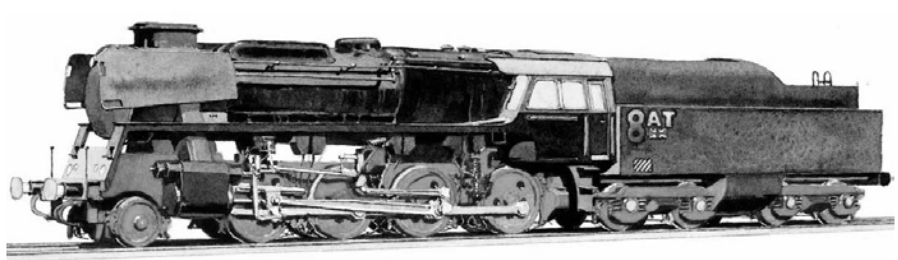
Transportation of Coal by Rail in Indonesia

The Steam Option



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1 Introduction

Coal-fired steam power provided the driving force behind the Industrial Revolution that transformed the world 200 years ago. For 125 years steam powered the world's railways when at the beginning of the 1950s, in the USA, it was suddenly and swiftly replaced by oil-fired diesel traction, a process that was followed in most other countries over the next 20 to 30 years. The last main-line steam operation on the Jitong Railway in China was replaced by diesel in 2004.

No official cost studies have ever been published by any railway authority to justify the massive cost of the rapid change-over to diesel, which in many cases involved the scrapping of large numbers of near-new steam locomotives and their replacement with diesels that failed to live up to expectations. Such justifications as were offered for the huge costs involved in the change-over, were based on subjective claims of improved performance, lower labour costs, reduced pollution, and lower fuel costs.

Steam technology has been kept alive over the last 50 years by a few dedicated engineers, most notably the Argentinean Livio Dante Porta. Porta developed many technical advancements in steam technology that were successfully proven in trials in several countries, however none was able to stem the change-over to diesel despite conclusive evidence that steam traction in many instances was substantially less costly to operate. Recent increases in oil prices and the expectation that these will continue to rise in the future, have renewed interest in solid-fuelled steam traction and to compare its present costs and future potential for improvement with those of oil-dependent diesel traction.

This paper presents detailed cost comparisons between steam, diesel and electric traction for the haulage of Indonesian coal over new railways that are being planned or built to move coal from mines to port. Its conclusions confirm that "modern steam" traction incorporating the advances pioneered by Porta, is by far the lowest cost option. Indeed, the paper makes it clear that steam should have an ongoing role in the 21st century in circumstances that favour its use – in particular where coal and labour costs are low. Indeed steam traction's cost competitiveness will broaden as diesel fuel prices continue to rise in the future.

2 History of Steam Locomotion

Steam power was the driving force behind the Industrial Revolution that began in Britain in the late 18th century, steam traction for railways being first demonstrated (by Trevithick) in 1803 and put into commercial use by George Stephenson in 1825. The steam locomotive's invention and early development by entrepreneurial artisans led to its ongoing development by similarly skilled people. As a consequence, even in the mid 20th century when the world's last steam locomotives were being designed and built, the design methodologies then employed were largely based on empirical rules, past experience, and tried-and-proven rules-of-thumb. As a result, most 1950s steam locomotives were slower, less efficient, less reliable and more polluting than they need have been. Furthermore the extraordinary robustness of the steam locomotive that allowed it to operate under the worst conditions and with inadequate maintenance meant that it did operate under the worst conditions and with inadequate maintenance, thus exacerbating its inadequacies.

“Museum steam” was therefore characterised by what can only be described as a “good enough” standards for both design and maintenance. These resulted in: low thermal efficiency (max 8%), low power/weight ratio (max 18 kW/tonne); high coal and water consumption; loose tolerances; high maintenance, servicing and labour costs, and an aura of dirt and pollution. These deficiencies were more than enough to make the diesel option look both modern and attractive, and contributed more than anything else to steam’s rapid replacement by diesel traction.

3 Evolution of “Modern Steam”

The one notable exception to the “good enough” engineering approach to steam locomotive design in the first half of the 20th century was a Frenchman by the name of André Chapelon who, in the late 1920s, pioneered the adoption of scientific (thermodynamic) theories in the design of locomotives. As a result of his work, over the next 20 years France produced a fleet of thermally efficient locomotives that far exceeded the performance of any others in the world (in weight-for-weight terms). Indeed one of his locomotives, his 1A242 of 1952 outperformed contemporary electric traction, forcing the redesign of a new class of electric locomotives to match the performance of Chapelon’s steam locomotive. Nevertheless, France being short of coal, was swift in getting rid of steam traction and replacing it with diesel and (nuclear powered) electric traction, and Chapelon’s post-war designs for a new fleet of steam locomotive (including a very high speed machine) were never built.

When Chapelon retired, his leading role in the development of steam traction was taken over by a young and brilliant Argentinean engineer by the name of Livio Dante Porta. In 1956 (at the age of 24) Porta made his first attempt at rebuilding a steam locomotive and in doing so equalled the best power/weight figures achieved by Chapelon. In 1960 Porta was promoted to the position of Director of Argentine’s National Technology Institute in Buenos Aires which position he held until he reached retirement age in 1982. During that time and over the succeeding years before his death in 2003, Porta pioneered several important advancements in the development of steam traction. These advances can be summarized as follows:

- Reduced fuel consumption and smoke emissions through the adoption of a Gas Producer Combustion System (or GPCS) firebox;
- Improved exhaust systems to minimize cylinder back-pressure and to maximize smokebox vacuum, using a formalized design methodology based on scientific principles;
- Improved valve liners and cylinder lubrication to allow the use of higher steam temperatures (necessary to increase thermal efficiency);
- Improved design and sealing methods to minimise steam leakage;
- Improvements to insulation materials and adoption of welded-in-place insulation covers to prevent insulation being removed or lost;
- Major advancements in water treatment that result in near-zero maintenance on the water-side of boilers even when operated with very hard water, and which can extend washout intervals to 6 or even 12 months;
- Improved adhesion by the use of modified tyre profiles (and diameters);

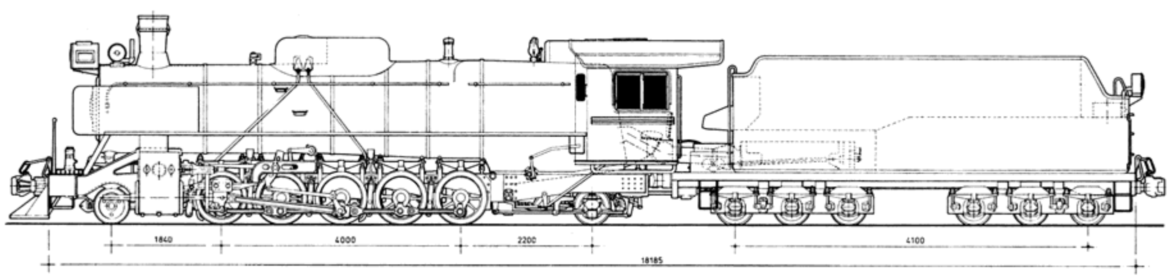
- Detail design improvements (e.g. to valve and piston rings) to reduce wear rates and extend the time periods between overhauls.

Detailed listings of the advances in both performance and maintenance/reliability of modern steam traction (relating specifically to the 8AT locomotive, but applying broadly to all modern steam designs) are presented in Appendices A and B of this paper.

4 Rio Turbio Coal Haulage Railway

Relevant to coal haulage requirements in Indonesia was Porta's long-time involvement, first as General Manager and later as consultant adviser, to the 270 km railway from Rio Turbio to Rio Gallegos in Patagonia at the southern end of Argentina. This railway was built in the early 1950s using 750 gauge track laid directly on the earth (no ballast) and fitted with light rail that limited the permissible axle load to 7.5 tonnes. A fleet of small 48 tonne "Santa Fe" (2-10-2) steam locomotives was purchased from Mitsubishi in Japan to operate the railway which was used to haul coal from a mine in Rio Turbio to the Atlantic coast port at Rio Gallegos.

The locomotives, as originally built, were capable of producing no more than 520 kW and suffered serious clinkering problems with the poor quality (low C.V.) coal that was available from the mine. Porta made several (relatively minor) modifications to these locomotives that eliminated the clinkering problem (by the adoption of GPCS) and boosted their power output by 75% (to 900 kW), enabling these diminutive locomotives to haul 1700 tonne trains over the poor quality and tightly curved track. On test, one of these locomotives hauled a 2000 tonne train over the full 270 km distance, and on another test, a 3000 tonne train was hauled by one of these locomotives, with a second locomotive only offering assistance over the uphill gradients. These figures are relevant to the discussion of locomotive haulage capacity in Section 7 below.



Diminutive 2-10-2 750mm gauge 48 tonne locomotives of Argentina's Rio Turbio Railway

5 Porta's Legacy

Most of Porta's efforts took the form of a rearguard action that attempted to give steam a chance to compete against the tide of dieselization that was then still sweeping the world. His efforts were mostly focussed within his home continent of South America, particularly in Argentina where he produced some remarkable improvements to a number of locomotives within the nationalised railway's fleet. He also made significant improvements to wood-burning locomotives in Paraguay, and in his later years he produced a very high performance rebuild of a locomotive that operated on Cuba's sugar cane railways. In all cases however, he was too late to change the minds of railway organizations that had already committed themselves to “progressive” but costly change-overs to diesel traction.

