ENGINEERS AUSTRALIA
RTSA

Feasibility of Steam Traction for Coal Transportation in Developing Countries

Chris Newman

BSc Eng

5AT Project Group

SUMMARY

Steam traction was never fully developed before it was superseded by diesel traction in the developed world in the 1950s and '60s, and more recently in developing countries. Despite its disappearance from the world's railways, development of the technology has continued in isolated areas, most notably in Argentina through the work of Ing. Livio Dante Porta who pioneered many design improvements that substantially increased the thermal efficiency of steam locomotives and reduced their operating and maintenance costs.

With the current rapid increases in oil prices that appear unlikely to abate, this paper reviews the feasibility of re-introducing steam traction where fuel and labour costs are low, and presents a comparison of costs between steam, diesel and electric haulage based on a hypothetical 100 km dedicated coal haulage railway.

The paper demonstrates that even reconditioned 20 year-old Chinese steam locomotives could offer substantial cost savings in appropriate circumstances. Furthermore the development of high efficiency "modern steam" traction would offer further savings in operating costs, making it highly competitive with both diesel and electric traction. Such cost savings are likely to increase as diesel fuel prices continue to rise.

The paper concludes that whilst steam traction will inevitably produce higher carbon emissions that either diesel or electric alternatives, such differences are insignificant in the wider picture. Furthermore, is pointed out that steam traction offers potential environmental benefits through its ability to burn any bio-fuel, whether solid liquid or gas. Thus reintroduction of steam traction could generate investor interest in further development of the technology that could result in future environmental gains.

Note all cost estimates in this paper are in US Dollars

INTRODUCTION

The idea of using steam traction for the hauling of coal on a modern railway is most unusual since this technology was abandoned by most railways in the 1950s and '60s. Hence the subject is introduced at some length for the benefit those of a younger generation who may be unfamiliar with it.

Despite a popular conception to the contrary, steam power is not an outdated technology. It is used in thermal power generation plants and the most advanced nuclear power plants and nuclear submarines. It is steam traction as used on the world's railways in the 19th and 20th century that in its latter days gained a reputation for being inefficient, slow, unreliable, dirty and generally outdated. This image was used by (and exaggerated by) commercial companies that were then promoting the new forms of traction, but it also reflected the very run-down condition that many of the world's steam locomotives were in after the traumas of World War 2.

Past generations of steam traction had low thermal efficiency compared to diesel and electric traction, and the few remaining operating steam locomotives are slow compared to the latest diesel and electric trains. This was not always so, and throughout its later days, steam generally provided higher speeds and greater reliability than the diesel locomotives that had been procured to replace them. No detailed cost studies were ever published to justify the enormous expenditure that was involved in the hastily organized replacement of often near-new steam locomotives with diesel. In fact, the most exhaustive study that was undertaken at the time showed strong evidence that the costs were not justified and the results of the change-over did not meet the expectations that had been made for it.[1]

Notwithstanding the questionable economic merit of the move away from steam motive power, the huge investment made in the development of both diesel and electric traction over the last 50 years has enabled the performance of the latest types of these locomotives to far exceed that of 1950s steam.

1 "The Economic Results of Diesel and Electric Motive Power on the Railways of the United States of America" by H.F. Brown, Ph.B., Fellow A.I.E.E. Copyright held by proceedings of Institution of Mechanical Engineers (London) Volume 175 No. 5 1961

At the same time, however, steam traction development has continued, albeit with minimal investment and on a very small scale. But the results achieved to date have been impressive and significant further improvement is undoubtedly possible.

A move away from empirical design of steam traction began with the French engineer Andre Chapelon in the 1920s and 1930s and was taken up by an Argentinean engineer by the name of Livio Dante Porta who through the second half of the 20th century pioneered several major advancements both in the performance of steam locomotives (achieving thermal efficiency levels twice those of most 1950s locomotive) and in the reduction of maintenance costs. Porta's theories have been applied by several engineers including Roger Waller of DLM in Switzerland and David Wardale who famously applied Porta's principles to two South African Railway locomotives in the 1980s, one of which (The Red Devil) showed a 60% increase in maximum power output compared to the original design, and a 40% reduction in specific fuel consumption.[2]

Fig 1: David Wardale's rebuilt SAR Class 25NC, "The Red Devil". Its power output was increased by 60% and its coal consumption reduced by 40%.

In 2001, Wardale put forward a proposal to build a new high performance 200 km/h steam locomotive dubbed the "5AT" for haulage of tour trains on the UK and Europe's high-speed railway networks. In 2005 Wardale completed the "fundamental design calculations" for the 5AT[3], verifying the technical feasibility of the design and defining all the main requirements for the detail design process. A Project Feasibility Study is currently being drafted.

Included in the 5AT Feasibility Study is a proposal for a 2-8-0 freight-haulage variant of the large wheeled 4-6-0 5AT – designated the "8AT" – which would have the capability of hauling 4000 tonne trains on level track at up to 70 km/h. It is believed that this locomotive could provide cost-effective haulage of coal (and other) trains in countries where coal and labour costs are low.

This "concept" 8AT locomotive is one of the alternative locomotive types that form part of this cost comparison between traction options.

LOCOMOTIVE COMPARISONS

For the purposes of this cost study, four types of locomotive have been compared, each being typical of the sort of traction used in developing countries for freight haulage. These are summarized as follows:

- **Electric Traction**: China National Railways (CNR) 138 tonne 4320 kW SS-3 class in widespread use throughout CNR's network.

Fig 2: Chinese Class SS-3 Electric Locomotive

- **Diesel Traction**: CNR's 138 tonne 2940 kW DF4-D class, in widespread use throughout CNR's non-electrified network.

Fig 3: Chinese Class DF4 Diesel Locomotive

- **"Old" Steam Traction**: CNR's 2200 kW QJ class heavy-freight locomotive, now seeing the end of its days in coal haulage on "private" short-haul railway lines in China.

Fig 4: Chinese QJ Locomotive

- **"Modern Steam" Traction**: The 8AT 2-8-0 derived from Wardale's 5AT express passenger engine (described above).

[2] Wardale D., "The Red Devil and Other Tales from the Age of Steam", published by the author, Inverness 1998.

[3] See 5AT project website at www.5at.co.uk.

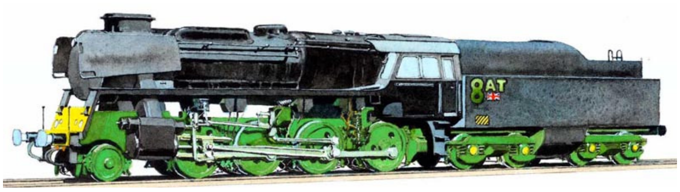

Fig 5: Artist's Impression of 8AT

Loco Type	QJ	8AT	DF4-D	SS-3
Loco Weight working order (t)	133.8	96.2[1]	138	138
Wheel Arrangement	2-10-2	2-8-0	Co-Co	Co-Co
Leading Axle Load (t)	13.40	12.0	-	-
Driving Axle Load (t)	20.10	21.0[1]	23.0	23.0
Trailing Axle (t)	19.90	-	-	-
4-axle Tender Wt loaded (t)	84	80	-	-
Tender Weight empty (t)	29.5	30	-	-
Coal Capacity (t)	14.5	15	-	-
Water Capacity (t)	40	35	-	-
Weight Loco + Tender (t)	219	176	138	138
Length of Loco + Tender (m)	26.0	22.1	20.3	?
Boiler Pressure (kPa)	1500	2100	-	-
Piston Diameter (mm)	650	450	-	-
Piston Stroke (mm)	800	800	-	-
Driving Wheel Diameter	1500	1325	-	-
Design Speed (km/h)	85	>100	100	100
Wheel Rim Power (kW)	2190[2]	2200[2]	2430	4320
Starting TE at wheel(kN)	287	206	480	487
Required Friction Coefficient	0.29	0.25	0.36	0.36
TE at 20 km/h (kN)	244	163	385	385

Note 1: The estimated weight and axle load of the 8AT includes ballast to optimize the friction coefficient at a value of 0.25 (adhesion factor = 4) at its full starting tractive effort to control slipping.
2: 8AT and QJ wheel-rim power estimated for a speed of 80 km/h and at approx 80% max boiler output.

