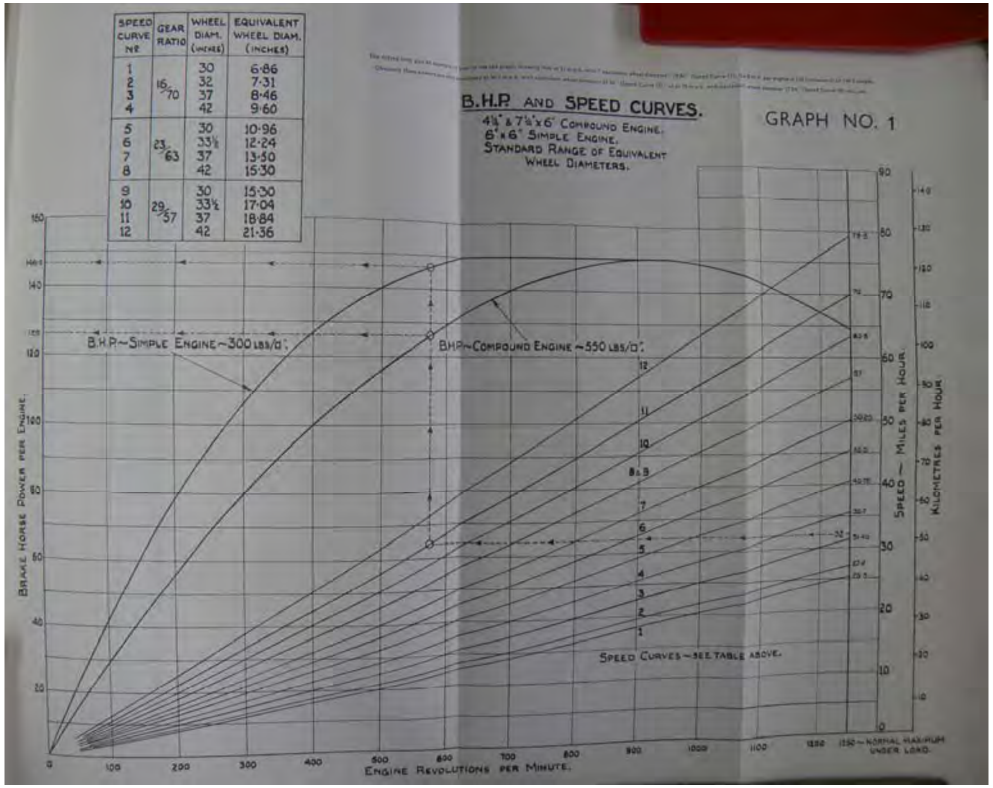

2 Axle 300hp




3 Axle 450hp

# Sentinel Performance Curves




| SPEED CURVE Nº | GEAR RATIO | WHEEL DIAM. (INCHES) | EQUIVALENT WHEEL DIAM. (INCHES) |
|---|---|---|---|
| 1 | 16/70 | 30 | 6·86 |
| 2 | | 32 | 7·31 |
| 3 | | 37 | 8·46 |
| 4 | | 42 | 9·60 |
| 5 | 23/63 | 30 | 10·96 |
| 6 | | 33½ | 12·24 |
| 7 | | 37 | 13·50 |
| 8 | | 42 | 15·30 |
| 9 | 29/57 | 30 | 15·30 |
| 10 | | 33½ | 17·04 |
| 11 | | 37 | 18·84 |
| 12 | | 42 | 21·36 |

# New Solutions

# Target Specifications

| Power | | Max TE | Max Speed | Min Endurance | Crew | Max Power |
|---|---|---|---|---|---|---|
| rhp | ihp | lbf | mph | days | | hours |
| 280 | 269 | 35,000 | 20 | 6 | 1 | 42.2 |

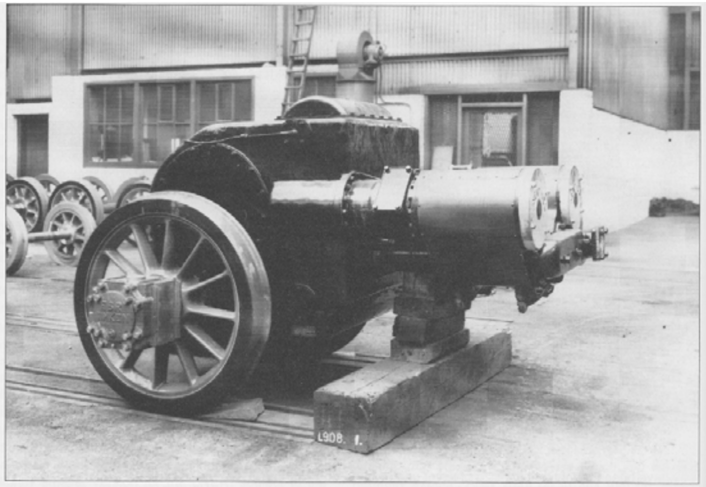
- Spec provides equal performance to Class 08
- Max Power Hours proxy for fuel and water capacities based on matching Class 08

# Technologies Assumed

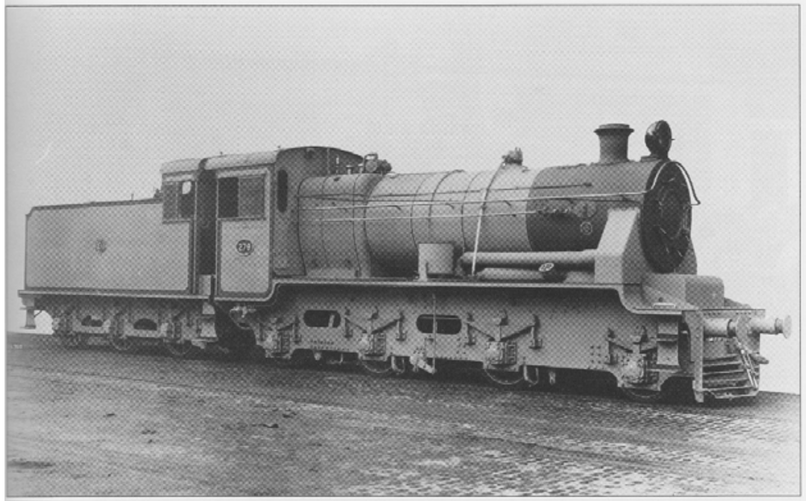
- Woolnough water tube boiler
  - Sentinel claimed that c.f. trad steam:
    - “50% saving in fuel burnt”
    - “steam raised in half time”
- Less advanced steam cycle than 5AT
  - 305psi, 400 deg C (750 deg F) steam temp
  - 14 psi cylinder back pressure
- Pulverised Coal Firing, same efficiency as hand firing
- Sentinel 6 cylinder single acting engine
- Sentinel geared drive
  - 2 gears, engageable when stationary from cab
- Rotary Cam poppet valve gear, fully variable cutoff
- Atmospheric Condensing to improve Availability