Several other engineers took up the challenge of putting into practice Porta’s design theories and principles, including English engineer David Wardale who adopted Porta’s methodology in the rebuilding of South African Railways Class 25 locomotive No 3450 nicknamed “The Red Devil”. Wardale’s work and his achievements in boosting the power output of the locomotive by 60% and reducing its specific coal consumption by some 40% are recorded in great detail in his book “The Red Devil and Other Tales from the Age of Steam”. Phil Girdlestone incorporated Porta’s thinking in less extensive rebuildings of locomotives in Australia and Russia, while Shan McMahon, now living in Argentina, has incorporated Porta’s theories in rebuilds of two locomotives operating on the FCAF railway in Ushuaia, and is now involved in plans to recommission some of the currently retired Rio Turbio Santa Fes to haul tour trains from Rio Turbio into Chile and perhaps even to return to the working of coal trains to the Atlantic coast.

David Wardale’s “Red Devil”. A rebuild of a South African Railways Class 25NC, the locomotive’s power output was increased by 60% and its specific coal consumption was reduced by 40%.

In his book “The Red Devil and Other Tales from the Age of Steam”, David Wardale promulgated the idea of building a new high speed steam locomotive that would be the first of a new generation of steam locomotives incorporating all of the technical advancements that had been developed by Porta. That concept is now being brought to reality by a group of engineers and professionals of other under disciplines under the banner of the “5AT Project”.

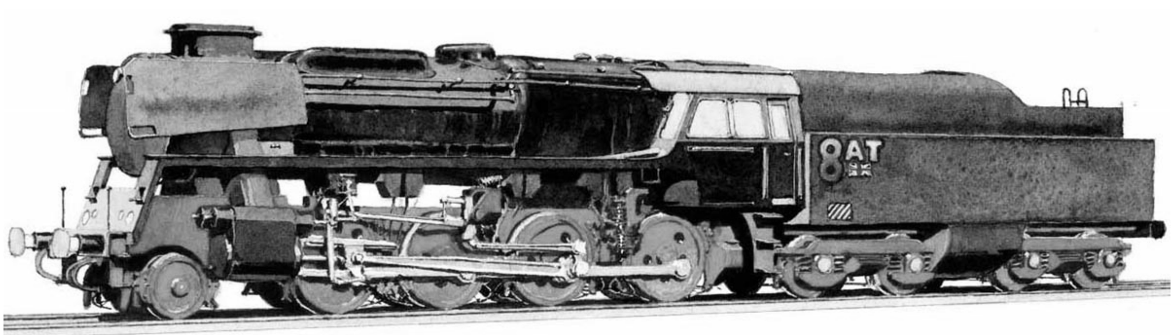
6 Describing the 5AT and 8AT Concepts

The 5AT locomotive is so named because its “Advanced Technology” design is based on the size and weight of the British Railways “5MT” locomotive of 1951. However whilst the 5MT had a maximum drawbar power of around 1000 kW (1350 HP) and a maximum speed of perhaps 85 mph on level track, the 5AT will be capable of developing 1890 kW

(2535 HP) at the drawbar and operating continuously at180 km/h (113 mph). Furthermore, it will have a maximum design speed of 200 km/h (125 mph), rendering it capable of raising the world speed record for steam. The locomotive is intended to provide motive power for tour trains in the UK and Europe where it is becoming difficult for "museum steam" traction to find paths on high speed main lines within which it can operate. Work on the Fundamental Design Calculations for the 5AT are complete and these demonstrate conclusively that the locomotive's remarkable performance predictions can and will be achieved.

The 5AT's Fundamental Design Calculations have been adapted to determine the performance capabilities of a freight-haulage version, dubbed the "8AT". Changing the 5AT's 4-6-0 configuration to a 2-8-0 and fitting of smaller driving wheels of around 1.325 mm (4' - 4") diameter, but sharing the same boiler, cylinders, cab and tender, produces an 80 tonne locomotive with a nominal tractive effort of 206 kN (46,400 lb) and a slightly higher drawbar power output than the 5AT[1]. It is estimated that the 8AT should be capable of hauling freight trains of between 3000 and 4000 tonnes gross weight on level track as described in Section 8 below. Appendix C presents a tabular summary of basic data for the 8AT locomotive showing comparisons with the 5AT.

Both the 5AT and 8AT concept designs are based on operating within the UK's very constricted moving vehicle diagram. Whilst this imposes some constraints on the 8AT's design, it does result in a locomotive that will be able to operate almost anywhere else in the world, making its potential market larger than would be the case for a larger sized machine.



Artist's impression of the 8AT "modern steam" freight locomotive

7 Estimating Haulage Capacity of 8AT Locomotive

There is a saying that a diesel locomotive cannot haul as much as it can start, while a steam locomotive cannot start as much as it can haul. This is associated with the fact that diesel locos generate a relatively constant power output which produces a very high

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[1] The 8AT should produce a hypothetical maximum 2100kW at the drawbar at 120 km/h. At its normal operating speed of 80 km/h it will produce 1800kW at the drawbar. Its drawbar power is higher than the 5AT because (with its smaller driving wheels) it reaches the same peak cylinder power as the 5AT but at a lower travelling speed at which its rolling resistance will be lower. Drawbar power = cylinder power – locomotive rolling resistance losses, the 8AT's drawbar power will be higher. The 8AT's Power and TE vs. Speed curves are presented in Appendix C.

tractive force at low speed that reduces in inverse proportion to the locomotive's speed. The steam locomotive, on the other hand, generates a more constant tractive force such that its power output increases as its speed increases, reaching a maximum value close to its maximum design speed. This can be seen on the graphical representation of the (calculated) tractive force and power outputs of the 8AT locomotive as presented in Appendix E.

By comparing the 8AT's tractive force at each speed with the rolling resistance of a train of wagons, it is a simple matter to estimate the limiting speed of the locomotive when hauling a range of train weights over a range of gradients. The rolling resistance of a train of wagons can be estimated from any one of a number of formulae that are commonly used in different countries. Some of these formulae are represented graphically in Appendix D in which the specific resistance figures (in Newtons per tonne of train weight) are shown over a range of speeds. Appendix F shows a graphical representation of the estimated "Speed-Gradient" curves for 8AT Locomotive which shows the limiting speed of the locomotive when hauling a range of train sizes over a range of gradients based on Koffman's (UK) wagon resistance formula. From this it can be deduced that the 8AT will be able to haul 4000 tonne trains on level track at up to 85 km/h.

There remains some uncertainty about the starting resistance of rail wagons for which very little data is available. One of the few sources of data comes from China National Railways which adopt a specific starting resistance of 3.5 kgf per tonne of train weight. If this figure is realistic, then the 8AT should reliably be able to start a 5,600 tonne train on level track. However Koffman gives a starting resistance figure of 7 kgf/tonne for British passenger carriages and if this figure is adopted then the 5AT will only be capable of starting a 2800 tonne train. As will be seen from the graphs presented in Appendix D however, the specific rolling resistance of passenger carriages (resistance per tonne weight) is higher than that of freight wagons, so it is reasonable to assume that the specific starting resistance for passenger coaches is also higher than that for freight wagons. It is therefore also reasonable to assume that the locomotive will be able to start and haul a train weighing 4000 gross tonnes (see Appendix G for confirmation).

8 Comparing Haulage Capacity for each Traction Type

Performance-related data for four types of locomotive: are compared – viz: electric, diesel, old steam and "modern steam". Chinese heavy-haul diesel and electric locomotive data are used because they have been made available to the author, as have cost, performance and haulage data for Chinese QJ steam locomotives.

For the modern steam alternative, performance estimates for the 8AT locomotive are used as described in Section 7 above. Two columns are included to cover the probable range of train size that the locomotive will be able to haul (as discussed above).

The DF4-D diesel locomotive is a development of the original DF-A design, the DFs being the near-ubiquitous diesel locomotive used throughout China's rail system. Passenger and freight versions differ only in the gear ratios of their drive systems. The SS-3 electric locomotive is a development of the SS1 and SS2 locomotives and is still being manufactured. The 2-10-2 QJ steam locomotive was China's standard freight locomotive design that was used throughout the country over the last 40 years of the 20th century, and a few examples of the type are still operating on private coal haulage railways. Some 4700 QJ locomotives were built over a 30 year period until the mid 1980s.

Chinese QJ standard heavy haul freight locomotive. Design dates from the 1950s.

Summarized in the table below are the principle data for each locomotive type including its actual or estimated haulage capability.

It may be noted that the QJ maximum load is given as 5000 tonnes "on test". No details of this test are currently available, but the test was conducted to compare the haulage capacity of an early DF4 diesel with its steam equivalent. In fact the haulage capacity of the two locomotives was found to be about the same, however somewhat higher estimate of traction capacity has been assumed for the DF-4 diesel which is a later, higher horsepower version of the machine that was tested. Calculations based on performance data for the QJ from China National Railways confirms that the locomotive should indeed be capable of hauling a 5000 tonne train on level track at close to its maximum design speed of 80 km/h, however a more conservative figure of 4000 tonnes is used for calculation purposes.

Principle Data for Four Types of Rail Traction					
	Old Steam	**Modern Steam**		**Diesel**	**Electric**
Loco Type	Chinese QJ	8AT 4000t	8AT 3000t	Chinese DF4-D	Chinese SS3
Power Rating kW (indicated/rated)	2600	2500	2500	2940	4320
Max Speed (km/h)	80	120	120	100	100
Loco Weight excluding tender (tonnes)	134	96	96	138	138
Adhesive Weight (tonnes)	100.5	84	84	138	138
Starting Wheel Rim Tractive Effort (kN)	282	206	206	480	490
Continuous Wheel Rim TE (kN)	260	192	192	341	317
Required Starting Friction Coefficient	0.286	0.250	0.250	0.355	0.362
Starting TE Differential	1.00	0.74	0.74	1.62	1.66
Continuous TE Differential	1.00	0.74	0.74	1.16	1.07
Power Differential	1.00	0.96	0.96	1.13	1.66
Assumed Haulage Capacity Factor*	**1.00**	**1.00**	**0.75**	**1.50**	**1.75**
Assumed Maximum Train Size (Gross Tonnes)	**5,000 on test say 4000**	**4,000**	**3.000**	**6,000**	**7,000**

* The “haulage capacity factor” included in the table above is the estimated haulage capacity of each locomotive type as compared to a QJ steam locomotive. As noted above, a DF4 diesel was tested against a QJ and shown to have equal haulage capacity, hence the figure adopted for the DF-4D may be slightly high. Similarly, the assumed haulage capacity of the electric locomotive may be slightly biased in its favour.