Table 1 – Comparison of Locomotive Parameters

It will be noted that the average friction coefficient that is available between wheel and rail is lower for steam traction than for diesel and electric traction. This is because the tractive force applied by a steam locomotive varies substantially during each wheel rotation due to the variation of steam pressure applied to its pistons during each stroke. In the case of two cylinder locomotives (as both locomotives listed are) the momentary peak starting tractive force can be as much as 30% higher than the average values. By comparison, diesel and electric locomotives can apply near-constant torque to their wheels.

PERFORMANCE PREDICTIONS FOR TRACTION OPTIONS

1. Tractive Force vs. Speed Characteristics

Tractive Force vs. Speed curves for each locomotive type can be used to estimate the haulage capacity of each locomotive.

The DF4-D curve is typical of diesel traction in offering a high starting tractive effort of around 480 kN which falls rapidly as speed rises such that at its top speed of 100 km/h it is only around 85kN.

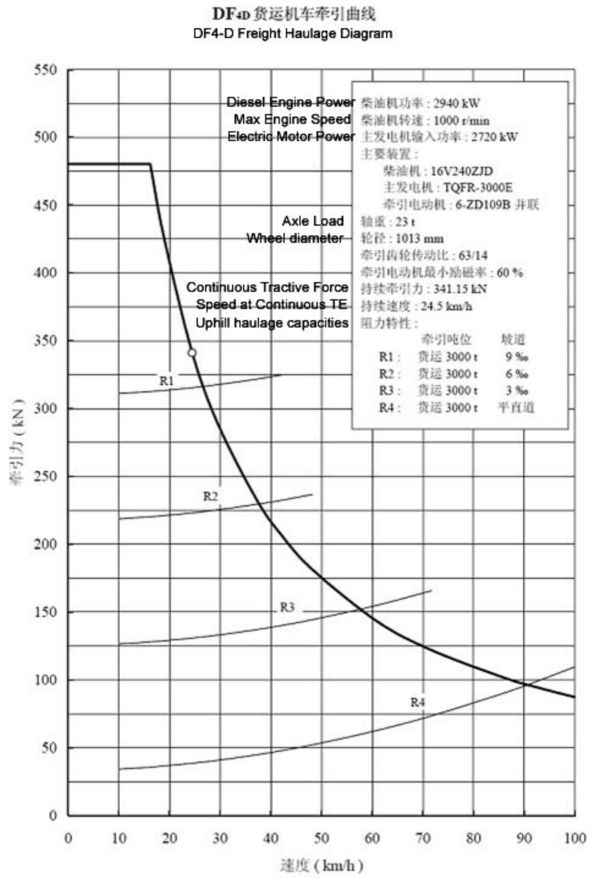

Fig 6: DF4-D Diesel Speed- TE Curve

The electric locomotive's starting tractive force is similar to that of the diesel, and remains high throughout its speed range as reflected in its higher power rating.

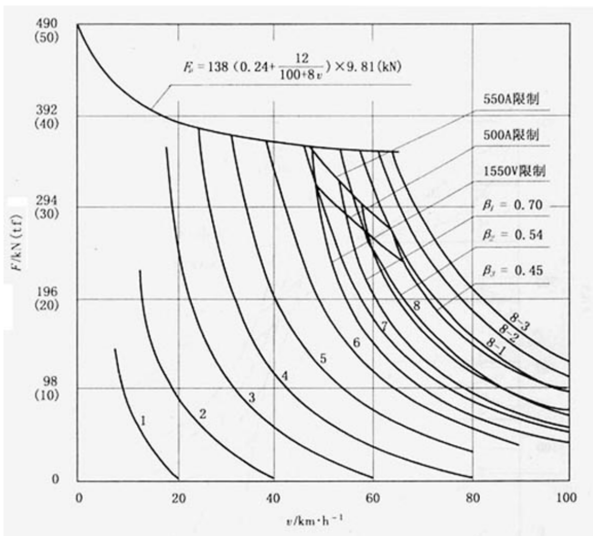

Fig 7: SS-3 Diesel Speed- TE Curve

The QJ Speed-Tractive Effort curves are shown below. Several curves are given, indicating the wheel rim tractive effort over a range of speeds, cut-offs[4] and steaming rates. The units for steaming rate are in "kg per square metre of heating surface per hour".

It is interesting to compare the Speed-TE curve for the DF4-D (Fig 7) with that of the QJ (Fig 6). Despite its much higher starting value, the diesel's tractive effort falls away more rapidly than the steam locomotive's, such that at 80km/h the QJ's tractive effort (at max steaming rate) is higher than that of the diesel. This illustrates an old adage that "steam locomotives can't start the loads that they can haul, while diesels can't haul the loads that they can start". In fact, as demonstrated routinely in the USA in the 1950s, steam locomotives had the ability to haul prodigious loads at high speeds, whereas the diesels that replaced them had to be coupled together into multiple units to haul the same loads[5].

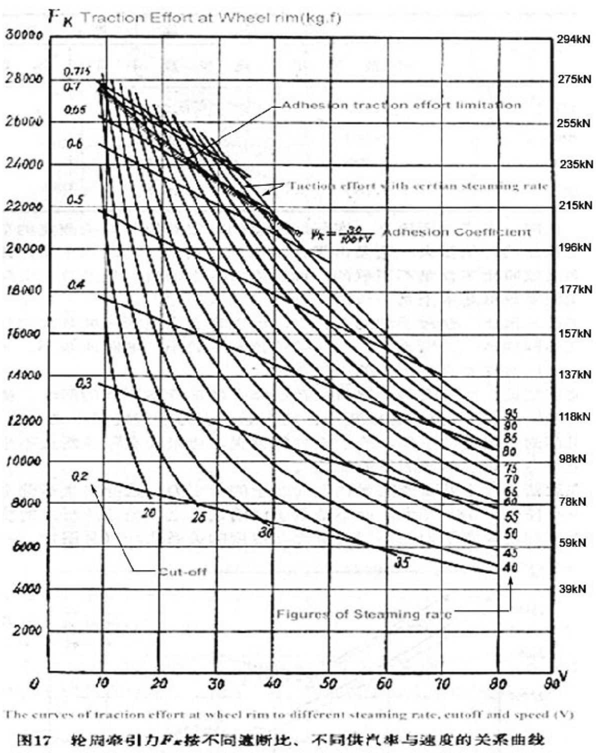

Fig 8: QJ (Steam) Speed- TE Curve

Tractive effort and power outputs have been derived from Wheel-rim TE vs. Speed curves produced by China National Railways for the QJ, DF4 and SS3 as illustrated above.

For the 8AT, tractive effort and power outputs are derived from adaptation of David Wardale's Fundamental Design Calculations for the 5AT locomotive, as shown below. In this case, it is the drawbar tractive force rather than the wheel rim tractive force that is shown.

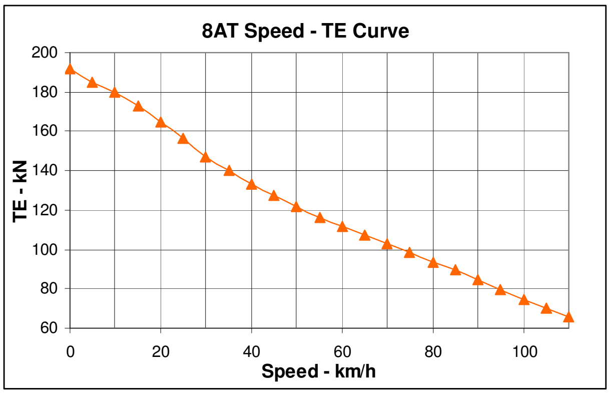

Fig 9: 8AT (Steam) Speed- TE Curve

Chinese TE values are given at the wheel-rim; hence wind, rolling and mechanical losses need to be deducted to determine the tractive effort at the drawbar. Koffman's formula has been used to estimate drawbar TEs for the DF4 and SS-3 in the absence of Chinese data, while a Chinese formula has been used to estimate that of the QJ. The resistance values thus calculated have been deducted from the wheel-rim values shown to estimate the drawbar tractive forces. A comparison of drawbar TE over a range of speeds is shown in Fig 10. Their values and associated power outputs are presented overleaf in Table 2.