All Proven Technology

# Alternative Cylinder/ Final Drive Configs.




*A Complete Sentinel engine unit for the Egyptian locomotives awaits fitting in the North British Locomotive Company's Workshops in Glasgow.* *(Author's collection)*



*Job Number 9299 as completed by the North British Locomotive Company for Egypt.* *(Author's collection)*

- Sentinel Enclosed Engine Unit
  - Fitted to 8 locos & 16 railcars
- Sentinel 6 Cylinder Single Acting Engine
  - Fitted to 163 railcars (52 LNER)

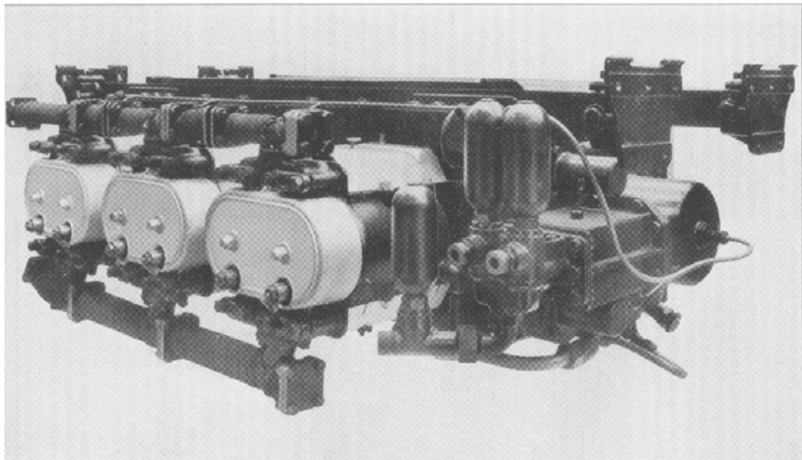
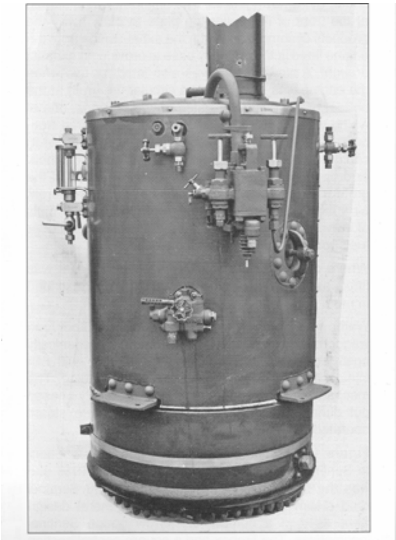
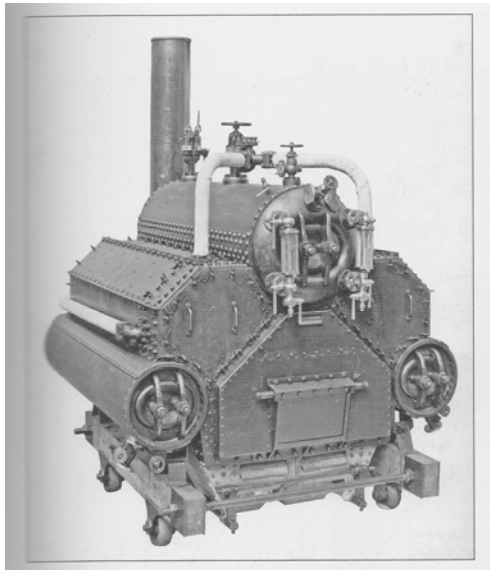


**Figure 17:** *The six-cylinder Mark I engine from the cylinder side.*

# Sentinel Boilers



A Super-Sentinel vertical boiler, complete with fittings. The



The Woolnough boiler fitted in LNER Job Numbers 7822 and 7823 from the firing end. (Author's collection)

| Type | Evap | HS | Grate Area |
|---|---|---|---|
| | lb/hr | ft2 | ft2 |
| Vertical | 1600* | 70 | 5 |
| Woolnough | 4500 | 233 | 9 |
| Woolnough | 5000 | 282 | 9 |
| Woolnough | 7500 | 393 | 12 |
| Woolnough | 10000 | 503 | 14.8 |
| Woolnough | 12500 | 580 | 18 |