9 Comparing Rolling Stock Requirements for each Traction Type

Using the train weights that each type of locomotive can haul and assuming the average travel speed that the trains can run at, it is possible to calculate the number of trains needed to haul a given quantity of coal over a given length of line to achieve a required annual tonnage throughput. Given the gross and tare wagon weights, it is also a straightforward matter to calculate the number of wagons that are needed to achieve the required throughput.

The following table summarizes the method of estimation.

Estimate of Rolling Stock Requirements for the haulage of 20 million tonnes of coal per year over a 270 km single track railway at an average speed of 52 km/h using 93 tonne gross weight, 23 tonnes tare weight wagons, and four types of rail traction					
Loco Type	**Chinese QJ**	**8AT 4000t**	**8AT 3000t**	**Chinese DF4-D**	**Chinese SS-3**
Assumed Haulage Capacity (tonnes)	4000	4000	3000	6000	7000
Number of Passing Loops	11	11	17	7	6
Number of wagons per train	43	43	33	65	74
Gross train weight (tonnes)	3999	3999	3069	6045	6882
Tare train weight (tonnes)	3010	3010	2310	4550	5180
Train Interval (hours)	0.87	0.87	0.58	1.30	1.48
Number of trains required (net)	14	14	18	10	9
Number of locos required (net)	14	18	14	10	9
Standing Trains and Locos	1	1	1	1	1
Stand-by Trains of Wagons	2	2	2	2	2
Number of trains required (gross)	17	17	21	13	12
Number of wagons required (gross)	**731**	**731**	**693**	**845**	**888**
Stand-by Locos (assumed)	3	2	2	1	1
Locos under overhaul	4	2	3	2	1
Locos under service	2	1	1	1	0
Number of Locos Required (gross)	**24**	**20**	**25**	**15**	**12**

Notes:

1. The above calculations assume the use of Chinese C70 wagons with a gross weight of 93 tonnes and tare weight of 23 tonnes.
2. The "net" total number of trains includes those that are travelling and those that are being loaded and unloaded at any point in time. This is based on assumptions such that (a) trains load and unload immediately on arrival at the loading and unloading stations; and (b) the loading and unloading rates are ample to allow trains to be filled and emptied in the time interval before the next train arrives. A loading/unloading rate of 6000 tonnes per hour is recommended.
3. One train is assumed to be standing at any time. This is to allow for brake and safety checks to be carried out before departure of empty trains from the unloading station.
4. Two full sets of standby wagons are assumed (arbitrarily) to allow for maintenance, repairs and other unspecified factors.
5. The assumed number of stand-by locomotives is based on subjective judgement. Two units are assumed for the modern steam option to allow for teething troubles during initial operations, however it is expected that these will prove to be at least as reliable as diesel traction.
6. The number of locomotives under overhaul has been calculated from the annual unit mileage estimated for each locomotive type, overhaul frequencies and the estimated duration of overhauls (see Section 10 below).
7. The number of locomotives under "service" allows for minor servicing, safety checks etc at the end of each round-trip. The figures adopted for diesel and steam may be conservative.
8. It is noteworthy that the size of wagon fleet reduces with smaller train sizes. Smaller trains allow greater utilization of individual wagons because their standing-time during loading and unloading operations is less than for wagons in longer trains. Thus running shorter trains reduces the number of wagon required but increases the number of locomotives. Other advantages of shorter trains include: less stress on locomotives and rolling stock drawbars etc, and reduced wheel flange and rail wear.

10 Estimating Maintenance Costs for Alternative Traction Types

1. **Chinese Locomotive Maintenance Data**: The following data has been obtained from China National Railways relating to the maintenance costs and frequencies of the three Chinese locomotive types that are included in this study. This data is summarized as follows:

	QJ Steam	DF4 Diesel	SS3 Electric
Major Overhaul Period	250,000 km or 3 years	700,000 km or 6 years	1,200,000 km or 10 years
Major Overhaul Cost	$100,000*	$200,000	$250,000
Intermediate Overhaul Period	83,000 km or 1 year	250,000 km or 2 years	400,000 km or 3 years
Intermediate Overhaul Cost	$25,000	$50,000	$65,000
Regular Maintenance Period	Daily	30,000 km or 3 months	40,000 km or 6 months
Regular Maintenance Cost	Unspecified	$10,000	$12,000
* Note - a figure of $45,000 has also been quoted for regular 3-year maintenance.			

2. **8AT Modern Steam Locomotive**: Since there is no historical data for the 8AT locomotive, it is instructive to look at the reliability records relating to the fleet of diminutive Mitsubishi 2-10-2 locomotives that operated the Rio Turbio Railway in southern Argentina as described in Section 4 above. These locomotives were “modernized” by Porta insofar as their performance was enhanced by improvements to fireboxes, boilers and exhausts, but the locomotive’s drive components were “old steam” including the use of plain (white metal) axle-box and motion bearings.

   The reliability of these machines can be assessed from the following data:

   - 480,000 km before main (white metal) bearings needed replacing = 180 million revolutions of the 850mm diameter driving wheels;
   - 70,000 km between tyre profiling = 26 million revolutions;
   - No superheater replacements in 500,000 km despite high steam temperatures (>400oC);
   - No boiler tube replacement in 400,000 km (apart from tubes damaged during installation);
   - No boiler repairs in 400,000 km of service;
   - Piston rod packings lasted 400,000 km (150 million revolutions);
   - Max steam leakage 1.7% of max evaporation after 70,000 km.

   Thus by taking into account the maintenance-reducing design improvements incorporated into the “modern steam” option (as listed in Appendix B), the following assumptions are made for the 8AT:

   - Indefinite periods between major boiler overhauls. Using Porta’s water treatment, it is quite possible that the original boiler will last the life of the locomotive and need no major repairs in that time.
   - >500,000 km (3 years) between major overhauls to bearings, cylinder and valve liner replacement etc;

- >100,000 km (1 year) between piston and valve ring replacements;
- >100,000 km (1 year) between tyre re-profiling;
- No daily lubrication requirements (other than topping up a central oil reservoir), nor daily firegrate or smokebox cleaning. However regular ash disposal will be needed.
- Boiler washouts every 6 to 12 months (instead of 30 days).

3. **Maintenance Cost Comparisons**: The following comparative table of cost and time estimates for locomotive maintenance and servicing is based on the above-listed assumptions:

Traction Type	**Recon'd QJ Steam**	**8AT Modern Steam**		**Diesel** ***1997 figs***	**Electric** ***1997 figs***
		4000t	**3000t**		
Major Overhaul Intervals	250,000 km	*500,000 km*	*500,000 km*	700,000 km	1.2 m km
Major Overhaul Cost	$100,000	*$100,000*	*$100,000*	$200,000	$250,000
Intermediate Overhauls Intervals	83,000 km	*167,000 km*	*167,000 km*	250,000 km	400,000 km
Cost per Intermediate Overhaul	$25,000	*$20,000*	*$20,000*	$50,000	$65,000
Routine Maintenance Intervals	*30,000 km*	*83,000 km*	*83,000 km*	30,000 km	40,000 km
Routine Maintenance Cost	*$5,000*	*$10,000*	*$10,000*	$10,000	$12,000
Train Capacity (net tonnes)	3,000	*3,000*	*2,250*	4,500	5,250
Number of Train Kilometres per year	3.600 m	*3.600 m*	*4.800 m*	2.400 m	2.057 m
Av. Travel per year per loco (km)	150,000	*180,000*	*192,000*	150,000	171,500
Annual Major Maint Cost per loco	$60,000	*$36,000*	*$38,400*	$42,800	$35,700
Annual Intermdt Maint Costs per loco	$18,000	*$10,000*	*$11,520*	$16,000	$13,900
Annual Regular Maint Costs per loco	$25,000	*$21,800*	*$28,700*	$50,000	$51,400
Annual Maintenance Costs	**$2.58 m**	**$1.37 m**	**$1.96 m**	**$1.74 m**	**$1.21 m**

Important Notes:

1. The above cost estimates for diesel and electric locomotive maintenance are based on 1997 data which has not been adjusted for inflation;
2. The above cost estimates for electrical traction maintenance exclude maintenance of electrical infrastructure (overhead lines, transformers, switchgear etc). This may add significantly to the maintenance cost of electric traction.
3. It is important to understand that steam locomotives are extremely robust machines that can operate under the worst conditions and with the minimum of maintenance. This was one of the great strengths of "old" steam. However it was also one of its great weaknesses in that steam locos were expected to run without adequate maintenance with the obvious result that they performed poorly and became unreliable. It is imperative that any "modern steam" operation be supported by proper maintenance undertaken in clean and safe working conditions (as given to diesel traction), to ensure that it meets its performance expectations.

11 Estimating Water Consumption

The following table of estimated water consumption and costs for steam locomotives only. In the case of the QJ locomotive, the consumption estimate is based on Chinese National Railways performance curves for that type of locomotive. The 8AT steam consumption is based on calculated performance predictions.