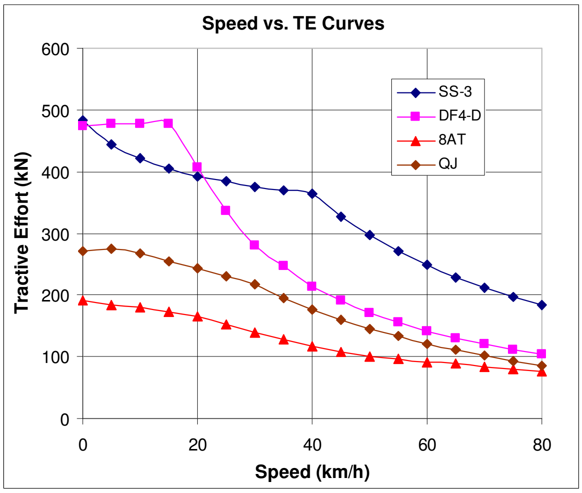

Fig 10: Speed- TE Curve Comparison

[4] The term cut-off refers to the piston position at the point where the steam supply to the cylinder is cut off by the valve gear. Cut-off is measured by dividing the piston travel at point of steam cut-off by the piston stroke length.

[5] "The Economic Results of Diesel and Electric Motive Power on the Railways of the United States of America" by H.F. Brown, Institution of Mechanical Engineers (London) Volume 175 No. 5 1961, covers this point in some detail.

Loco Speed	QJ[1]		8AT[2]		DF4-D		SS-3	
	TE	kW	TE	kW	TE	kW	TE	kW
0	271	0	192	0	475	0	482	0
10	267	741	180	500	479	1329	421	1169
20	244	1353	163	906	405	2252	391	2173
30	216	1804	139	1161	281	2345	376	3131
40	176	1954	117	1301	213	2370	365	4054
50	146	2021	100	1389	170	2366	*296*	*4116*
60	121	2021	91	1515	141	2354	*248*	*4139*
70	102	1980	84	1626	120	2335	*212*	*4129*
80	85	1886	77	1711	105	2333	*185*	*4106*

Note 1: For the QJ, the TE and Power values are estimated from the Speed-TE curves supplied by China National Railways at steaming rate of 75 kg/hr/m^2. In the case of the SS-3, the TE figures in italics have been reduced below those shown on the CNR curve in order to keep its wheel rim power at or below its rated power.

Note 2: The QJ can deliver 2600 kW at full boiler output; the 8AT should produce 2100 kW at the drawbar at full power. In order to base the 8AT's performance on the same assumption as the Chinese locos, its calculated maximum drawbar tractive effort values have been reduced in the same proportion as those of the QJ resulting from the adoption of a 75 kg/hr/m^2 steaming rate instead of its maximum of 95 kg/hr/m^2. Thus the 8AT's estimated TE and power values have been reduced progressively from zero at low speeds up to 20% at 80 km/h.

Table 2 – Comparison of Tractive Efforts and Power Outputs

2. Coal Quality

As with diesel traction, the performance of steam locomotives is dependent on the quality of coal used for their fuel. Use of low calorific value fuels can have a disproportionate effect on the fuel consumption as exemplified by a trial in the UK in the late 1950s where a 20% reduction in calorific value resulted in a 150% increase in fuel consumption[6]. Locomotive coal should meet several quality standards, including:

- NAR ("Net as received") Calorific Value >24 MJ/kg (> 5700 kcal/kg)
- Lump size: say 50 to 100mm for normal firebox; 20 to 50 mm for a GPCS (Gas Producer Combustion System) firebox[7];
- High volatile matter: say >30%;
- Low ash content: <10% if possible;
- High ash fusion temp: >1400°C;
- Low caking properties
- High reactivity.

Most importantly, coal for locomotive use should be of consistent quality to allow locomotives and crews to deliver consistent performances. Screening and washing of selected coals is therefore strongly recommended for locomotive use.

3. Train Rolling Resistance

Each locomotive's train hauling capacity is determined by comparing its tractive effort with train rolling resistance at a speed of 80km/h.

China National Railways' formulae for rolling resistance were adopted, being comparable to most other railways. These formulae are:

- **Starting Resistance Loaded Wagons**: R_S = 3.5 N/kN = 34.3 N/tonne
- **Rolling Resistance Loaded Wagons**: $R_L = 0.92 + 0.0048V + 0.000125V^2$ N/kN, where V is the speed of the train in km/h.
- **Rolling Resistance: Empty Wagons**: $R_E = 2.23 + 0.0053V + 0.000675V^2$ N/kN, where V is the speed of the train in km/h.

Additional allowance must be made for gradients and track curvature. In the case of gradients, the specific resistance is given by the formula:

- **Specific Gravitational Resistance from Gradients**: $R_G = 10 \times G$ N/kN where G is the gradient in percent (%).

In the case of curves, the simplified formula for single continuous (i.e. non-reverse) curves is:

- **Specific Resistance from Track Curvature**:

$R_C = (600/r) \times L_C/L_T$ when $L_C < L_T$ N/kN
or $R_C = (600/r)$ when $L_C \geq L_T$ N/kN,

where r = the curve radius in metres,
L_C = the curve length and
L_T = the train length.

Using these formulae it is possible to estimate the resistance of any train weight on any curve and gradient and to compare it with the drawbar tractive force exerted by the locomotive to determine the speed at which the locomotive can haul the train. This can be done most effectively by combining the values of tractive force and resistance into a single equation that defines the gradient up which a locomotive will haul a given train load up a given speed. Assuming straight track, this can be derived from the simple formula:

At constant speed: TE_{DB} = Train Rolling Resistance + Gradient Resistance

or: Gradient Resistance = TE_{DB} – Train Rolling Resistance.

From which: $G \times 10 \times (W_T + W_L) = TE_{DB} - R_R \times W_T$

where W_T is the train weight and W_L the loco weight,

$$\text{or: } G = \frac{(TE_{DB} - R_R \times W_T)}{10 \times (W_T + W_L)} \%.$$

---

[6] Refer "Red Devil and Other Tales from the Age of Steam", Wardale, D., pages 502 and 503.

[7] The Gas Produce Combustion System was adapted for locomotive fireboxes by Argentinean engineer, Ing. L.D. Porta.

Tables can thus be derived for each locomotive type. An example of the QJ table is shown in Table 3 below:

Speed km/h	dbTE	Train Resist	tonne 1000	tonne 2000	Tonne 3000	tonne 4000	tonne 5000
	kN	N/t	Climbable Grade % at given load and speed				
5	275	9.3	2.26	1.19	0.79	0.58	0.45
10	267	9.6	2.19	1.15	0.76	0.55	0.43
15	255	10.0	2.08	1.09	0.72	0.52	0.40
20	244	10.5	1.98	1.03	0.68	0.49	0.38
25	228	11.0	1.84	0.95	0.62	0.45	0.34
30	212	11.5	1.70	0.88	0.57	0.40	0.30
35	194	12.2	1.54	0.78	0.50	0.35	0.26
40	177	12.9	1.39	0.70	0.44	0.30	0.22
45	160	13.6	1.25	0.62	0.38	0.26	0.18
50	146	14.4	1.11	0.54	0.33	0.21	0.14
55	134	15.3	1.00	0.48	0.28	0.18	0.11
60	122	16.3	0.90	0.42	0.23	0.14	0.08
65	113	17.3	0.81	0.36	0.19	0.11	0.05
70	103	18.3	0.72	0.31	0.15	0.07	0.02
75	93	19.5	0.63	0.25	0.11	0.04	-0.01
80	85	20.6	0.55	0.20	0.07	0.01	-0.04

Table 3 – Max Gradients at Constant Speed
for QJ class loco operating at 75 kg/m^2/hr steaming rate.