* calculated

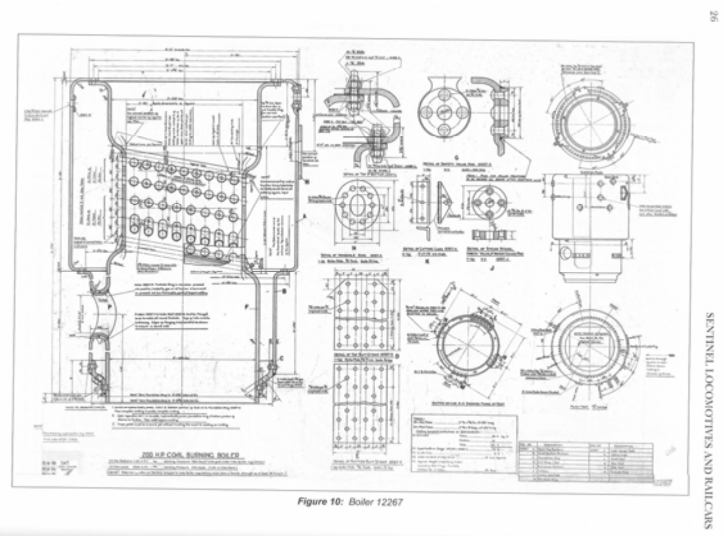
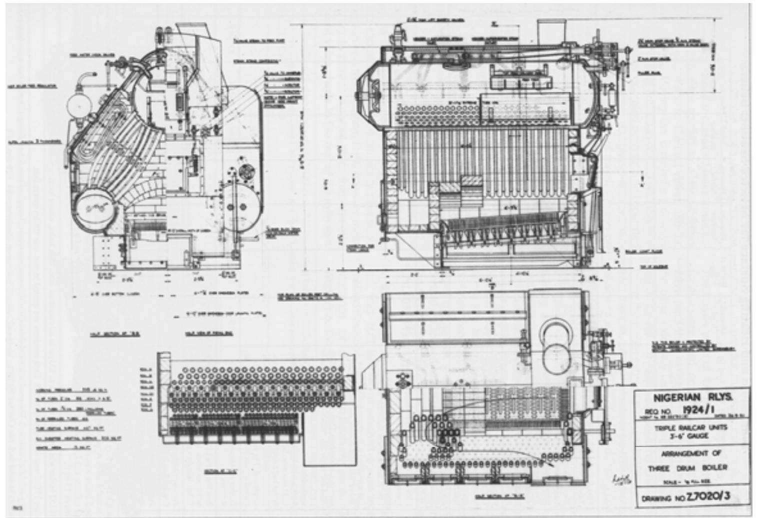



Figure 10: Boiler 12267




Drawing of Woolnough boiler fitted in the Nigerian Railways Railcars supplied in 1953.

# The Real Thing @ Bucks Rly Centre

# Design

# Parametric Design

- Power curves scaled from Colombian Loco T.E. Curve
- Thermodynamic Performance estimated from 1st principles
- Roosen for Condenser
- Weight Estimates derived from Sentinel locos
- *Deviate as little as possible from traditional Stephenson form to minimise risk*
  - Traditional Steam shunters had lost to D.E. – need to do something different, but credible

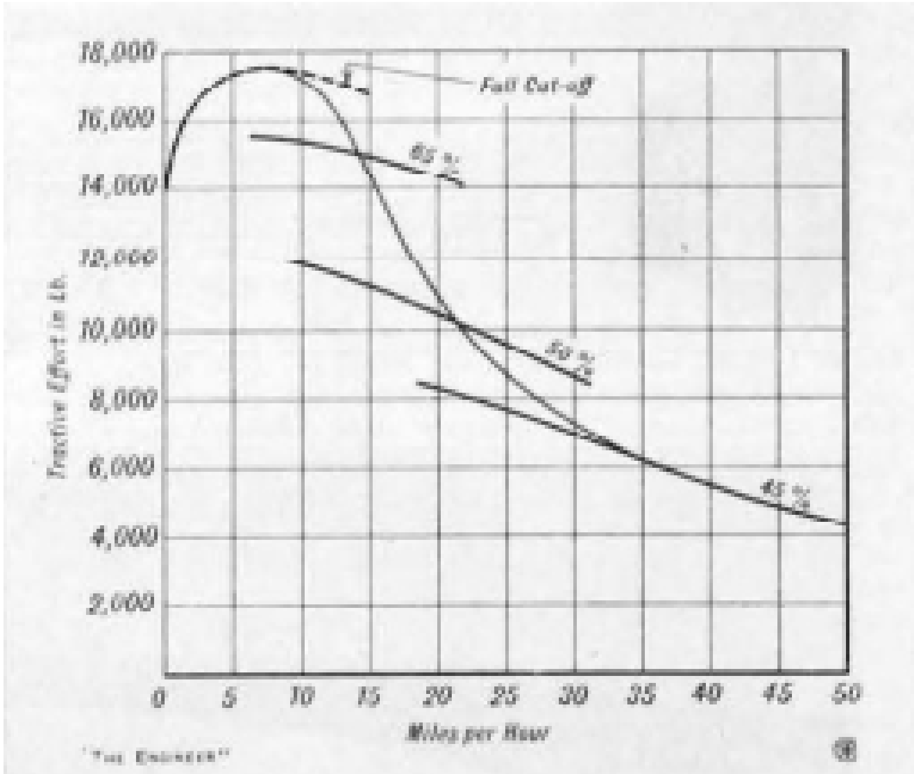
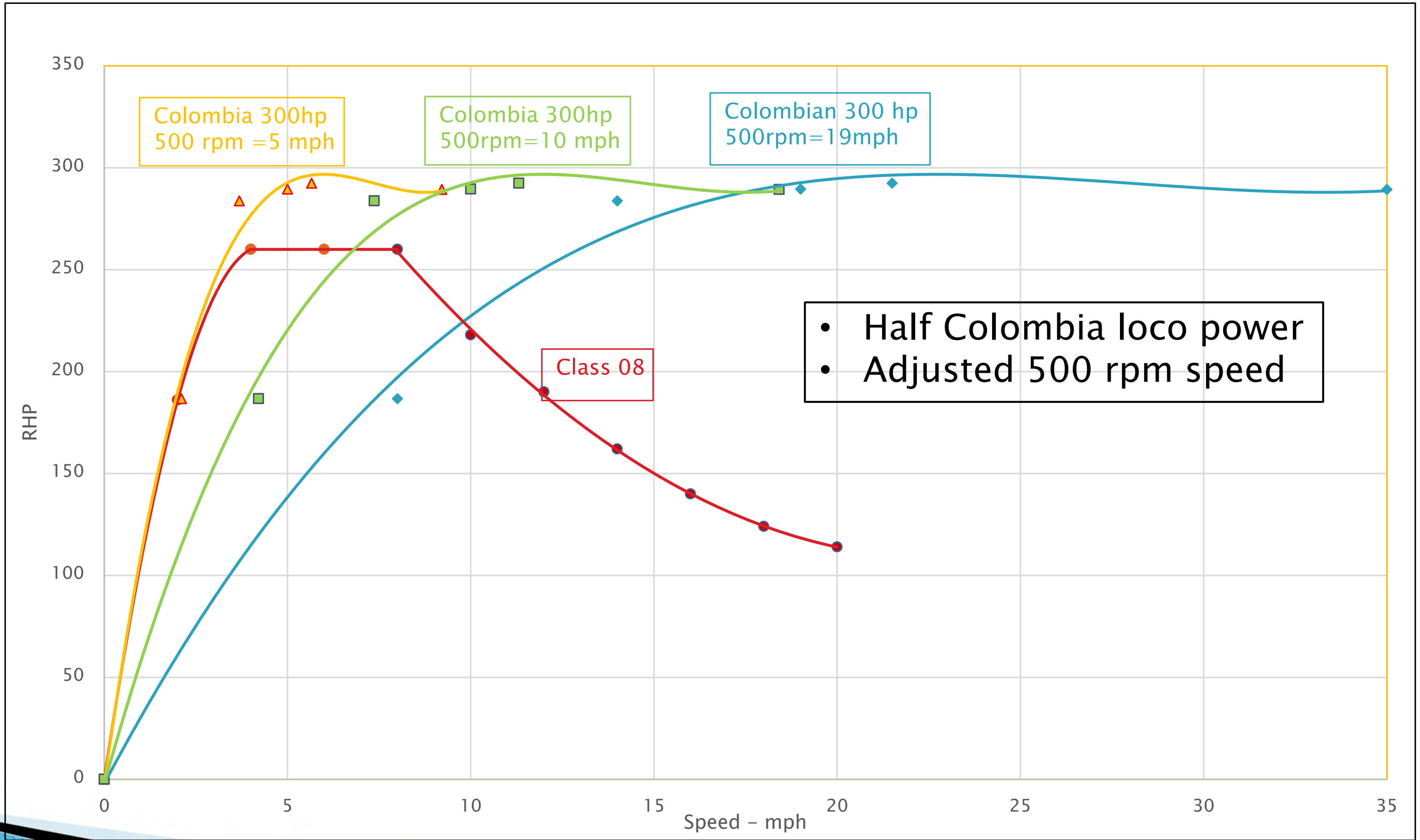