Traction Type	**QJ Steam**	**8AT Modern Steam**		**Diesel** DF4-D	**Electric** SS-3
		4000t	**3000t**		
Water consumption – tonnes per round trip (from spreadsheet)	218	174	131	-	-
Number of round trips per year	6,667	6,667	8,889	-	-
Total water consumed (tonnes)	1.45 m	1.16 m	1.16 m	-	-
Water Cost - assumed per tonne	$0.30	$0.30	$0.30	-	-
Water Treatment Cost – per tonne	$1.10	$1.10	$1.10	-	-
Total Water Costs (per year)	**$2.07 m**	**$1.65m**	**$1.77m**	**-**	**-**

12 Estimating Labour Costs

In the following comparative estimates for labour costs, it is assumed that steam locomotives will require two-man crews and that the diesel and electric locomotives will require single-man crewing. It is believed that the assumed labour cost-rate is somewhat high for Indonesia. If so, this will bias the results in favour of diesel and electric traction.

As noted before, no allowance is made for electrical infrastructure maintenance nor for the labour cost of attending to it.

Traction Type	**QJ Steam Reconditioned**	**8AT Modern Steam**		**Diesel DF4-D**	**Electric SS-3**
		4000t	**3000t**		
Shifts per day	3	3	3	3	3
Crew per loco	2	2	2	1	1
Total Loco Crew	144	120	150	48	36
Servicing Crew per shift	5	2	2	2	2
Total Servicing Crew	15	15	15	6	6
Wage Rate per year	$5,000	$5,000	$5,000	$5,000	$5,000
Labour Cost per Year	**$795,000**	**$630,000**	**$780,000**	**$270,000**	**$210,000**

13 Estimating Capital/Depreciation Costs for each Traction Type

China National Railways capital cost data applying to the QJ, DF4-D and SS-3 locomotives have been adopted for this study. In addition, electrical infrastructure costs supplied by China National Railways is also adopted

The development and manufacturing costs that are assumed for the 8AT locomotive are based on detailed estimates that have been prepared for the 5AT, but take into account the lower speed requirement for the 8AT (reducing complexities associated with dynamic stability verification) and the likelihood that some of the design for the 8AT and much of the manufacture and assembly might be done in Indonesia or China.

A life-expectancy of 25 years is assumed for each of the new locomotive types, and 10 years for reconditioned QJ locomotives. In fact, steam locomotives can be expected to last considerably longer than this.

China National Railway 2001 costs for electrification have been used as applying to a single track railway (includes allowance for stations, yards etc – see second table in Section 14.2 below).

Chinese supplied locomotives include allowances for delivery and shipping costs.

Traction Type	**QJ Steam**	**8AT Modern Steam**		**Diesel DF4-D**	**Electric SS-3**
		4000t	**3000t**		
Development/Infrastructure Costs		Assumed development **$6.0m**	Assumed development **$6.0m**		270km x **$425,000** = $114.75 m
Purchase Cost	$0.4 m	$1.5 m	$1.5 m	$1.5 m	$1.5 m
No Locos Needed	24	20	25	14	12
Total Investment	$9.6 m	$36.0 m	$43.5 m	$21.0 m	$132.75 m
Life Expectancy (assumed)	10 years	25 years	25 years	25 years	25 years
Annualized Cap Cost	**$0.96 m**	**$1.44 m**	**$1.74 m**	**$0.84 m**	**$5.31 m**

14 Estimating Fuel Costs

As will be shown, fuel costs represent the most decisive factor in this comparison. Hence it is covered in greater detail to demonstrate that the deduced figures are representative and reliable. This will be done as follows:

1. Comparing the theoretical cost per unit of power (kW-h) consumed by each locomotive type in delivering its traction requirements;
2. Reviewing historical records of steam and diesel locomotive fuel consumption (and electrical power consumption) rates in China;

3. Estimating the fuel/power consumption for each locomotive type under the same haulage conditions based on a 2,800 tonne train which is understood to be the normal size of coal train currently hauled in Indonesia;
4. Estimating the fuel/power consumption for each locomotive type when hauling its nominated maximum gross train load;
5. Compare the estimated fuel/power consumption rates with Chinese data;
6. Apply the estimated fuel power consumption rates to determine the cost of fuel/power for the haulage of assumed tonnage of coal over the assumed length of railway.

14.1 Estimating Fuel Consumption from Calorific Value and Thermal Efficiency

The tabulation below is based on the following assumptions:

- Calorific values of fuel used are assumed figures based on Indonesian data;
- Fuel and electrical power costs are believed to be represented for Indonesia (coal assumed to be sourced from the mine mouth from which the railway operates).
- Maximum drawbar thermal efficiencies are believed to be representative of each traction type. It should be noted that diesel locomotive manufactures normally state efficiency values in terms of "crank-shaft thermal efficiency", giving values of around 30% or higher. Diesel manufacturers seldom if ever quote drawbar efficiency values that take account of electrical and mechanical transmission losses. A figure of 25% for diesel locomotive drawbar efficiency is believed to be a reasonable estimate.
- The "fuel consumption" figure given for electric locomotive is a measure of kWh consumed divided by kWh supplied based on the stated drawbar efficiency.
- Electrical losses are assumed to be 20% from power supply to locomotive drawbar.

	QJ Steam	**Modern Steam**	**Diesel DF4-D**	**Electric SS-3**
Conversion Factor kcal/kW-h	860	860	860	-
Max Drawbar Thermal Efficiency	8%	15%	30%	-
Assumed Drawbar Efficiency	6%	10%	25%	80%
Fuel Calorific Value - kcal/kg	**6,800**	**6,800**	10,200	-
Fuel Consumption - kg/kW-h	2.108	1.265	0.337	1.250
Fuel Cost – US$ per tonne	$20	$20	$700	$0.08
Cost of Fuel - US cents per kW-h	**4.22c**	**2.53c**	**23.6c**	**10.0c**

Notes:

1. It should be noted that the very large cost advantage that coal-burning steam traction offers in comparison to electric and especially diesel traction, as demonstrated in this simple calculation, is the foundation on which this "Case for

Steam" is developed. Of course this advantage will increase as oil costs (inevitably) increase in the future.

2. It is sometimes suggested that it would be more correct to use the export price of the coal in the above cost comparison rather than the ex-mine price. It should however be recognised that the export price of the coal includes allowances for the costs of: loading; transportation; storage; blending; loading onto ship plus profit. With the possible exception of the first and last items, none of these costs apply to the coal as loaded into the locomotive tender.

   Furthermore, it has been suggested to the author that a more realistic ex-mine cost for the locomotive coal might be $16 per tonne instead of the $20 per tonne used for these estimates.

14.2 Fuel Consumption Data from China

The following table sets out historical data from China National Railways that compares the fuel consumption and failure rates for steam and diesel traction over the period that Chinese rail traction changed from steam to diesel (and electric). It may be noted that both fuel costs and failure rates for diesel were consistently higher throughout the period, though "failure rate" cannot necessarily be regarded as an accurate measure of reliability.

Data from Official Statistics of the Operation Department of China's National Railway.
Note: The figures do not include contemporary fuel costs;
2003 costs have therefore been adopted for comparative purposes only.

Year	Available Locos Per Day (sets)		Gross Train Movements 10^6 Tonne-kilometres		Loco Failures per 10^6 ton-km		Average fuel consumption Tonnes per 10^6 t-km		Unit Price of fuel (RMB)		Unit Price of traction (RMB/ 10^6 t-km)	
	Steam	Diesel	Steam	Diesel	Steam	Diesel	Steam	Diesel	Steam	Diesel	Steam	Diesel
1987	5317	3282	770,009	750,090	3.0	11.0	11.09	2.59	200	3050	2218	7900
1995	3061	6224.2	268,998	1,495,365	3.4	16.8	13.74	2.43	200	3050	2748	7412
1999	1013	7825.6	32,475	1,682,046	0	13.1	**20.66**	2.62	200	3050	4132	7991
2003	-	8585.5	-	1,384,996	-	7.0	-	**2.54**	200	3050	-	7747

It may noted that the fuel consumption of the steam loco fleet increased substantially over the 15 year period (from 11 tonnes per million tonne-km to over 20 tonnes per million tonne-km), and it may be assumed that this increase was the result changing circumstances that almost certainly included:

- Lower steam-hauled train mileages;
- Lower steam-hauled train weights;
- Lower steam loco coal quality;
- Lower steam loco maintenance standards.

It may thus be assumed that the figure of 20.66 tonnes per million tonne-km is a worst case scenario at the death of steam, and that the figure of 11.09 tonnes per million tonne-km represents the normal scenario in the late heyday of Chinese steam.

Additional China National Railway cost data are listed as follows:

Supplementary Cost Data supplied by China National Railways		
Average cost for normal electric railway construction, including infrastructure, contact wire, signalling system, stations and marshalling yards	>30 m RMB per km	>$3.75 m per km
2001 Average Cost for Main Line Electrification	>3.4 m RMB per km	**>$425,000 per km**
2001 Fuel Consumption – Steam	19.5 tonnes per 10^6 t-km	
2001 Fuel Consumption – Diesel	2.57 tonnes per 10^6 t-km	
2001 Power Consumption – Electric	**11310 kW-h per 10^6 t-km**	
2005 Cost – Diesel Fuel	3970 RMB / tonne	$496 per tonne
2005 Cost – Electric Power	0.65 RMB/kW-h	***$0.081 cents per kW-h***

It may be noted that the fuel consumption rates quoted for steam and diesel in 2001 are consistent with the figures given in the previous table.

14.3 Comparing Fuel Consumption with 2800 tonne train over 270km at 45 kph

The following table is based on fuel and power consumption rates as calculated in Section 14.1 above. The following points are noted:

- The purpose of this table is to compare the fuel/power consumption for each locomotive type when hauling a 2,800 tonne train which is understood to be the normal size of coal train hauled in Indonesia;
- 2 x 100 tonne 2000 HP diesels are assumed since these are understood to be the commonly used traction for hauling 2800 tonne coal trains in Indonesia;
- Rolling resistance is based on China National Railways' formula – refer Appendix D.
- A nominal factor of 45% is added to the calculated train rolling resistance to take account of track curves and gradients.