These results and similar ones derived for each of the other locomotive types are summarized in Table 4 below:

Loco Type	units	QJ	8AT	DF4-D	SS-3
Max Design Speed	km/h	85	110	100	100
Max Speed - 2,000 t	km/h	85	105	100	100
Max Speed - 2,500 t	km/h	85	95	100	100
Max Speed - 3,000 t	km/h	85	90	100	100
Max Speed - 3,500 t	km/h	85	85	95	100
Max Speed - 4,000 t	km/h	**80**	**75**	90	100
Max Speed - 5,000 t	km/h	70	65	**80**	100
Max Speed - 6,000 t	km/h	65	(55)	70	95
Max Speed - 7,000 t	km/h	60	-	65	90
Max Speed - 8,000 t	km/h	(55)	-	60	85
Max Speed - 9,000 t	km/h	-	-	55	**78**
Max Speed - 10,000t	km/h	-	-	50	75
Max load at 80km/h on level track	t	4,100	3,200	5,000	8,900
Note: David Wardale has recorded an instance of a QJ under test hauling 4100 tonnes up a gradient of 0.7% at a constant speed of 25 km/h, which is significantly better than could be predicted by the calculations or by CNR's performance curves. Numbers in parenthesis indicate estimated speeds with loads that exceed the starting capacity of the locomotive.					

Table 4: Train Haulage Capacity Estimates

ESTIMATING LOCOMOTIVE FLEET SIZES

1. Principles of Train Operation

For the purpose of cost comparisons, an estimate needs to be made as to the number of each type of locomotives that are required to operate a railway, taking into account the method of operation and the maintenance and downtime required for each locomotive type.

An idealized railway and operating system is assumed with the following characteristics:

- Length: 100 km;
- Max gradient: 0.5%;
- Average running speed for full and empty trains 50 km/h; max speed 80 km/h;
- Dedicated to coal transportation from mine site to single delivery point (no connecting railway, no other traffic);
- Balloon loops at each end with track layout and gradient to allow "in-consist" train loading and unloading with locomotives remaining attached to their trains;
- A "just-in-time" synchronized sequencing of train movements such that trains arrive and depart at preset intervals, with coincident arrivals at passing loops such that all trains are either in motion, or being filled or emptied, or undergoing brake tests (or locos undergoing servicing) at all times.

The spacing of passing loops thus define the frequency of train movements and are selected such that the train sizes are sufficient to meet the target daily throughput of freight whilst remaining within the load capacity of the locomotive type. An idealized sequencing diagram for QJ traction hauling 3720 tonne trains is shown in Fig 11 based on a target daily throughput of 83,000 tonnes. This requires four passing loops and therefore five trains in transit plus one each at the loading and unloading stations.

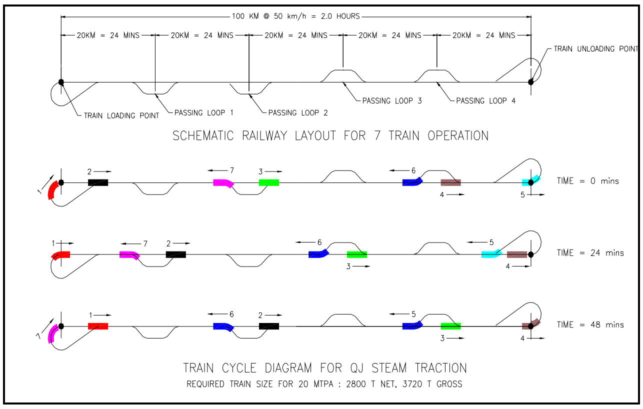

Fig 11: Rail Operation Diagram for QJ haulage

Using the same assumptions for each locomotive type, the following deductions can be tabulated – refer Table 5, based on the use of Chinese C70 or K70 wagons with net capacity of 70 tonnes and tare weight of 23 tonnes.

Item	units	QJ	8AT	DF4	SS3
Max Loco Capacity (ex Table 4)	t	4,100	3,200	4,700	8,700
Equivalent net load in C70/K70 wgns	t	3,086	2,409	3,538	6,548
Minimum required trains per day	No.	27	34.6	23.6	12.7
Max dist between trains @ 50km/h	km	44.4	34.7	50.9	94.3
Max dist between passing loops	km	22.2	17.3	25.5	47.1
No. of passing loops in 100 km	No.	3.50	4.77	2.93	1.12
Min No. of Passing Loops	No.	4	5	3	2
Min No. of Trains in Transit	No.	5	6	4	3
Dist between passing loops	km	20.0	16.7	25.0	33.3
Train Arrival Frequency	mins	48	40	60	80
Required net tonnes per train	t	2,778	2,315	3,472	4,630
Minimum number of 70 t wagons	No.	40	34	50	67
Actual train load (net)	t	2,800	2,380	3,500	4,690
Actual train weight (gross)	t	3,720	3,162	4,650	6,231
% of loco's haulage capacity	%	91%	99%	99%	72%

Table 5 – Estimating Optimum Train Sizes to deliver 83,000 tonnes per day

2. Train Loading and Unloading Operations

Additional trains and locomotives are required to allow for loading and unloading times and servicing times for locomotives. These will depend on the method of loading and unloading, and detailed consideration of servicing requirements (which will not be discussed here). However, based on the provision of adequate over-rail buffer storage for filling trains and the use of one 5000 t/h rotary unloader for emptying the trains, the deductions drawn with regards rolling stock requirements are summarized in Table 6.

Item	Units	QJ	8AT	DF4	SS3
Net train capacity	t	2,800	2,380	3,500	4,690
Train Frequency	mins	48	40	60	80
Train loading downtime	mins	20	20	15	15
Available time for train loading	mins	28	20	45	65
Required Filling Loading Rate	t/h	6046	7191	4667	4329
No. of trains at Loading Station	**No.**	**1**	**1**	**1**	**1**
Assumed unloading capacity	t/h	5000	5000	5000	5000
Time required to unload	mins	34	29	42	56
Time available for servicing etc	mins	14	11	18	24
No of trains at Unloading Station	No.	2	2	2	1
No. of trains at Unload Station	**No.**	**2**	**2**	**2**	**1**
No of trains in transit (Table 5)	No.	5	6	4	3
Total number of locos required	No.	8	9	7	5
Number of trains required	No.	8	9	7	5
Number of wagons required	No.	320	306	350	335

Table 6 – Trains and Locos required at Loading and Unloading Stations

It is interesting to observe that even though the diesel and electric locos require fewer trains, the total number of wagons required to deliver the tonnage throughput is higher than for steam traction, the reason being that their wagons spend more idle time waiting to be loaded and unloaded.

3. Train Loading and Unloading Operations

Additional locomotives (and wagons) are required to cover the downtime required for maintenance and breakdowns. This requires consideration of locomotive mileage and maintenance scheduling.