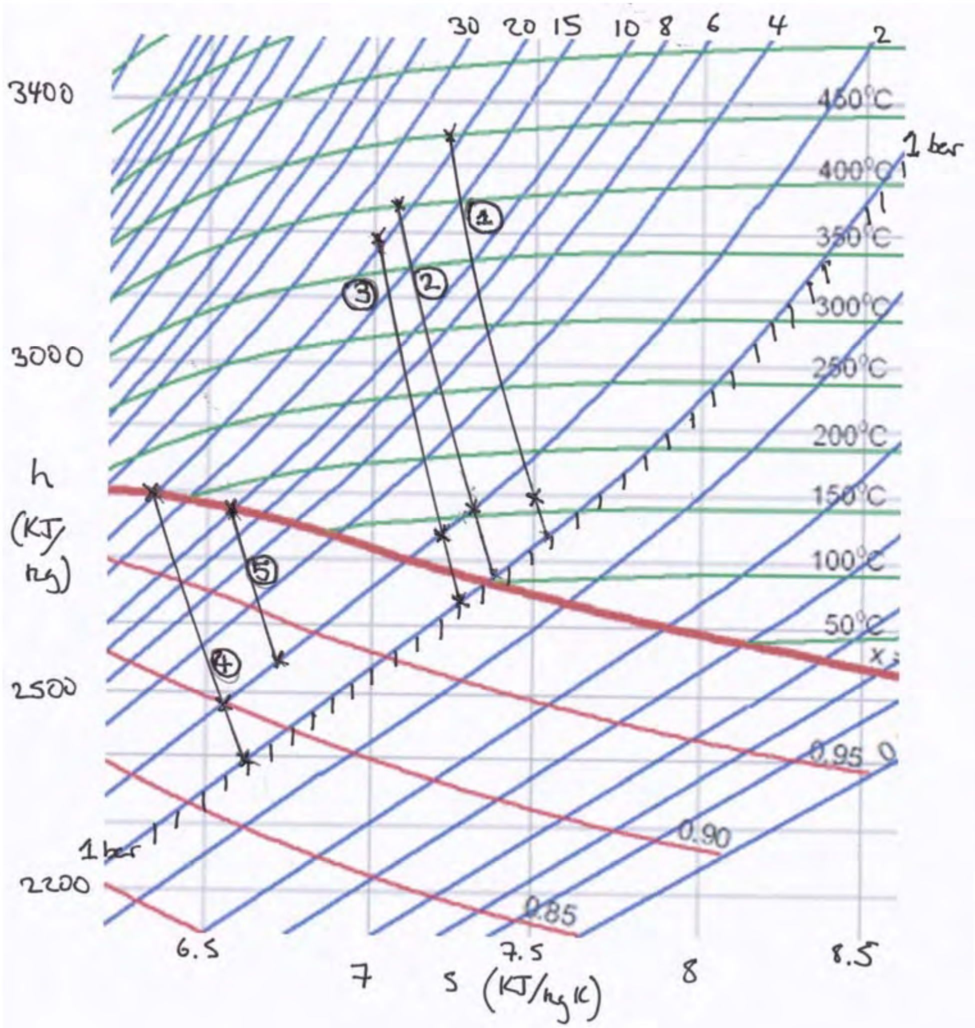

FIG. 16 TRACTIVE EFFORT AT VARIOUS SPEEDS

# Class 08 Equiv – 3ATT Options



# hs Diagrams – Shunters

| | | Pressure | SH Temp | | Isen. Effy | Delta h | % 5AT Cycle |
|---|---|---|---|---|---|---|---|
| | | psig | Deg C | Deg F | % | KJ/kg | % |
| 1 | 5AT | 305 | 450 | 842 | 85 | 550 | 100% |
| 2 | Woolnough | 305 | 400 | 750 | 80 | 437 | 79% |
| 3 | Woolnough | 305 | 370 | 700 | 80 | 417 | 76% |
| 4 | Woolnough | 305 | Sat | Sat | 75 | 307 | 56% |
| 5 | 3F | 160 | Sat | Sat | 75 | 213 | 39% |