(see Table overleaf)

Comparing Fuel Consumptions with 2800 tonne train over 270km at 45 kph				
	QJ Steam	**8AT Steam**	**2x2000 HP Diesels**	**SS-3 Electric**
Fuel Consumption per kWh	2.108	1.265	0.337	1.250
Length of Railway	270 km	270 km	270 km	270 km
Average Train Speed	45 kph	45 kph	45 kph	45 kph
Loco Weight	134 t	80 t	200 t	100 t*
Gross Train Weight	2800 t	2800 t	2800 t	2800 t
Rolling Resistance (from Chinese data)	14.2 N/t	14.2 N/t	14.2 N/t	14.2 N/t
Train Rolling Resistance (level track)	39.6 kN	39.6 kN	39.6 kN	39.6 kN
Loco Rolling Resistance (estimated)	9.6 kN	6.2 kN	11.9 kN	5.9 kN
Total Rolling Resistance (level track)	49.3 kN	45.8 kN	51.5 kN	45.6 kN
Factor to allow for curves and grades	45%	45%	45%	45%
Total Rolling Resistance (curved track)	71.5 kN	66.5 kN	74.7 kN	66.1 kN
Power Required to overcome resistance	894 kW	831 kW	934 kW	826 kW
Fuel Consumption for Loaded Train	**41.9 kg/km**	**23.3 kg/km**	**7.0 kg/km**	**23.0 kWh/km**
Fuel Consumed over Loaded Journey	11.30 t	6.30 t	1.89 t	6,197 kWh
Cost of Fuel	$20/t	$20/t	$700/t	$0.08/kWh
Fuel Cost per Loaded Journey	**$226**	**$126**	**$1,323**	**$496**
Fuel Consumed over Empty Journey	4.81 t	2.41 t	0.85 t	2,346 kWh
Fuel Cost per Empty Journey	**$96**	**$48**	**$595**	**$188**
Total Fuel Cost – round trip	**$322**	**$174**	**$1,918**	**$683**

It is understood that the above calculated figure for diesel fuel consumption is consistent with Indonesian experience, which gives confidence that the estimates for steam traction are reasonably accurate, and that the estimated fuel consumption rates can be adopted to calculate fuel consumption for the assumed actual haulage requirements (as described in Section 14.4 below).

14.4 Comparing Fuel Consumption at Max Loading Capacity

Adopting the same assumptions used in 14.4 above (including fuel consumption figures per unit of power output as calculated in 14.1) to estimate the fuel consumptions for an actual haulage requirement of 20 million tonnes of coal per year over a 270 km railway, the following results are calculated:

(see Table overleaf)

Comparing Fuel Consumption at Max Loading Capacity of Trains hauling 20 Million Tonnes of Coal per Year					
	Old Steam QJ	**Modern Steam 8AT**		**Diesel DF4-D**	**Electric SS-3**
Loco Weight	134 t	96 t	96 t	138 t	138 t
Fuel Consumption – kg or kWh per kWh	2.389	1.433	1.433	0.422	1.250
Length of Railway	270 km	270 km	270 km	270 km	270 km
Average Train Speed	52 kph	52 kph	52 kph	52 kph	52 kph
Gross Train Weight	3999 t	3999 t	3069 t	5394 t	6882 t
Rolling Resistance (from Chinese data)	15.4 N/t	15.4 N/t	15.4 N/t	15.4 N/t	15.4 N/t
Train Rolling Resistance (level track)	61.5 kN	61.5 kN	47.2 kN	82.9 kN	105.8 kN
Loco Rolling Resistance (estimated)	10.3 kN	6.6 kN	6.6 kN	8.8 kN	8.8 kN
Total Rolling Resistance (level track)	71.8 kN	68.1 kN	53.8 kN	91.7 kN	114.5 kN
Factor to allow for curves and grades	45%	45%	45%	45%	45%
Total Rolling Resistance (curved track)	104.0 kN	98.7 kN	78.0 kN	132.9 kN	166.1 kN
Power Required to overcome resistance	1503kW	1426 kW	1126 kW	1920 kW	2399 kW
Fuel Consumption for Loaded Train	**60.9 kg/km**	**34.7 kg/km**	**27.4 kg/km**	**12.5 kg/km**	**57.7 kWh/km**
Fuel Consumed over Loaded Journey	16.45 t	9.36 t	7.40 t	3.36 t	15,572 kWh
Cost of Fuel	$20/t	$20/t	$20/t	$700/t	$0.08/kWh
Fuel Cost per Loaded Journey	$329	$187	$148	$2,354	$1,245
Fuel Consumed over Empty Journey	5.85 t	3.00 t	2.51 t	1.07 t	4,748 kWh
Fuel Cost per Empty Journey	$117	$60	$50	$752	$380
Total Fuel Cost – round trip	**$446**	**$247**	**$198**	**$3,105**	**$1,625**
Consumption per million tonne-km loaded	15.24 t	8.67 t	8.93 t	2.31 t	8380 kWh
Consumption per million tonne-km empty	21.39 t	10.98 t	12.26 t	3.21 t	10333 kWh
Consumption per million tonne-km average	15.56 t	9.18 t	9.59 t	2.44 t	8768 kWh

It may be noted from the above figures that the fuel consumption rates per million tonne-kilometres for steam and diesel traction are consistent with Chinese historical data (refer 14.2 above). Electrical consumption is however lower than the Chinese figure (for reasons that are not presently understood).

14.5 Final Estimate of Fuel Costs for each Traction Type

Using the above fuel consumption figures, the following summary of fuel costs can be deduced for operating a 20 million tonne per year coal haulage operation over a 270 km rail system:

Traction Type	QJ Steam	8AT Modern Steam		Diesel DF4-D	Electric SS-3
		4000t	3000t		
Total Loaded (Gross) Tonne-km (x106)	7,175	7,175	7,175	7,175	7,175
Total Empty Tonne-km ($x10^6$)	1,775	1,775	1,775	1,775	1,775
Total Tonne-km ($x10^6$)	8.950	8.950	8.950	8.950	8.950
Consumption t or kWh per 10^6t-km	16.56	9.18	9.56	2.44	8,768
Total Consumption - tons or kWh/year	148,153	82,144	85,804	21,854	78.4m
Fuel/Power Cost per tonne or kWh	$20	$20	$20	$700	$0.08
Total Fuel Cost per Year	**$2. 96m**	**$1.64m**	**$ 1.72m**	**$15.30m**	**$6.28m**

It bears repeating that the very high cost of diesel fuel will increase in the future as oil prices inevitably rise, making coal-fired steam an ever-more attractive alternative.

15 Final Cost Comparisons

The following table summarizes the costs estimated in the above discussions relating to the haulage of 20 million tonnes of coal per year over a 270 km railway:

Traction Type	Recon'd QJ Steam	8AT Modern Steam		Diesel DF4-D	Electric SS-3
		4000t	3000t		
Annualized Cap Cost	$0.96 m	$1.44 m	$1.74 m	$0.84 m	$5.31 m
Maintenance Cost	$2.58 m	$1.37 m	$1.96 m	$1.74 m	$1.21 m
Fuel/Power Cost	$2.96m	$1.64m	$ 1.72m	$15.06m	$6.28m
Water Cost	$2.07 m	$1.65m	$1.77m	-	-
Labour Cost	$0.80 m	$0.63 m	$0.78 m	$0.24 m	$0.21 m
Total Cost per Year	**$9.37 m**	**$6.74 m**	**$7.97 m**	**$17.88 m**	**$13.01 m**
Cost Differential per Year	$2.63 m	-	$1.23 m	$11.14 m	$6.27 m
Cost per Tonne hauled	$0.47	$0.34	$0.40	$0.89	$0.65
% Cost Differential	39%	-	18%	165%	93%

The following observations are offered (repeated in previous sections):

- Maintenance costs for the diesel and electric locomotives are likely to be higher than indicated, because the base figures used are from 1997 and are not adjusted for inflation. This would make the steam option even more competitive.
- Maintenance of the electrical power supply and cabling systems have not been included in the cost estimates for the electric traction alternative. These costs are likely to be significant in hot and humid climatic conditions and will add to the cost of electric traction, making the steam option even more competitive.
- The operation of shorter trains using steam traction reduces the rolling stock requirement. At $70,000 per wagon (ex-China price) this represents a potential capital cost saving of perhaps $8 million for steam compared to diesel traction making the steam option even more competitive. Furthermore, the lower traction forces required to pull shorter trains should reduce rail, wagon wheel and drawgear wear.
- The development cost of the 8AT “modern steam” locomotive would be substantially reduced if similar locomotives are built for other railways both in Indonesia and elsewhere. This is likely to happen once the performance of the locomotive is demonstrated and acknowledged.
- The development costs of the 8AT would be recovered from the cost savings achieved (compared with diesel) within about six months of the start of operation.
- The total extra capital cost of the 8AT option would be recovered from costs saved (compared to diesel) within 18 months of the start of operation.

16 Environmental Considerations

It is inevitable that coal burning steam locos will generate more CO_2 than diesels, because coal has a higher carbon content than diesel oil and because of steam’s lower thermal efficiency. Notwithstanding, the total “carbon footprint” from the burning locally available coal may not very much greater than that from drilling, extracting, shipping, refining, transporting and burning of oil in a diesel locomotive.

It is important to realise that “modern steam” is not nearly as polluting as “old steam”. This is because its greater thermal efficiency reduces fuel consumption and therefore carbon emissions. Secondly, the use of a GPCS firebox ensures more complete combustion and thus practically eliminates the production of black smoke and the emission of solid particles.

The coal that would be consumed by a “modern steam” locomotive fleet hauling 20 million tonnes per year over 270km would be no more than 0.4% of the coal being hauled – an insignificant quantity compared to the overall carbon that will be emitted from the coal carried in the train.