Chinese maintenance schedules are used for the three Chinese locomotives, and an estimate is made for the 8AT based on the records from the RFIRT coal haulage railway in Argentina, on which Porta-modified locomotives operated successfully for three decades. The method of calculation is summarised in Table 7 below:

Item	Units	QJ	8AT	DF4	SS3
Loco time at loading station	mins	48	40	60	80
Loco time at unloading station	mins	96	80	60	80
Travel time on line (both ways)	mins	120	120	120	120
Turnaround time for each loco	hours	6.4	6.0	6.5	7.1
No. round trips per day per loco	unit	3.8	4.0	3.7	3.4
Distance travelled per round trip	km	200	200	200	200
Km travelled per loco per day	km	750	800	738	675
Annual km for each loco	kmx1000	24.0	25.6	23.6	21.6
Major overhaul period	kmx1000	25.0	50.0	70.0	120.0
Time to complete major overhaul	days*	15	15	15	15
Intermediate overhaul period	kmx1000	83.3	12.5	23.3	40.0
Intermediate overhaul time	days*	6	6	6	6
Scheduled maint. period	kmx1000	22.5	24.0	30.0	40.0
Scheduled maintenance time	days*	2	2	2	2
No. of major overhauls p.a.	unit	0.96	0.51	0.34	0.18
Time under major o'hauls p.a.	days*	14.4	7.9	4.4	2.7
Intermediate overhauls per year	unit	1.92	1.54	0.68	0.36
Time under intermediate o'hauls.	days*	11.5	9.2	3.5	2.2
No of scheduled maint. p.a.	unit	10.67	10.67	6.86	4.86
Time under scheduled maint.	days*	21.3	21.3	11.9	9.7
Total time under maint. p.a.	days*	47.3	38.2	19.8	14.6
% time under maintenance	%	15%	12%	6%	5%
% of loco fleet under maint.	%	15%	12%	6%	5%
No. of locos in operation (table 6)	unit	8	9	7	5
No. of locos to cover maint.	theory	1.18	1.08	0.43	0.23
No. of locos to cover maint.	actual	2	2	1	1
Stand-by locos (breakdown etc)	est'd	3	3	2	1
Total Loco Fleet Required	**unit**	**13**	**14**	**10**	**7**
* Estimated maintenance times are based on 24 hour per day operation. These times will increase if working days are shorter.					

Table 7 – Locos Required to cover Servicing and Maintenance Downtime

COST ESTIMATES

Having determined the number of locomotives required to operate the railway, it is necessary to estimate the costs associated with their procurement and operation viz: maintenance, fuel, labour and water costs (for steam traction only). All cost estimates are in US dollars. Where Chinese cost data are used, an exchange rate of RMB 7.5 per US dollar is assumed.

1. Capital Costs

Capital costs estimates are derived as follows:

- **Locomotive refuelling and servicing facilities**: No detailed cost estimates have yet been made for these facilities. However, when their assumed costs are amortized over the anticipated life of the railway, their annual value becomes insignificant in comparison with other depreciation and operating costs. For the purposes of this study, therefore, costs have been assumed as follows:
  - Steam servicing and refueling facilities: $4,000,000
  - Diesel servicing and refueling facilities: $2,000,000
  - Electric servicing facility: $1,000,000.

  All are depreciated over a 25 year period at a constant rate of amortization.
- **Electrical Infrastructure**: China National Railways have provided a budget cost of $450,000 per kilometre for electrification infrastructure based on 2001 costs. Since world copper prices have quadrupled since 2001, and other costs have risen substantially, a conservative value of around $530,000 per km has been adopted.

  The railway track length, including passing loops, balloon loops and sidings is approx 115 km, thus the electrical infrastructure cost is estimated to be $61.3 million, with depreciation period of 25 years.
- **QJ Steam Locomotives**: In 2006 the quoted price for QJs was $149,000 per loco for purchase and transportation for repair, plus $106,350 for overhaul plus transportation to port. An additional $49,500 was added for modification (mostly to the boiler) to meet USA Federal Railroad Administration (FRA) specifications. Total cost was therefore $304,580. For the purpose of this cost comparison, an additional $50,000 is added to cover shipping costs, and a further contingency of $50,000 is added to cover likely price increases since 2006. Thus a cost of **$400,000** per locomotive is assumed with a depreciation period of 10 years.
- **DF4-D Diesel Locomotives**: The 2006 ex-works price for a 2940 kW DF4-D diesel locomotive was $995,000 USD without dealer mark-up. Adding 20% for dealer fees and other costs, the price assumed for this study is **$1.2 million** with a depreciation period of 25 years.
- **SS-3 Electric Locomotives**: The 2006 ex-works price for a 4320 kW SS-3 electric locomotive was $975,000 USD "without dealer mark-up". Adding 20% for dealer fees and other costs, the assumed cost for this study is **$1.2 million** with a depreciation period of 25 years.
- **8AT Modern Steam Locomotives**: Extensive study by the 5AT Project planning committee has produced a 2007 cost estimate of $19 million for the design and manufacture of a prototype 5AT locomotive and $4 million per production locomotive, based on design and construction being carried out in Europe.

  It is thus assumed that the development of an 8AT prototype will cost approximately $20 million, however the cost of production units could be substantially reduced if they were manufactured under license in China or other developing country. A cost of $2 million per locomotive is therefore adopted plus a license fee of $0.5 million per locomotive to cover the development costs – i.e. a unit cost of **$2.5 million** is assumed with a depreciation period of 25 years.

Table 8 below summarizes the above data:

Item	units	QJ	8AT	DF4	SS3
Electrical infrastructure cost	$m				61.3
Servicing infrastructure cost	$m	4.0	4.0	2.0	1.0
Number of locomotives (Table 7)	unit	13	14	10	7
Cost per locomotive	$m	0.40	2.5	1.25	1.25
Cost of locomotive fleet	$m	5.20	35.0	12.0	8.40
Infrastructure depreciation period	years	25	25	25	25
Depreciation period for locos	Years	10	25	25	25
Amortized cost of infrastructure	$m/a	0.160	0.160	0.080	2.493
Amortized cost of locomotives	$m/a	0.520	1.400	0.480	0.360
Total Amortized Cost of Locos	**$m/a**	**0.680**	**1.560**	**0.560**	**2.829**
Min number of wagons required	unit	320	306	350	335
Unit cost of wagons	$1000	72.5	72.5	72.5	72.5
Total cost of wagon fleet	$m	23.25	22.24	25.43	24.34
Depreciation period for wagons	years	30	30	30	30
Amortized cost of wagons	**$m/a**	**0.872**	**0.824**	**0.969**	**0.974**

Table 8 – Capital Cost and Depreciation Estimates

2. Maintenance Costs

The following locomotive maintenance cost data from China is used in this study:

Item	QJ	DF4	SS3
Major Overhaul Period	250,000 km or 3 yrs	700,000 km or 6 yrs	1,200,000 km or 10 yrs
Major Overhaul Cost	$45,000 (2006)	$200,000 (1997)	$250,000 (1997)
Intermediate Overhaul Period	83,000 km or 1 yr	250,000 km or 2 yrs	400,000 km or 3 yrs
Intermediate Overhaul Cost	$25,000 (2006)	$50,000 (1997)	$65,000 (1997)
Regular Maintenance Period	22,500 km (assumed)	30,000 km or 3 mths	40,000 km or 6 mths
Regular Maintenance Cost	$5000 (assumed)	$10,000 (1997)	$12,000 (1997)

Table 9 – Maintenance Schedules for Chinese Locos

Obviously there is no 8AT maintenance cost data, so the following assumptions are made based on Table 9 above and on RFIRT (Argentina) records as follows:

Major Overhaul Period	500,000 km or 3 yrs
Major Overhaul Cost	$50,000
Intermediate Overhaul Period	125,000 km or 1 yr
Intermediate Overhaul Cost	$25,000
Regular Maintenance Period	24,000 km
Regular Maintenance Cost	$5000
Note – The above estimates are taken from Argentina's RFIRT railway which operated smaller locomotives than the 8AT, running on much smaller wheels and travelling over very poor quality track. The estimates are therefore likely to be conservative.	

Table 9a – Proposed Maintenance Schedule for 8AT Locomotives

Cost data for infrastructure maintenance is not currently available and are not included in these cost estimates. Whilst such costs are likely to be insignificant for steam and diesel traction, electrical infrastructure maintenance costs may be substantial. This must be borne in mind when comparing the cost of electric traction with steam and diesel costs.

In table 10 below, the 1997 maintenance cost data for diesel and electric traction have been increased by 15% to allow for inflation. However as noted above, maintenance costs for the electrical infrastructure are not included.