# Woolnough Thermodynamics

| Woolnough Open Cycle | | Pressure | Temp | h | isen eff | SSC | |
|---|---|---|---|---|---|---|---|
| Coal MJ/kg | 30 | psig | deg C | KJ/kg | % | Lb/ Ihp-hr | Lb/ DBHP-hr |
| SH Exit | | 305 | 399 | 3243 | | | |
| HP Steam chest | | 290 | 399 | 3245 | | | |
| Cyl exit | isen. | 15 | 120 | 2699 | 80% | | |
| | adiab. | 15 | 170 | 2808 | | | |
| Total Cyls Adiabatic | | | | 437 | | | |
| Total Cyls | | | | 415 | | | |
| 5 mph | | | | | | 14.3 | 14.8 |
| 20 mph | | | | | | 14.3 | 16.8 |

| Woolnough Condensing | | Pressure | Temp | h | isen eff |
|---|---|---|---|---|---|
| Coal MJ/kg | 30 | psig | deg C | KJ/kg | % |
| SH Exit | | 305 | 399 | 3243 | |
| HP Steam chest | | 290 | 399 | 3245 | |
| Cyl exit | isen. | 15 | 120 | 2699 | 80% |
| | adiab. | 15 | 170 | 2808 | |
| Turbo In | | 15 | 170 | 2808 | |
| Turbo Out | isen. | 0 | 100 | 2657 | 80% |
| | adiab. | 0 | 101 | 2680 | |
| Total Cyls Adiabatic | | | | 437 | |
| Total Cyls | | | | 415 | |
| Turbo | | | | 129 | |

| | Speed | Rpm | Power | | | Coal | Evap | Cyl Feed | SSC | DB Effy |
|---|---|---|---|---|---|---|---|---|---|---|
| | mph | | IHP | LR (hp) | DBHP | lb/hr | lb/hr | lb/hr | Lb/ihp-hr | % |
| 3ATT/ | 5 | 500 | 269 | 10 | 259 | 546 | 4009 | 3836 | 14.3 | 7.7 |
| 3ATTC | 20 | 500 | 269 | 40 | 229 | 546 | 4009 | 3836 | 14.3 | 7.7 |

| Full Power | 42.2 | Hours |
|---|---|---|
| Coal | 10.3 | tons |
| Water | 16,936 | gall |
| per day | 2,823 | gall |

# Auxilliaries Design

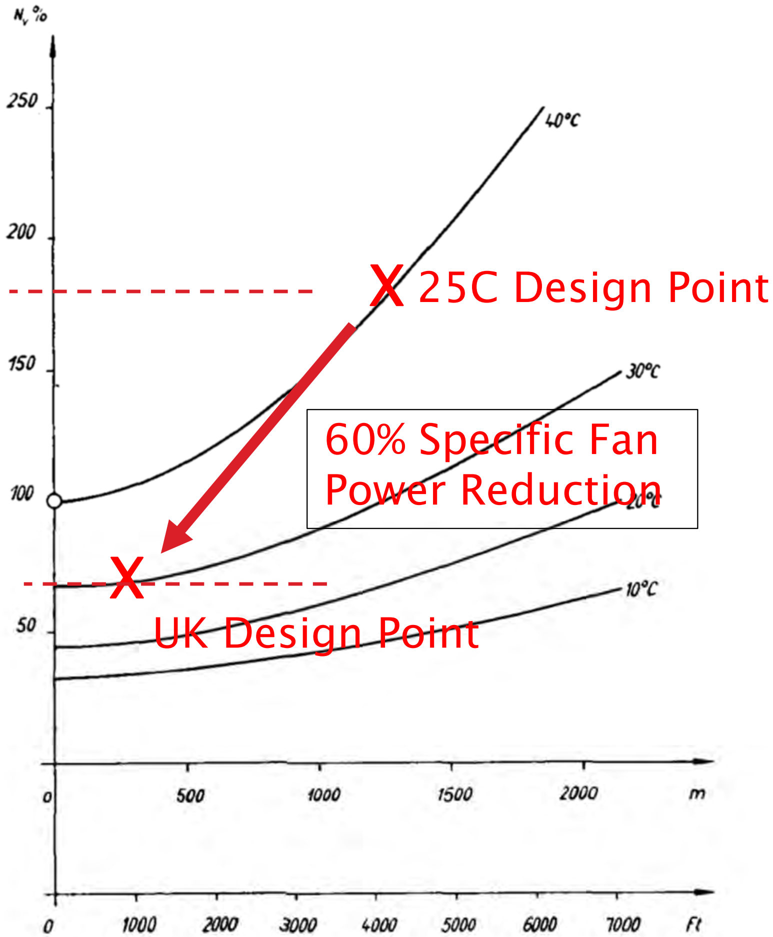
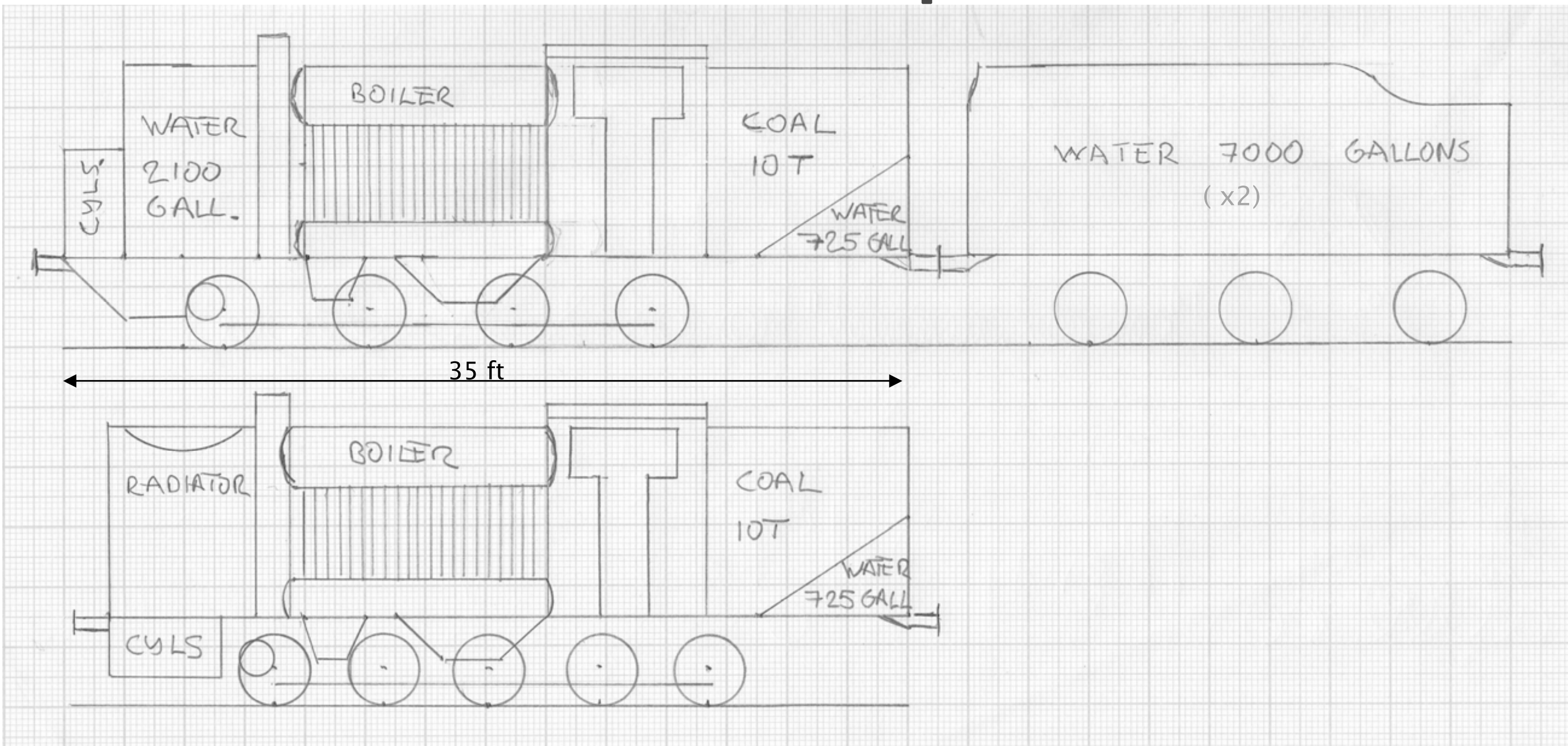