It is estimated that even if a $100 per tonne carbon tax was applied, “modern steam” traction would still be the lowest cost option for Indonesian coal transportation.

Coal-fired steam locomotives produce lower toxic (NO_x) emissions than diesel locomotives.

In terms of "smoke nuisance" to the general public, the amount of coal burned by a "modern steam" locomotive hauling a 4000 tonne train is estimated to be no more than 40kg per kilometer. This is an insignificant quantity in terms of smoke "nuisance" to anyone living or working beside the railway line. In any case, diesel locomotives are not unknown to emit smoke (see photo below).

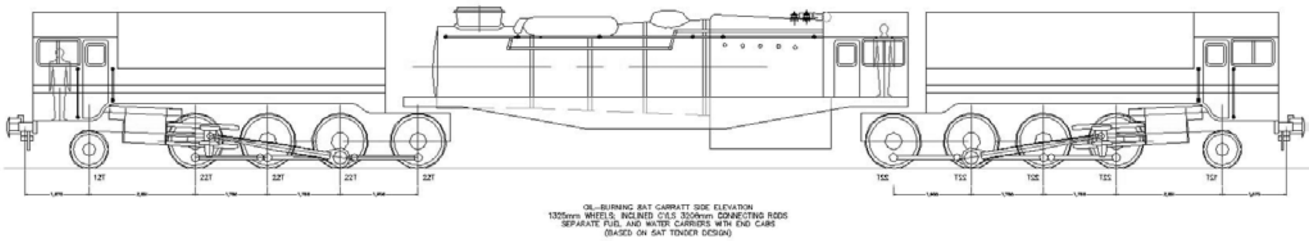
Steam traction does (<u>and will</u>) attract tourists which may be advantageous to the local economy. Historic steam locomotives are operated on hundreds of railways all over Britain and are almost universally welcomed by local communities because of the tourism that they attract.

The re-establishment of steam traction technology is likely to be an important step in the development of renewable fuels for rail transport, since steam locomotives can burn almost any solid or liquid form of bio-fuel (as discussed in Section 17 below).

17 Future Development Possibilities for Steam Traction and the 8AT

There are several lines of development that would make steam traction more fuel efficient and more attractive for railway operators. Some of these include:

- Developing a "Garratt" locomotive based on the 8AT using common components such as cylinders, wheels and motion but fitted with a larger boiler suspended between two engine units. This would have a potential haulage capacity of >8000 tonnes with approximately 90% of its weight available for adhesion;



Schematic "Garratt" development incorporating two 8AT engine chassis supporting a large central boiler.

- A Garratt configuration would be more adaptable for operation on metre-gauge or 1067mm track because the firebox width would not be restricted.
- A Garratt could be designed with cabs fitted at each end, with remote control and monitoring of the locomotive. Such a development would allow multiple-unit operation as is possible with diesel traction.
- The use of pulverized coal would improve combustion and facilitate automated handling and firing of the fuel;
- Development of technology for burning of renewable (bio) fuels in both solid and liquid form.
- The development of an effective steam condensing system would increase thermal efficiency, reduce water consumption and hence reduce the frequency of water replenishment;
- The development of a steam turbine drive could improve thermal efficiency and reduce maintenance costs;
- Regenerative braking could be developed to boost thermal efficiency;
- With adequate investment in research and development, there is no reason why steam traction should not achieve thermal efficiency values >20%.

These development possibilities suggest a potential market development for modern steam traction that could even see it take over from diesel traction in some developed countries as oil prices become prohibitively expensive.

18 Conclusions

The cost figures derived for this paper suggest that there is a very substantial cost advantage in the use of steam traction for coal haulage in Indonesia. Indeed, the cost advantage is so great that the additional capital cost required to develop and built a fleet of modern (8AT) steam locomotives in place of diesel locomotives, would be recovered in about 18 months.

The figures presented in this paper serve to confirm the off-hand response given to the author by a manager on China's last main line steam operation – the Jitong Railway in Inner Mongolia - who, when asked if steam was cheaper to run than diesel, replied: "Of course it's cheaper, but we had to convert to diesel in conformity with Central Government policy".

The figures also confirm the conclusions of earlier studies, such as that by David Wardale in the 1980s who showed conclusively that South African Railways could have saved vast sums of money by retaining steam traction to burn the country's indigenous coal supplies instead of making themselves dependent on imported oil (and on diesel manufacturers' spare parts).

The cost advantage for steam that is presented in this paper will inevitably grow as diesel prices continue to escalate. Indonesia is well positioned to take advantage of the opportunity to save costs and to develop a new industry by adopting "modern steam" technology for the transportation of its vast coal resources. It also offers the opportunity of reducing dependence on overseas equipment suppliers, because almost all replacement components for a modern steam locomotive can be manufactured locally.

Whilst there is no existing design for a modern coal haulage locomotive, the predicted performance of the 8AT is assured since it is based on proven technology and proven designs. By basing the design of the 8AT on that of the 5AT, advantage can be taken of the Fundamental Design Calculations that have been completed for the 5AT locomotive, most of which can be applied directly to the 8AT, the remainder being easily adaptable to the 8AT. Indeed, the performance predictions for the 8AT are derived entirely by adaptation of the 5AT's performance calculations.

The skills still exist to design and build new steam locomotives in the 21st century. For example, several new modern steam locomotives were built for tourist railways in Switzerland during the last decade of the 20th century. In 2006 a new locomotive was built in South Africa and delivered to a tourist railway in Argentina. And in the UK, the final components are currently being assembled to complete a brand new replica of a 1950 express passenger locomotive weighing in excess of 150 tonnes.

5AT project planners stand in front of the A1 replica locomotive current being completed in the UK

It may be safely concluded that "modern steam" for rail traction has an important role to play in the 21st century, and that this role may expand in future as the technology is developed further. As soon as one railway puts "modern steam" onto its tracks, it is almost inevitable that others will follow suit.

CJEN
3rd July 2007

Appendix A – Advanced Performance Features of the 8AT Design

The 8AT design incorporates many technical advances over 1950s steam designs that result in its improved performance. Some of these features are listed as follows:

- **Engineering Design** based on proven principles instead of empirical methods;
- **Higher Steam Pressure and Temperature** to improve thermal efficiency;
- **Improved Exhaust System** to reduce back-pressure and thus increase cylinder efficiency, and to increase combustion airflow and thus improve combustion efficiency;
- **Gas-Producer Combustion System (GPCS) Firebox** to improve combustion and reduce smoke emissions;
- **Feedwater and Combustion Air Preheating** to improve thermal efficiency;
- **Large Streamlined Steam Pipes, Passages and Steam Chests** to improve steam flow and cylinder efficiency;
- **Large Valves and Valve Ports** to facilitate free steam-flow in and out of cylinders and improve steam flow and cylinder efficiency;
- **Long Stroke Pistons and Valves with Diesel-Quality Rings** to reduce steam leakage and improve steam flow and cylinder efficiency;
- **Tight Tolerances** equivalent to modern diesel standards, to improve performance and reduce maintenance costs;
- **High Quality Insulation** to prevent heat loss and improve thermal efficiency;;
- **Air Sanding system and Enhanced-Adhesion Wheel-rim Profiles** to reduce wheel slip.
- **Improved brake performance** to reduce stopping distances.
- **Light weight motion** to reduce inertia forces and thus reduce hammer blow effects.

Appendix B – Maintenance Improvements of the 8AT Design

Several other technical advances will significantly reduce the maintenance frequency and maintenance costs of the 8AT locomotive**:**

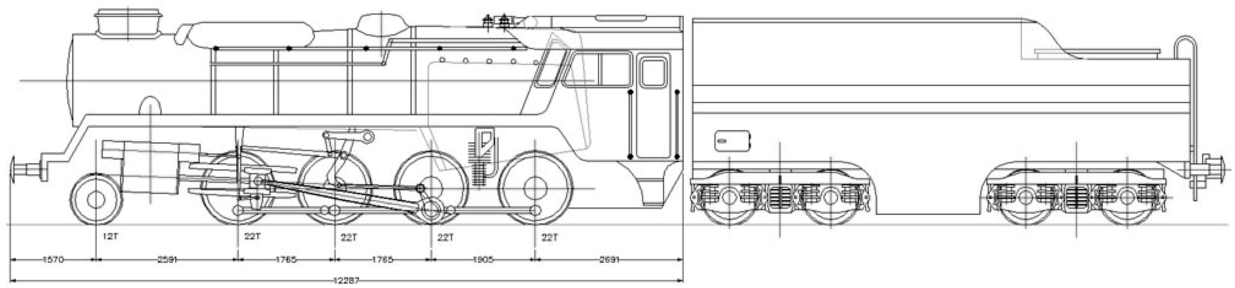
General Improvements

- **Improved component design** based on sophisticated technologies such as Finite Element Analysis, reducing stress concentrations, minimising wear and fractures;
- **Better materials** – including bearings, lubricants, wear components, insulation etc;
- **Closer tolerances and better fit-up -** facilitated by CAD technology;
- **Replacement of bolted or riveted connections by welded ones** (where possible), eliminating the possibility of components becoming loose.
- **Simplicity of the concept (two cylinder simple)** minimises number of moving components compared to a multi-cylindered engine. No inaccessible components.
- **The use of AAR rules where appropriate**: AAR* rules are generally considered to be the most robust design rules where empirical methods have to be used.