Item	units	QJ	8AT	DF4	SS3
Major overhaul frequency	km x 1000	250	500	700	1.2m
Major overhaul cost	$ x 1000	45	50	230	288
Intermediate overhaul frequency	km x 1000	83	125	233	400
Intermediate overhaul cost	$ x 1000	25	25	58	75
Regular maint frequency	km x 1000	22.5	24	30	40
continued across page					
continued from bottom of page					
Regular maintenance cost	$ x 1000	5	5	11.5	13.8
Average loco km per year	km x 1000	111	123	115	123
Major maint cost/loco/year	$ x 1000	19.9	12.3	37.8	29.6
Intermediate maintenance cost/loco/year	$ x 1000	16.6	16.5	14.2	11.5
Reg maint cost/loco/year	$ x 1000	24.6	25.7	44.1	42.6
Total maint cost/loco/year	$ x 1000	61.1	54.5	96.2	83.7
Number of locos in fleet	Unit	13	14	10	7
Total maint cost per year	**$m**	**0.795**	**0.763**	**0.962**	**0.586**

Table 10 – Loco Maintenance Cost Estimates

It is noted that the above estimates of maintenance costs show that the costs for the 8AT are only marginally lower than those for the QJ. This implies that the costs assumed for the 8AT are likely to be over-estimated.

3. Labour Costs

In comparing labour costs, the following assumptions are made:

- Each operating steam loco will require 2 operators or "enginemen";
- Each operating diesel and electric loco will require 1 operator;
- "Old steam" traction will require 8 people per shift for locomotive servicing duties;
- "Modern steam" traction will require 4 people per shift for servicing duties;
- Diesel traction will require only 2 servicemen per shift;
- Electric traction will require 6 servicemen per shift, including 2 at the servicing depot and one linesman in each section of track between passing loops;
- No allowance is made for maintenance personnel whose costs are included in subsection 2 above.
- Operating and servicing personnel cost $5,000 per annum, based on labour costs in China.

Item	units	QJ	8AT	DF4	SS3
Labour shifts per day		3	3	3	3
Crew members per loco		2	2	1	1
Number of locos in operation		8	9	7	5
Total loco crew		48	54	21	15
Servicing crew per shift		8	4	2	6
Total servicing crew		24	12	6	18
Total labour requirement		72	66	27	33
Unit labour cost per annum	$	5000	5000	5000	5000
Labour cost per annum	**$m**	**0.360**	**0.330**	**0.135**	**0.165**

Table 11 – Labour Costs related to loco operation

4. Water Costs

Water costs apply only to steam traction, and include both the cost of the water used by the locomotives and the cost of water treatment.

Water and Water Treatment Costs: For the purpose of this study, a cost of $0.30 per tonne is assumed for water. For water treatment, a figure of $1.00 per tonne is used based on UK cost data.

Water Consumption: The performance curves for the QJ locomotive can be used to estimate water consumption based on the steaming rate required to maintain the horsepower outputs derived in Table 14 below. 8AT consumption figures are conservatively estimated to be 80% those of the QJ loco hauling the same load. Table 16 below demonstrates the principle and calculates the total water cost for each locomotive type:

Item	Units	QJ	8AT
Gross train weight (from Table 5)	t	3,720	3,162
Wheel rim TE at 50 km/h (see note 1)	kN	146	-
Wheel rim power at 50 km/h	kW	1,653	-
Steam consumption per hour per m^2	kg	59	
Heating surface area (excluding superheater)	m^2	255.3	-
Steam production	t/hr	15	-
Journey time over 100 km railway	h	2.0	-
Steam consumption	t	30	-
Empty train weight	t	920	-
Wheel rim TE at 50 km/h (see note 1)	kN	85	-
Wheel rim power at 50 km/h	kW	1,181	-
Steam consumption per hour per m^2	kg	43	-
Heating surface area	m^2	255.3	-
Steam production	t/h	11	-
Journey time over 100 km railway	h	2.0	-
Steam consumption	t	22	-
Total water consumption per round trip	**t**	**52**	**38**
Number of round trips per year	unit	7,143	8,403
Total Water Consumed	1000t	372	321
Water cost including treatment	$/t	1.30	1.30
Total Water Cost including treatment	**$m**	**0,483**	**0.416**

Note: 1: The wheel rim TE values are the train rolling resistance values from Table 14 (include the 100% load factor) plus the estimated rolling resistance of each loco at 50 km/h (based on China National Railways rolling resistance formulae).

Table 12 – Water Consumption Estimates

FUEL CONSUMPTION AND COST ESTIMATES

Locomotive fuel consumption can be estimated from its thermal efficiency, the calorific value of its fuel, and the energy that is required to overcome the rolling resistance of itself and its wagons.

1. Fuel Cost per kWh of Energy

The tabulated calculation below is based on the following assumptions:

- Typical calorific values for coal and diesel fuel.
- Drawbar thermal efficiency values are representative of each traction type. It should be noted that diesel locomotive manufactures do not normally quote drawbar thermal efficiencies. "Crank-shaft thermal efficiency" values of around 30% or higher are quoted from which electrical and mechanical transmission losses need to be deducted to produce a drawbar value. A figure of 25% for diesel locomotive drawbar efficiency is considered a reasonable average.
- The "fuel consumption" figure given for electric locomotive is a measure of kWh consumed divided by kWh supplied based on the stated drawbar efficiency.
- A figure of 20% for electrical losses from the point of supply to the locomotive's drawbar is considered a reasonable average.
- Rates of $0.08 per kWh of electricity and $1000 per tonne for diesel fuel, based on commercial rates applying in China in 2008.
- An ex-mine cost for coal of $30 per tonne, being an industry average value. The ex-mine cost is used rather than its export price, since the export price of coal includes allowances for loading; transportation; storage; blending; loading onto ship plus profit. With the exception of the first item, none of these costs apply to the coal as loaded into the locomotive tender.

Item	Units	QJ	8AT	DF4	SS3
Energy Conversion Factor	kcal/kW-h	860	860	860	-
Max d.b. thermal efficiency	%	8%	15%	30%	-
Av. d.b. thermal efficiency	%	6%	10%	25%	80%
Fuel Calorific Value	Kcal/kg	6,500	6,500	10,200	-
Fuel Consumption	Kg/kWh	2.205	1.323	0.337	1.250
Fuel Cost per tonne	$/t	$30	$30	$1,000	$0.08
Fuel Cost / kW-h output	**US cents**	**6.62**	**3.97**	**33.73**	**10.00**

Table 13 – Fuel Consumption per kW-h Energy Output

2. Fuel Consumption and Cost Estimates for Loaded and Empty Journeys

Using the fuel consumption rates calculated in Table 13, it is possible to estimate locomotive fuel consumption for the loaded and empty return workings on the hypothetical 100km railway, based on the average power outputs required from the locomotives from which the total energy expended by them in moving their trains can be estimated.

Chinese wagon rolling resistance formulae are used giving values of specific rolling resistance of 15.0 N per tonne of loaded train weight on level track and 42.6 N per tonne of empty train weight on level track both at 50 km/h. An arbitrary factor of 100% is added to the rolling resistance estimates to account for losses associated with stopping, starting, climbing hills, braking when descending hills and negotiating curves. As will be seen, this factor brings the fuel consumption rates per million tonne-km into good alignment with published Chinese statistical data.