FIG. 8
EFFECT OF ALTITUDE AND AMBIENT AIR TEMPERATURE ON POWER DEMAND $N_v$, RELATED TO SEA LEVEL AND 40°C = 104°F.

| Radiator Design Conditions | | | | |
|---|---|---|---|---|
| | Steam Mass Flow | Heat Transfer | Design Altitude | Design Amb Temp |
| | | | Alt | Temp |
| | t/h | KW | ft | deg C |
| 25C | 25 | 17,132 | 4500 | 40 |
| 3ATTC | 1.8 | 566 | 1000 | 30 |

| | Alt & Temp Factor | N fans | Rad Area Ratio | Fan Power Factor | Fan Power | Induced Draft Fans | Total Fan Power |
|---|---|---|---|---|---|---|---|
| | | | | | hp | hp | hp |
| 25C | 1 | 5 | 1 | 1 | 550 | 150 | 700 |
| 3ATTC | 0.36 | 0.13 | 1 | 1 | 14 | 11 | 25 |
| | 0.36 | 1 | 0.5 | 0.48 | 7 | 11 | 18 |

# 3ATT/3ATTC Class 08 Equivalent




| Loco | N Axles | Max IHP | 500 rpm Speed | Cyls | | | Driver Dia | Gearing | Starting T.E. | Empty Weight | Max Weight | Max Axle Load |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | n | dia | stroke | | | | | | |
| | | | mph | | in | in | in | | Lbf | T | t | t |
| 3ATT/ 3ATTC | 4 | 269 | 5 | 6 | 6.62 | 7 | 36 | 10.71 | 35,021 | 53.7 | 76.6 | 19.1 |
| | 5 | | 20 | | | | | 2.68 | 8,756 | | | 15.3 |

# 3ATT vs Traditional Steam

| | | 3F | Z | Sentinel CEDG | Sentinel Rod Drive | Sentinel Colombian | 3ATT (Woolnough) |
|---|---|---|---|---|---|---|---|
| Boiler Pressure | psig | 160 | 180 | 275 | 275 | 550 | 305 |
| Grate Area | ft2 | 16 | 18.6 | 5.1 | 5.1 | 18 | 9 |
| Evap | ft2 | 1064 | 1279 | 73 | 73 | 580 | 233 |
| S/H | ft2 | 0 | 0 | 13 | 13 | 253 | 102 |
| IHP | hp | 500* | 600* | 100 | 200 | 600 | 269 |
| Loco Empty weight | t | 42.6 | 63.0 | 18.7 | 44 | 40 | 53.7# |
| Coal | t | 2.3 | 3.0 | 0.75 | 1.8 | 3 | 10.3 |
| Water | gall | 1200 | 1500 | 300 | 850 | 1200 | 2823 |
| T.E. | lbf | 20,835 | 29,376 | 15,962 | 31,924 | 14,000 | 35,234 |
| Mu (Empty) | | 0.22 | 0.21 | 0.39 | 0.33 | 0.16 | 0.291 |

*Calculated from Johnson Ratios for sat.steam
# includes ballast

# Assessment & Conclusions

# Assessment

| Diesel Equiv. | Assessment |
|---|---|
| Class 08 | Technology to match Class 08 performance with steam available in 1950s |
| | Steam individual CAPEX much lower |
| | Potential for Steam to match Diesel OPEX |
| | Steam much lower technical and operational risk |

| Requirements vs. Traditional Steam | 3ATT | 3ATTC |
|---|---|---|
| Cleaner | | |
| Less Manual Labour | X | X |
| Low Speed Performance | X | X |
| Reduced OPEX | X | X |
| Increased Operating Endurance | X | X |
| Increased major repair intervals | | |