Specific Improvements:

- **Roller Bearings** on all major joints (axles, crankpins, motion and valve gear). More reliable than plain bearings, they require "no field attention" with near-zero wear and hence reducing vibration;
- **Self Adjusting Wedges** at all driving and coupled axleboxes to eliminate axlebox-frame gaps, and thus pounding and vibration associated with axlebox wear;
- **Robust Horn Stays** - minimises risk of frame cracking at top corners of horns;
- **Improved Valve and Cylinder Tribology** - greatly reduces wear of rings and liners;
- **Tail Rods on Pistons** – dramatically reduces piston ring and cylinder wear
- **All-Welded Boiler** – eliminates problems caused by riveted seams and screwed stays, especially no possibility of leakage and caustic embrittlement;
- **Effective Boiler Water Treatment** that practically eliminates boiler maintenance.
- **Superior Firebox Stay Design -** reduces incidence of fractured stays;
- **Rigid Engine-Tender Drawgear -** eliminates 'stamping' and vibrations at this point;
- **'Drop-Type' Firebox Fusible Plugs** - safer than the usual lead filled plug;
- **Corrosion-Resistant Steel** for tender and smokebox to minimise corrosion;
- **Improved Boiler/Frame Connections** – improves rigidity and reduces frame flexing;
- **Clasp Brakes** eliminate axle and axle bearing loads due to braking forces.
- **Centralized Lubricant Dispensing System** for automatic lubrication of sliding surfaces etc;
- **Valve Liners Cooled with Saturated Steam** to protect lubricants from higher steam temperatures.

Appendix C – Data Sheet for 8AT Locomotive



The following table includes comparative figures for 5AT

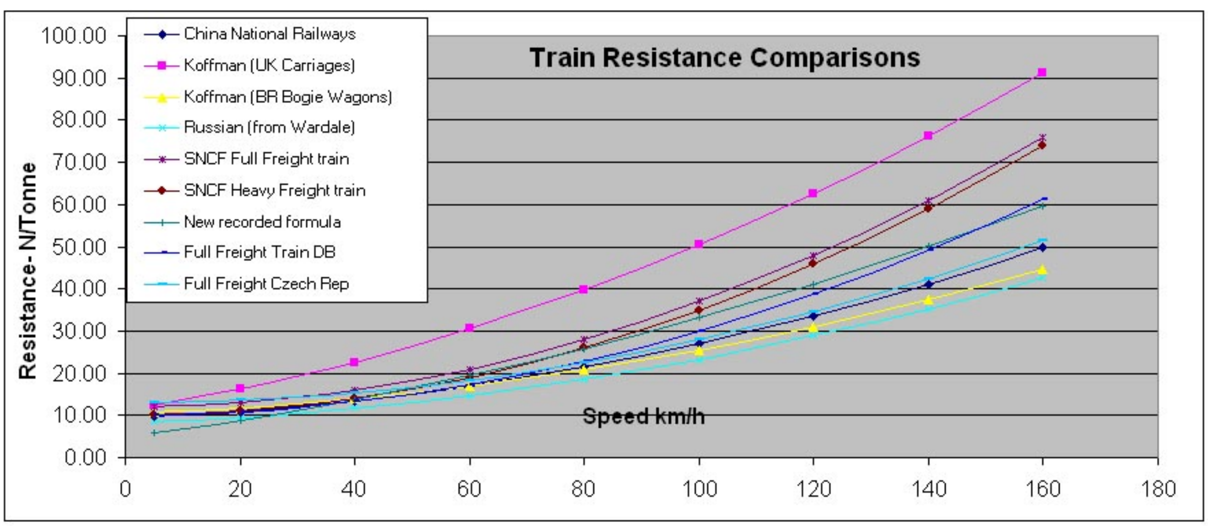
Item	8AT	5AT
Wheel Arrangement	2-8-0	4-6-0
Weight of loco in working order	96 tonnes	80 tonnes
Driving Axle Load	21 tonnes	20 tonnes
Tender Weight (full)	80 tonnes	80 tonnes
Boiler Pressure	2100 kPa (305 psi)	2100 kPa (305 psi)
Superheated Steam Temperature	450^{o}C (840^{o}F)	450^{o}C (840^{o}F)
Firebox Grate Area	2.67 m^2 (28.7 ft^2)	2.67 m^2 (28.7 ft^2)
Evaporative Heating Surface (inc firebox)	154 m^2 (1657 ft^2)	154 m^2 (1657 ft^2)
Max Evaporation Rate	17,000 kg/h (37,500 lb/h)	17,000 kg/h (37,500 lb/h)
Cylinder Diameter	450mm (17.7”)	450mm (17.7”)
Piston Stroke	800mm (31.5”)	800mm (31.5”)
Driving Wheel Diameter	1325mm (4’-4¼”)	1880mm (6’-2”)
Nominal Wheel-Rim Tractive Effort	206 kN (46,300 lbf)	145 kN (32,500 lbf)
Adhesive Weight	84 tonnes	60 tonnes
Required Coefficient of Friction for Starting	0.25	0.25
Max Drawbar Power	2100 kW at 90 km/h	1882 kW at 113 km/h
Drawbar Tractive Force at Max Power	84 kN	60 kN

Appendix D – Wagon Rolling Resistance Curves

The diagram below shows wagon resistance curves over a range of speeds based on resistance formulae from various countries. The one exception is the pink curve which shows the resistance values for UK passenger carriages for which specific rolling resistance (resistance per tonne weight) is higher than that of freight wagons. The reason for this can be visualised by comparing the resistance of a 400 tonne train of UK passenger carriages consisting (typically) of 11 coaches, with that of a 400 tonne freight train that might consist of 4 or 5 wagons.

China National Railways	$R = 0.92 + 0.0048V + 0.000125V^2$ N/Kn
Full Freight Czech Rep	$R = 1.3 + 0.00015V^2$ daN/tonne
Russian (from Wardale)	$R = 0.7 + (3 + 0.1V + 0.0025V^2)/L$ daN/tonne where L = axle-load
Koffman (UK Bogie Wagons)	$R = 0.7 + (8 + 0.1V + 0.0025V^2) / L$ daN/tonne where L = axle-load
Full Freight Train DB	$R = 1+0.1 \times 0.2*(V/10)^2$ daN/tonne
New recorded formula	$R = 4.83 \times 10^{-1} + 1.83 \times 10^{-2} \times V + 1 \times 10^{-4} \times V^2$ daN/tonne
SNCF Heavy Freight train	$R = 1 + V^2 / 4000$ daN/tonne
SNCF Full Freight train	$R = 1.2 + V^2 / 4000$ daN/tonne
Koffman (UK carriages)	$R = 1.1 + 0.021V + 0.000175V^2$ kg/tonne

Speed km/h	0	5	20	40	60	80	100	120	140	160	Axle Load
China National Railways	34.30	9.65	10.87	13.37	16.90	21.45	27.01	33.60	41.20	49.83	Tonnes
Full Freight Czech Rep		13.04	13.60	15.40	18.40	22.60	28.00	34.60	42.40	51.40	
Russian (from Wardale)		8.53	9.57	11.71	14.71	18.56	23.27	28.84	35.27	42.55	23.35
Koffman (BR Bogie Wagons)		10.67	11.71	13.85	16.85	20.70	25.42	30.98	37.41	44.69	23.35
Full Freight Train DB		10.05	10.80	13.20	17.20	22.80	30.00	38.80	49.20	61.20	
New recorded formula		5.77	8.89	13.75	19.41	25.87	33.13	41.19	50.05	59.71	
SNCF Heavy Freight train		10.06	11.00	14.00	19.00	26.00	35.00	46.00	59.00	74.00	
SNCF Full Freight train		12.06	13.00	16.00	21.00	28.00	37.00	48.00	61.00	76.00	
Koffman (UK Carriages)	68.60	12.33	16.21	22.63	30.48	39.76	50.46	62.59	76.15	91.13	

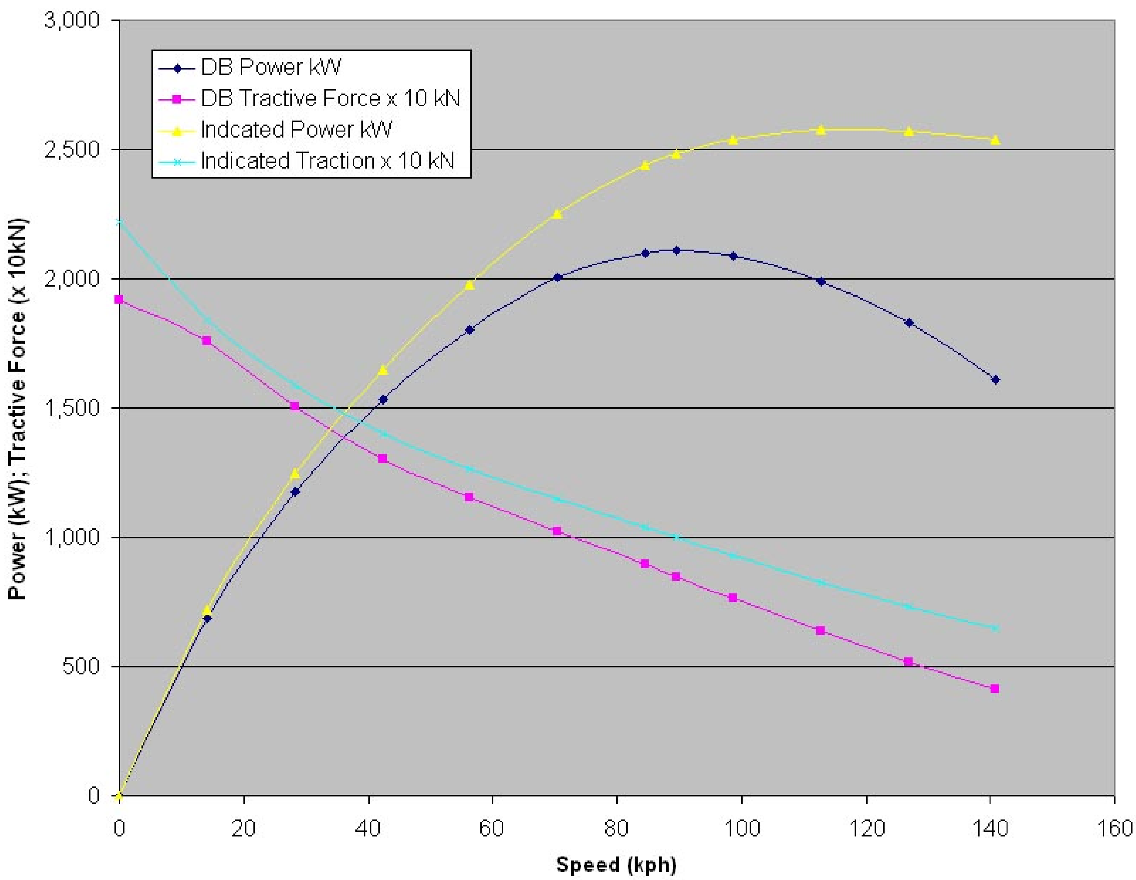


Appendix E – Power/TE vs. Speed Curves for 8AT Locomotive

The diagram below shows tractive force (tractive effort) and power output as calculated for the 8AT locomotive over a theoretical speed range. Its maximum speed based on the AAR recommended maximum wheel rotation rate of 504 rpm would be 127 km/h, however its maximum design speed would be no more than 100 km/h.