Item	Units	QJ	8AT	DF4	SS3
Gross train wt (from Table 5)	T	3,720	3,162	4,650	6,231
Specific rolling resistance full train	N/t	15	15	15	15
Rolling resistance (level track)	kN	55.8	47.5	69.8	93.5
Load factor to cover curves and grades etc	%	100	100	100	100
Rolling resistance (curved track)	kN	111.7	94.9	139.6	187.1
Power used overcoming train resistance	kN-km/h	5,584	4,746	6,980	9,353
Ditto	kW	1,511	1,319	1,939	2,599
Specific fuel consumption - Kg/kWh or kW/kWh (Table 13)		2.205	1.323	0.337	1.250
Fuel consumption rate for loaded journey - kg/h or kWh/h		3,421	1,745	654	3,248
Fuel consumption for loaded journey kg/km or kWh/km		68.4	39.4	13.1	65.0
Fuel consumed on loaded trip	T	6.84	3.94	1.31	6,496
Fuel consumption per million tonne-km	**t or kWh**	**18.39**	**11.04**	**2.81**	**10,426**
Fuel cost per tonne or per kWh	$	30	30	1,000	0.08
Fuel cost per km travelled	$/km	2.05	1.05	13.08	5.20
Fuel cost per 100km loaded trip	$	205	105	1308	520
Tare weight of empty train	T	920	782	1,150	1,541
Specific rolling resistance empty train	N/t	42.6	42.6	42.6	42.6
Load factor for curves and grades	%	100	100	100	100
Rolling resistance (curved track)	kN	78.4	66.7	98.1	131.4
Power consumed overcoming resistance	kW	1,090	926	1,362	1,825
Fuel consumption for empty journey kg/km or kWh/km		48.1	24.5	9.2	45.6
Fuel consumption per million tonne-km	**t or kWh**	**52.24**	**31.34**	**7.99**	**29,614**
Fuel cost per km travelled	$/km	1.44	0.74	9.19	3.65
Fuel cost per 100km empty journey	$	144	74	919	365
Fuel cost per round trip	**$**	**349**	**178**	**2,227**	**885**

Table 14 – Fuel Consumption per 100 km Journey

3. Fuel Consumption Figures from Chinese Statistical Data

Several official statistics relating to locomotive fuel consumption and failure rates were published in the Chinese National Statistics in 2004, deriving from China National Railways' Operating Department's records. The figures are summarized in Table 15.

Year	Loco Failures per 10^6 ton-km		Av. fuel consumption Tonnes per 10^6 t-km	
	Steam	Diesel	Steam	Diesel
1987	3.0	11.0	11.09	2.59
1995	3.4	16.8	13.74	2.43
1999	0	13.1	20.66	2.62
2001	not given	not given	19.5	2.57
2003	-	7.0	-	2.54

Table 15 – Published Statistics from the Operation Department of China's National Railway

An additional figure was given for electric traction average power consumption in 2001 of 11,310 kWh per million gross tonne-km of freight hauled.

It may also be 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 maintenance standards;
- Greater utilization on non-productive shunting duties.

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 period when Chinese railways were fully steam operated.

It can be seen that the Chinese fuel consumption figures are consistent with those derived above in Table 14, though it can be shown that lower fuel and power consumption figures might be applied to all traction types[8]. Notwithstanding, Table 14's consumption figures are adopted in calculating fuel costs as follows:

[8] Simulation modelling of the four locomotive types operating on an actual railway shows significantly lower consumption rates than those assumed for this paper.

Item	Units	QJ	8AT	DF4	SS3
Tonnage Throughput	mt/y	20	20	20	20
Length of journey	km	100	100	100	100
Total net mt-km/y	mt-km/y	2,000	2,000	2,000	2,000
Gross wagon weight	t	93	93	93	93
Net wagon weight	t	70	70	70	70
Gross to net ratio	-	1.33	1.33	1.33	1.33
Total gross mt-km/y	mt-km/y	2,657	2,657	2,657	2,657
Fuel used per 10^6t-km	t or kWh	18.39	11.04	2.81	10,426
Total fuel for full trains	t or kWh	48,871	29,322	7,474	27.7m
Total tare mt-km/y	mt-km/y	657	657	657	657
Fuel used per 10^6t-km	t or kWh	52.24	31.34	7.99	29,614
Total fuel for empties	t or kWh	34,330	20,598	5,250	19.5m
Total fuel consumed - full and empty trains	t or kWh	83,201	49,921	12,725	47.2m
Fuel cost per t or kWh	$	30	30	1,000	0.08
Cost of Fuel per year	**$m/y**	**2,496**	**1.498**	**12.725**	**3.773**

Table 16 – Fuel Cost Comparisons

OVERALL COMPARISON OF COSTS

It is now possible to add together each cost component to create an overall comparison of costs between each traction type. The costs can be summarized as follows:

Item	Units	QJ	8AT	DF4	SS3
Amortization Costs – Table 8	$m/y	0.680	1.560	0.560	2.829
Annual maint. cost - Table 10	$m/y	0.795	0.763	0.962	0.586
Labour cost per year - Table 11	$m/y	0.360	0.330	0.135	0.165
Annual cost of water - Table 12	$m/y	0.483	0.417	Nil	nil
Annual cost of fuel - Table 16	$m/y	2.496	1.498	12.725	3.773
Total Cost per Year	**$m**	**4.815**	**4.568**	**14.382**	**7.353**
Cost per tonne of freight	$/t	0.24	0.23	0.72	0.37
Cost per 10^6-net-tonne-km	$/mt-km	2,407	2,284	7,191	3,677
Cost ratio compared to 8AT	%	105%	-	315%	161%
Cost difference compared to 8AT	$m/y	0.246	-	9.814	2.785

Table 17 – Overall Annual Cost Comparisons

It should be noted that the electrical costs do not include electrical infrastructure maintenance which may add significantly to the overall cost of electric traction. They also assume that sufficient electrical capacity is available to service the railway's traction requirements.

It is noteworthy that when comparing the cost of the 8AT with diesel traction, the additional capital outlay involved in the procurement of locomotives and servicing facilities will be recovered in less than 4 years. In fact it is probable that most of the costs for the 8AT will be lower than assumed in this study.

SENSITIVITY ANALYSIS

Given the very substantial cost savings that steam traction evidently offers, only very large changes in cost assumptions are likely to affect steam's cost supremacy. From spreadsheet analysis, the effects of various cost adjustments can be summarised as follows:

Item	QJ	8AT	DF4	SS3
Calculated Operating Cost per Year from Table 21	4.815	4.568	14.382	7.353
Doubling of labour costs to $10,000 p.a.	5.174	4.897	14.516	7.518
Doubling of water cost to $2.60 per tonne	5.186	4.888	14.382	7.353
Doubling steam locomotive maintenance costs	5.609	5.331	14.382	7.353
Doubling steam loco and infrastructure capital cost	5.495	6.128	14.382	7.353
Doubling steam locomotive fuel cost (to $60 per t)	7.310	6.065	14.382	7.353
50% increase in price of diesel (to $1050 per t)	3.983	4.069	20.744	7.353

Table 18 – Sensitivity of Cost Comparisons
Annual costs in $ million, taken from spreadsheet analysis

Quite evidently, even large changes in assumed costs have little effect on the overall cost advantage of steam traction. Even the application of a $25 per tonne carbon "tax" would leave the "modern steam" option with a clear cost advantage over all other types (see table 21).

Quite evidently also, the cost of diesel traction is highly sensitive to the cost of diesel fuel because fuel represents its largest cost component. It need hardly be emphasised that a 50% increase in the price of diesel fuel is a more probable event than any of the other cost increases listed above.

Finally it is noteworthy that even a 20-fold increase in wage rates (to $100,000 per year) leaves "old steam" with a 40% cost advantage over diesel, and leaves "modern steam" on a par with electric, suggesting that steam traction in coal haulage might be competitive in high-wage countries.