# Uncomfortable Questions

- Is the boiler the achilles heel of the steam locomotive ?
  - Inspection requirements – safety
  - Maintenance costs
  - ➔ Low Availability ?
  - *6 day operating cycle allows boiler inspections to be performed on 7th day without affecting availability*

  - Frequent Servicing Required
    - Water, Ash, Fuel
    - ➔ Low Utilisation ?
    - *Coal for 6 days carried, daily water refill (open cycle) or condensing*
    - *Ash ?*

- Does direct side-rod drive inevitably mean low annual mileages ?
  - Fluctuating, asymmetric loads imposed on frames, axleboxes etc.
  - Mitigations - Tandem coupling rods, Franklin Wedges etc.
  - *Geared drive minimizes effects ?*

# Conclusions

- Yes, BR could have done something different
- Proven technologies were available
- Performance is the easiest issue to address
  - *Manual firing not an issue, but single manning essential*
- Competitiveness of steam dependent on price ratio of coal/oil (and environmental acceptability)
- Availability & Utilisation constraints of steam may be limiting factors, not performance
  - *Design to match diesel 6 day operating cycle*

- Still To Come:
  - Multiple Units
  - British Superpower
  - What Does it All Mean ?

# End of Part 4
# Presentation

# Main References

- Sentinel Locomotives
  - "Sentinel Locomotives & Sentinel-Cammell Railcars", Hutchings, IRS, 2020
  - "Sentinel General Service Locos", Sentinel brochure 1930s
- Performance
  - 5AT FDCs, Wardale & Newman, ASTT, 2015
  - "Top Shed", Townend, Ian Allan, 1975
- Condensing
  - "Camels & Cadillacs". Phil Girdlestone, Stenvalls 2014
  - "Class 25 Condensing Locomotives on SAR – Design & Operating Experiences", Roosen, IMechE paper 1960

# Weight Estimate

| Loco | Rly | Config | Max Power | Starting Tractive Effort | Empty No Ballast | Ballast | Empty With Ballast | Coal | Water | Full | Naxles driving | Mu | | Max Axle Load |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ihp | lbf | ton | | | ton | gall | | | Full | Empty | Full |
| 08 | LMS/BR | 0-6-0T | 269 | 35,000 | 45 | | | | | 49 | 3 | 0.32 | 0.35 | 16.3 |
| 3F | LMS | 0-6-0T | | 20,835 | 43 | | | 2.3 | 1,200 | 50.3 | 3 | 0.19 | 0.22 | 16.8 |
| Z | SR | 0-8-0T | | 29,376 | 63 | | | 3.0 | 1,500 | 72.7 | 4 | 0.18 | 0.21 | 18.2 |
| Sentinel CEDG | LNER | 0-4-0T | 100 | 15,962 | 18.7 | | | 0.75 | 300 | 20.8 | 2 | 0.35 | 0.39 | 10.4 |
| | | | | 12,600 | | | | | | | | 0.28 | 0.31 | 10.4 |
| Sentinel rod drive | Dorman Long | 0-6-0T | 200 | | 44 | | | 1.8 | 850 | 50.0 | 3 | 0.00 | 0.00 | 17 |
| Sentinel | SNCF Colombia | Co-Co | 600 | 17,500 | 40 | | | 3 | 1200 | 48.0 | 6 | | | 8.0 |
| Sentinel | LNER Bogie | Bo-Bo | 600 | 21,804 | 40 | | | 3 | 1300 | 48.4 | 4 | 0.07 | 0.08 | 12.1 |
| 3ATT | | 0-8-0T | 269 | 35,000 | 40 | 13.7 | 53.7 | 10.3 | 2,823 | 76.6 | 4 | 0.21 | 0.29 | 19.1 |
| 3ATTC | | 0-10-0T | 269 | 35,000 | 40 | 13.7 | 53.7 | 10.3 | 2,823 | 76.6 | 5 | 0.21 | 0.29 | 15.3 |

| | 2 Cyl | 3 Cyl |
|---|---|---|
| T.E. (lbf) | 35,000 | 35,000 |
| Usable Mu | 0.25 | 0.291 |
| Reqd Adhesion (t) | 62.5 | 53.7 |