Maximum drawbar power is shown as approximately 2100 kW at 90 km/h.

Fig 1.1.1 - Tractive Force and Power vs. Speed



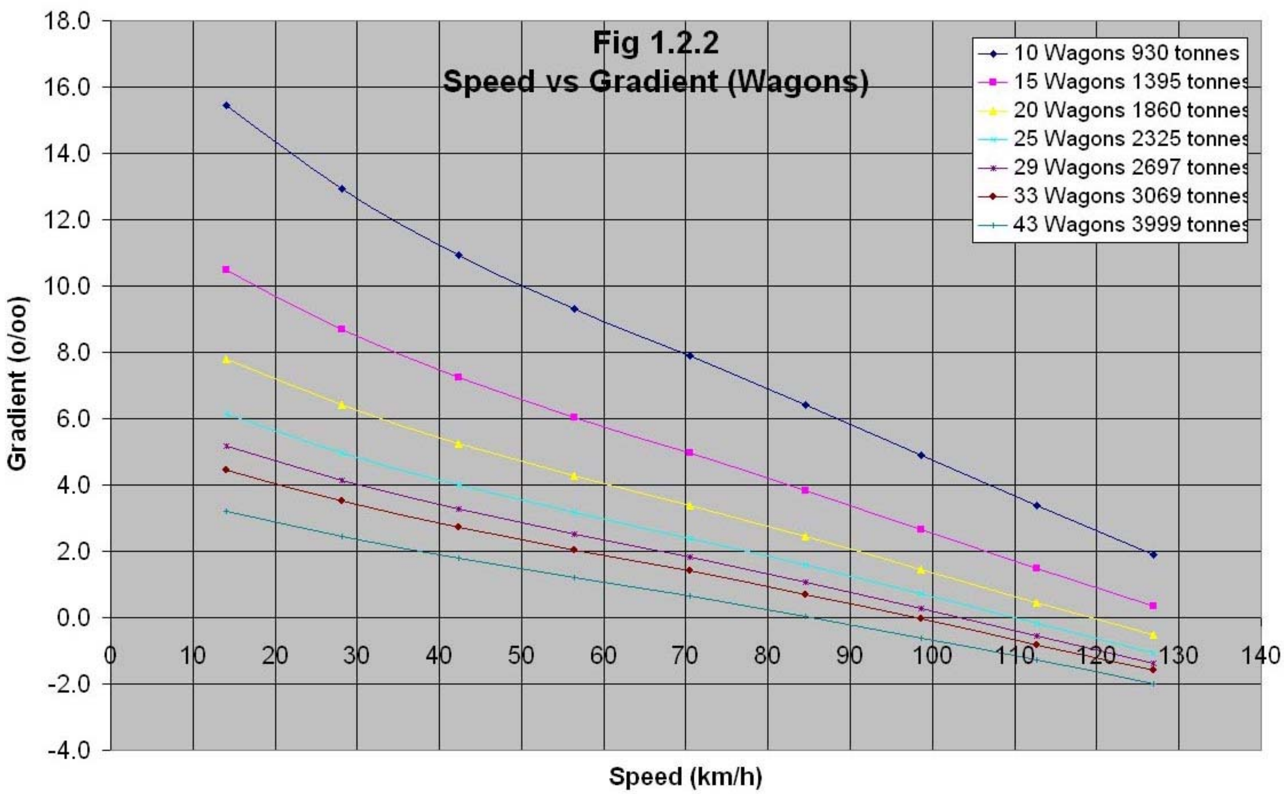
Appendix F – Speed-Gradient Curves for 8AT Locomotive

The diagram below shows the speed-gradient curves for the 8AT locomotives as calculated using the methodology used for on the 5AT Fundamental Design Calculations.

Gradient values are shown in $^{o}/_{oo}$ values – i.e. tenths of a percent. A gradient of $10^{o}/_{oo}$ is therefore the same as a 1% gradient.

It may be seen from the bottom graph that the 8AT should be able to haul a 4000 tonne train at approximately 85 km/h on level track, and should be able to maintain around 15 km/h on a $3^{o}/_{oo}$ or 0.3% gradient.

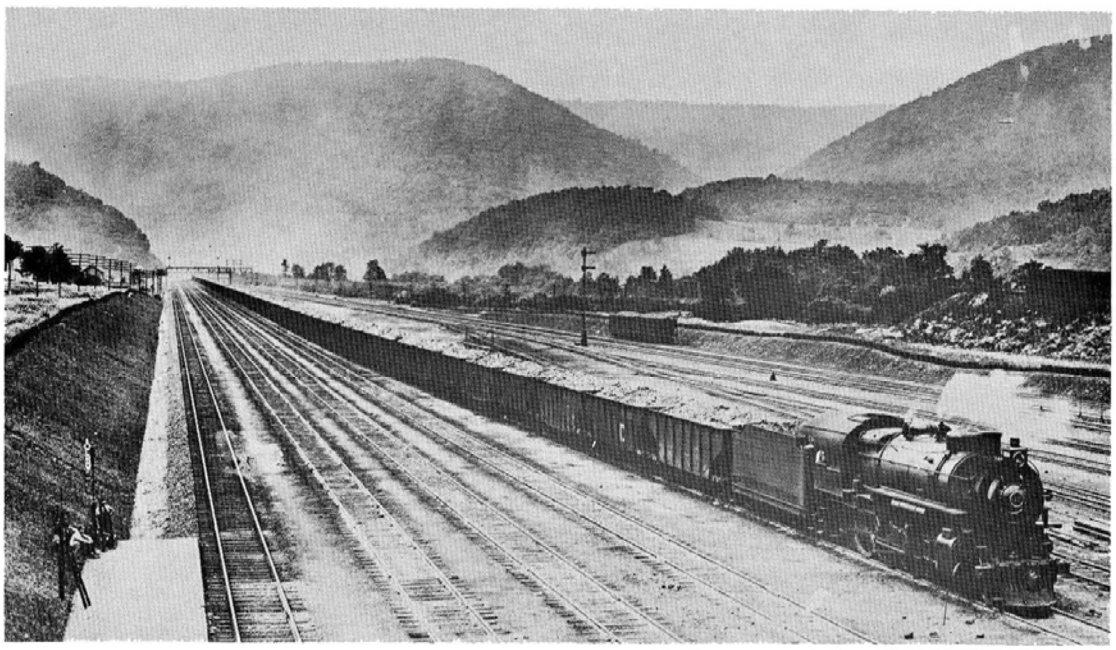
Train weights are based on 93 tonne gross weight wagons. Wagon rolling resistance is estimated using Koffman's (UK) formula for bogie wagons.



Appendix G – Haulage Capacity of 2-8-0 Locomotive

The photograph below illustrates the haulage capability of a 2-8-0 steam locomotive of similar size to the proposed 8AT. The photo caption indicates that the 4,888 foot long train "carries 6450 tons", implying that this figure does not include the tare weight of the wagons.

The locomotive is a Pennsylvania H8b 2-8-0 of 1908 design, and is quite primitive in comparison to the 8AT. Whilst its starting tractive force is similar to the 8AT's, it has a lower boiler pressure (1400 vs. 2100 kPa), no superheat (i.e. low steam temperature), and journal bearings throughout (i.e. higher internal resistance), each of which would serve to reduce its cylinder power capacity. Its steam passages and exhaust system would also be highly constricted, further reducing its power output. Furthermore, wagons in those days were fitted with journal bearings making their starting and rolling resistances higher those that of modern roller-bearing stock. It can therefore be deduced that an 8AT locomotive would be capable of hauling a similar sized train at significantly higher speed than the 12 mph average recorded on this test train.



Test train of 100 loaded cars was handled from Altoona to Enola yards (127 miles) by a single H8b, 1221. Length of train was 4,888 feet, it carried 6,450 tons, and average speed was 12 M.P.H.

Pennsylvania Railroad

Appendix H – Alternative 8AT Outline

Artist Robyn Barnes has produced two illustrations, shown below, showing an alternative outline for the 8AT. This outline incorporates several modifications that would be well suited to a new railway operation in Indonesia where clearance requirements are less restricted than in the UK. His proposed modifications include:

- Larger cab for improved working conditions;
- Taller chimney for enhanced drafting and performance;
- Large sandbox mounted on the boiler;
- Clearance openings in the plating in front of the piston valves;
- Forward and reverse lighting;
- Windscreen wipers on forward cab windows;
- Central knuckle-type couplers.