ENVIRONMENTAL CONSIDERATIONS

1. CO_2 Emissions

It is inevitable that coal burning steam locos will generate more CO_2 than diesels, because coal has a higher carbon content than oil and because of steam's lower thermal efficiency. Even "modern steam" traction cannot compete with diesel in terms of carbon emissions. A recent study by Brian McCammon[9] has produced the following estimates of carbon dioxide "equivalent" footprints for different traction types, taking into account not only direct carbon dioxide emissions, but emissions of other greenhouse gasses such as nitrous oxide and methane both from the locomotives and from the mining, processing and transportation of their fuels:

Item	units	Old Steam	Mod'n Steam	Elect'c	Diesel
Fuel		**Sub-bituminous Coal**			**Gas Oil**
Drawbar efficiency (assumed)	%	6	10	23	25
Average drawbar power (estimated)	kW	932	932	932	932
Drawbar energy output	kW-h	2071	2071	2071	2071
Energy input	kW-h	34,518	20,711	9,005	8,282
Energy input	GJ	124.3	74.6	29.8	32.4
Fuel net calorific value	MJ/kg	20.9	20.9	20.9	42.7
Mass of fuel burned	Tonne	5.6	3.4	1.5	0.6
Direct Emissions Factor	kg CO_2-e/GJ	92.8	92.8	92.8	82.6
Fugitive Emissions Factor	kg CO_2-e/GJ	1.9	1.9	1.9	11.8
Total Emissions Factor	kg CO_2-e/GJ	94.7	94.7	94.7	94.4
Total Emissions	tonnes of CO_2-e	11.8	7.1	3.1	2.8
Total Emissions per tonne of fuel burned	t-CO_2-e/t fuel	2.11	2.11	4.33	2.11
Total Emissions per tonne-km of haulage	gm - CO_2-e	42.0	25.2	11.0	10.1
Total Emissions per unit of energy output	kg(CO_2)/db-kWh	5.70	3.42	1.37	1.19

Notes: 1: "CO_2-e" = "CO_2 equivalent" = the equivalent weight of CO_2 in terms of greenhouse effects caused by other gases such as nitrous oxide and methane that are released in the mining, processing, transportation and burning of the fuels.
2: The efficiency of electric traction includes power station and transmission losses as well as the railway's local losses. The assumed value applies to average thermal power generation plants (not to the latest combined cycle plants that have a higher thermal efficiency)

Table 19 – CO_2-e Emission from Traction Types
when hauling a 2800 tonne train at 45 km/h over 100 km, taken from report by Brian McCammon[9]

While developing countries remain outside the Kyoto Protocol, the environmental cost of carbon emissions do not have to be considered when comparing traction types. However as mentioned above, it is instructive to look at the potential effects of the application of a carbon tax (or carbon credits) on the alternative traction options.

Table 20 below shows how the cost of fuel is affected by the application of a tax or credit charge of $25 per tonne of CO_2-equivalent emitted. The effect on the cost of electrical energy is not shown, but it can be shown to result in a $0.02 per kW-h increase, per Table 20 below.

Item	Units	QJ	8AT	DF4	SS3
Fuel Consumption (from Table 17)	Kg/kWh	2.205	1.323	0.337	1.250
Assumed cost of fuel	$/t or $/kWh	30	30	1000	0.08
CO_2-e per tonne of fuel (Table 23)	t-CO_2-e/t	2.11	2.11	4.33	2.11
CO_2-e per tonne tax rate (assumed)	$/t CO_2-e	25	25	25	25
Carbon tax charge	$/t of fuel	53	53	108	53
Effective fuel cost (including tax)	$ per t or $ per kWh	83	83	1,108	0.10
Cost of energy input (including tax)	cents per kWh	18.25	18.25	37.38	13.01

Table 20 – Effects of a $25 CO2 Emissions Charge on Traction Costs

The fuel effective cost of fuel can now be substituted into Tables 16 and 17 to determine the effects of the carbon tax, as follows:

Item	Units	QJ	8AT	DF4	SS3
Total fuel used per round trip (from Table 16)	t or kWh	83,201	49,921	12,725	47.2 m
Cost of Fuel per tonne or kWh (from Table 20)	$	83	83	1,108	0.10
Cost of Fuel per year of operation	**$m**	**6.884**	**4.131**	**14.102**	**4.908**
Total Amortization Cost of Locos and servicing infrastructure (Table 17):	$m	0.680	1.560	0.560	2.829
Total cost of maintenance per year (Table 17):	$m	0.795	0.763	0.962	0.586
Labour cost per year (Table 17):	$m	0.360	0.330	0.135	0.165
Total water cost including treatment (Table 17):	$m	0.483	0.417	Nil	nil
Total Operating Cost per Year	**$m**	**9.203**	**7.201**	**15.759**	**8.488**
Cost per tonne of freight hauled	$/t	0.46	0.36	0.79	0.42
Cost per million-net-tonne-km	$/mt-km	4,602	3,601	7,880	4,244

Table 21 – Effects of a $25 CO2 Emissions Charge on Traction Costs

Thus it can be seen that even the application of a substantial carbon tax (such as would increase the price of coal by almost 3 times) still leaves modern steam offering the lowest annual ownership costs. Of course, by the time such impositions are made, diesel fuel prices may be expected to be much higher than those assumed in the above estimate and electricity charges are likely to have risen too.

To put the CO_2 emissions issue into perspective, the increase in carbon emissions resulting from the use of steam traction instead of diesel when hauling a 3720 tonnes train over 100 km, is less than 0.2% of the amount that will subsequently be emitted by the coal that it is hauling.

[9] Unpublished paper by B. McCammon titled "Comparison of Greenhouse Gas Emission Footprints for Different Railway Traction Systems", Nov 2007"

2. Smoke Emissions from Steam Traction

Steam traction is sometimes criticized for the smoke nuisance that it creates. However it is important to understand that a properly operated steam locomotive burning high quality (lump) coal does not emit large quantities of smoke. Even "old" Chinese steam locomotives, which often burned coal with a high fines-content, were remarkable for their white steam in winter conditions and for their smokeless operation in summer. Small amounts of smoke will inevitably be emitted when coal is placed into the firebox caused by fine coal particles being caught up by the combustion air before it lands on the fire and then being drawn through the boiler and out of the chimney. Similarly transient smoke may be emitted under any circumstance that causes combustion to be incomplete.

Fig 12: White winter steam from QJ locomotive.

In any discussion about locomotive smoke emissions, it can be pointed out that diesel locomotives are not smoke-free and, like steam, they can emit substantial amounts of smoke when poorly handled or poorly maintained, as witnessed in the photo below.

Fig 13: EWS Class 37 in need of attention.

3. Positive Environmental Considerations relating to Steam Traction

Steam traction is an old technology that never achieved (or even got close to achieving) its maximum potential. It is also a technology that is unique in its capability of generating carbon-neutral power for the haulage of trains and other forms of transport with its ability to burn almost any solid or liquid form of bio-fuel. It is thus a valuable technology in a world that is facing environmental challenges and diminishing supplies of fossil fuel. In the past, steam engines (both stationary and locomotives) have commonly burned carbon-neutral fuels including wood, biomass and agricultural waste such as bagasse; palm oil waste, coconut fibre and rice husks, and they remain capable of doing so in the future.

McCammon's research[9] into comparisons between carbon footprints of steam, diesel and electric traction show that coal-fired "modern steam" traction as currently developed will produce emissions of CO_2 that are only slightly more than twice those produced by diesel and electric traction. Further development of steam traction along a path of progress that can be predicted and therefore planned, will lead to much higher thermal efficiencies which will see its carbon footprint reduced much further, even when burning coal as a fuel.

CONCLUSION

Steam traction, both old and modern, is shown to be an economically attractive alternative to both diesel and electric traction in circumstances where fuel and labour costs are low.

The technical advances in steam locomotive technology pioneered by L.D. Porta in Argentina have been highlighted as have the substantial savings in fuel and maintenance costs that "modern steam" traction offers.

An example of a "modern steam" 8AT freight locomotive has been introduced, derived from a design by David Wardale for a high speed passenger locomotive. The 8AT is shown to offer very substantial cost savings compared to all other forms of traction, with the exception of reconditioned Chinese QJ locomotives which have the advantage of very low capital cost.

Environmental issues associated with CO_2 and smoke emissions have been put in perspective, and it has been shown that a substantial carbon tax still leaves the "modern steam" option with a clear cost advantage over all other traction types.

Finally it has been shown that steam traction offers environmental opportunities that will only be grasped through further development of the technology. The opportunity of demonstrating the capabilities and cost advantages of steam traction on coal haulage in developing countries, together with the publicity that it would inevitably create, might raise investor interest in further development of the technology. It could thus be an important step towards the further development of an old technology in order to gain environmental benefits for the future.