| Ballast | 8m x 2m |
|---|---|
| tons | t (m) |
| 6 | 0.05 |
| 14 | 0.11 |

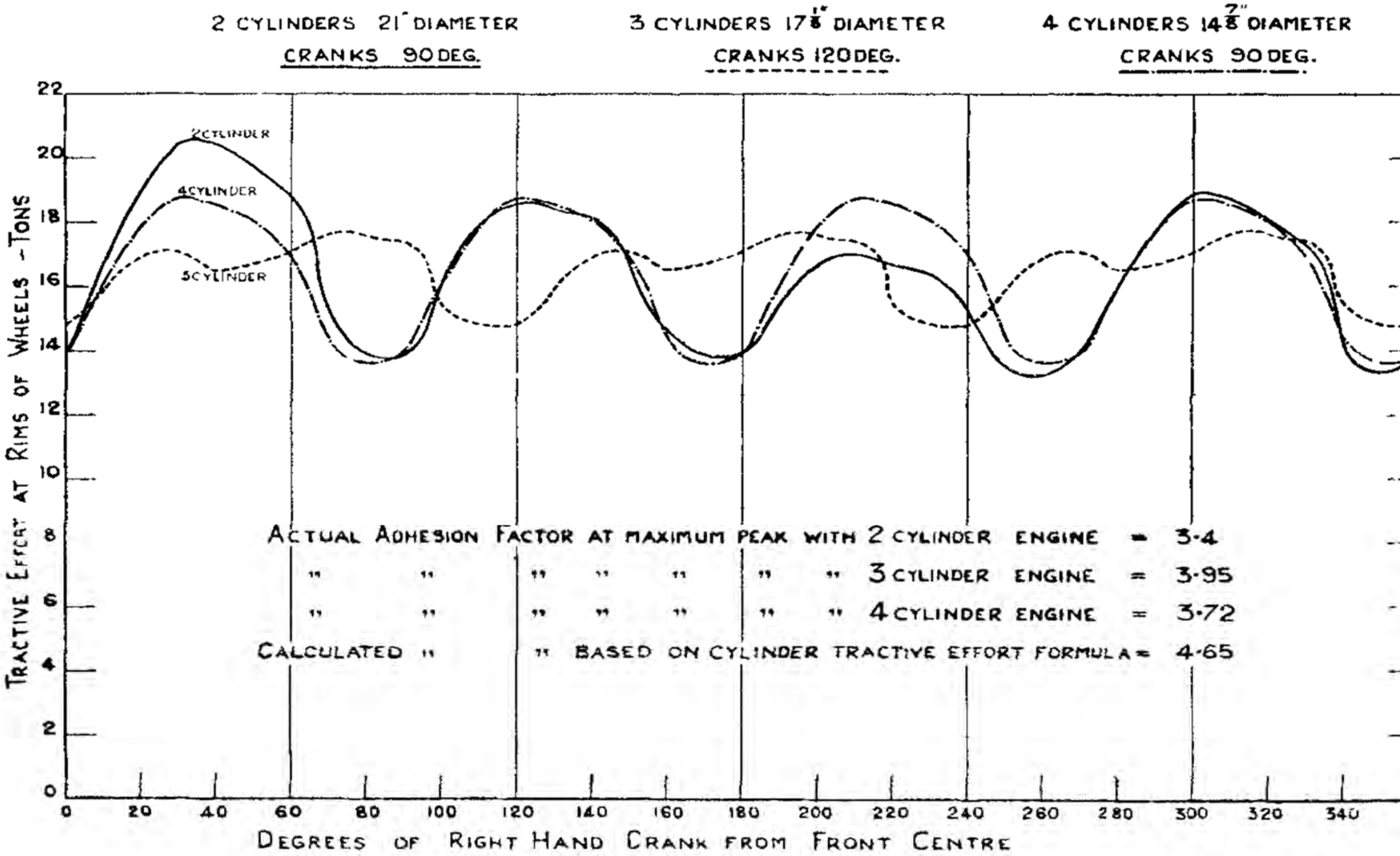
# 3 Cylinders

- Constant calculated coefficient friction (= 0.215) for 2,3,4 cyl designs of equal cyl volume
- 3 Cylinders give a more even turning moment than either 2 or 4 Cylinders and hence a 14% higher useable coefficient of friction than 2 cyl designs

| N Cyl | Peak Mu |
|---|---|
| 2 | 0.294 |
| 3 | 0.253 |
| 4 | 0.269 |
| Calc | 0.215 |

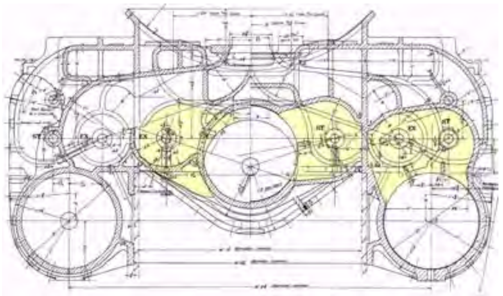
FIG. 2. *Variation in Tractive Effort at Rims of Wheels for one Revolution with 2, 3 and 4 Cylinder Engines of Equal Cylinder Volume.*

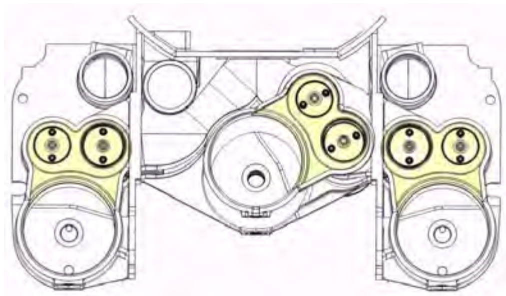
Boiler Pressure 180 lb. per sq. inch. Stroke 28 inches. Wheel Diameter 56 inches.
Cut-off 75 per cent. Connecting Rod 8 times crank radius. Adhesive Weight 70 tons.

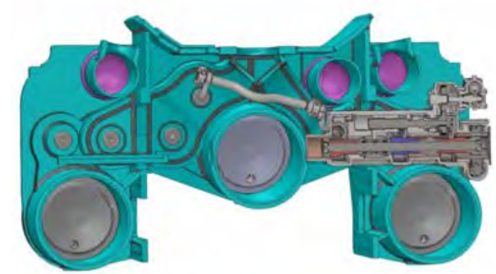


# Valve Gear

- "All valve gears give practically the same diagram"
  – Porta, Fundamentals of the Porta Compound System
- Personal preference is for rotary cam poppet valve gear
  - Technically most elegant
  - Enclosed, therefore lower maintenance (Bond)
  - Lighter, therefore more suited to high speed
    (Chapelon 5kg poppet valve cf. 100kg piston valve)
  - ➔ RC Lenz, Franklin B or British Caprotti







2001 original Gresley P2
Large centre cyl clearance vol

2007 P2 redesign
Reduced clearance vols, rocking shaft
Drive to centre cyl inlet valve

# Sentinel Design Parameters – 1930s Gen Svc Locos

| | Performance | | Endurance | |
|---|---|---|---|---|
| | Av Steam Consumption | Evap | Coal | Water |
| | lb/BHP-hr | lb water / lb coal | hrs | hrs |
| Compound | 14 | 9 | 5 | 2 |
| Simple | 17.5 | 7.2 | 4 | 1.5 |

| Woolnough Boiler Pressures & Temps | | | | | |
|---|---|---|---|---|---|
| | S/H out | steam chest | receiver | S/H temp | Back pressure |
| | psi | psi | psi | deg F | psi |
| compound | 550 | 500 | 140 | 750 | 5 |
| simple | 335 | 300 | | 750 | |

| Woolnough Boiler Standard Sizes | | |
|---|---|---|
| Evap | HS | Grate Area |
| lb/hr | ft2 | ft2 |
| 4500 | 233 | 9 |
| 5000 | 282 | 9 |
| 7500 | 393 | 12 |
| 10000 | 503 | 14.8 |
| 12500 | 580 | 18 |