Economics of Steam Traction
for the
Transportation of Coal by Rail

Chris Newman
Beijing, China

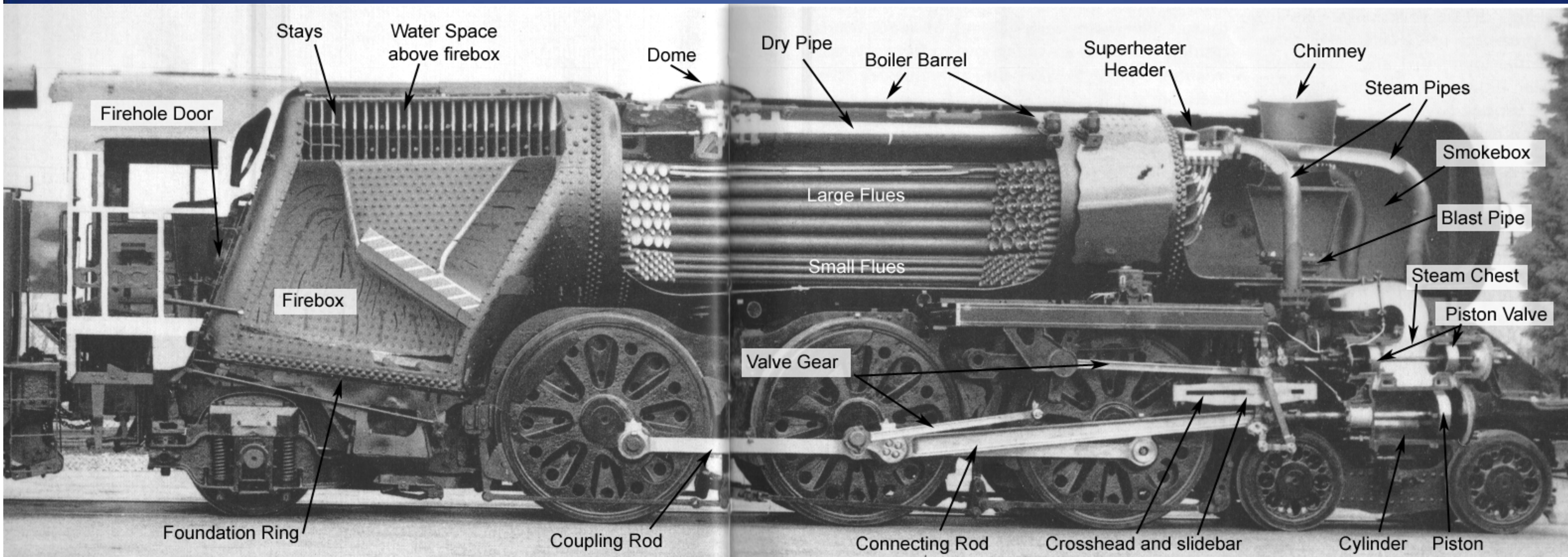
Synopsis

- There is unfinished business in improving the design of steam traction;
- Development continued through the second half of the 20th century by the late A Chapelon and L.D. Porta, with a doubling of the thermal efficiency.
- Economics of steam traction for coal haulage appear much better than diesel or electric traction in developing countries – even with old locomotives.
- Ability to burn a variety of renewable fuels, though this needs further development.
- Future development of steam traction could see efficiency levels approaching those of diesel traction.

Introduction to Steam Traction

- Technology dates from 1803 during the time of the Industrial Revolution in Britain;
- Developed empirically over 150 years with inadequate understanding of scientific principles;
- Steam locomotives were slower, less efficient, less reliable and more polluting than they need have been;
- Steam's ability to operate without adequate maintenance meant that it did operate with inadequate maintenance;
- Steam traction has never had an effective marketing campaign to rival that of GM and other diesel builders.

Inside a Locomotive

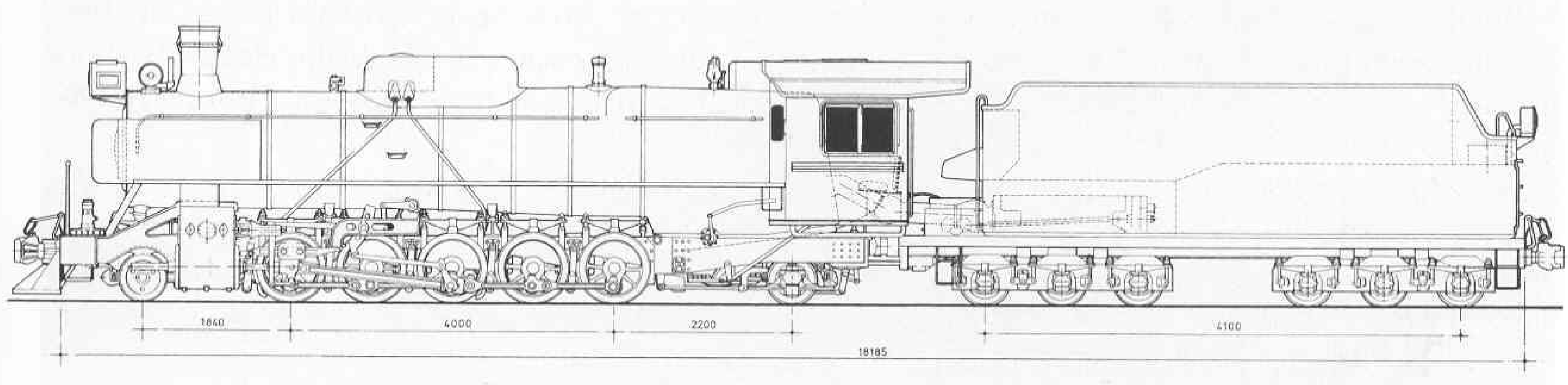


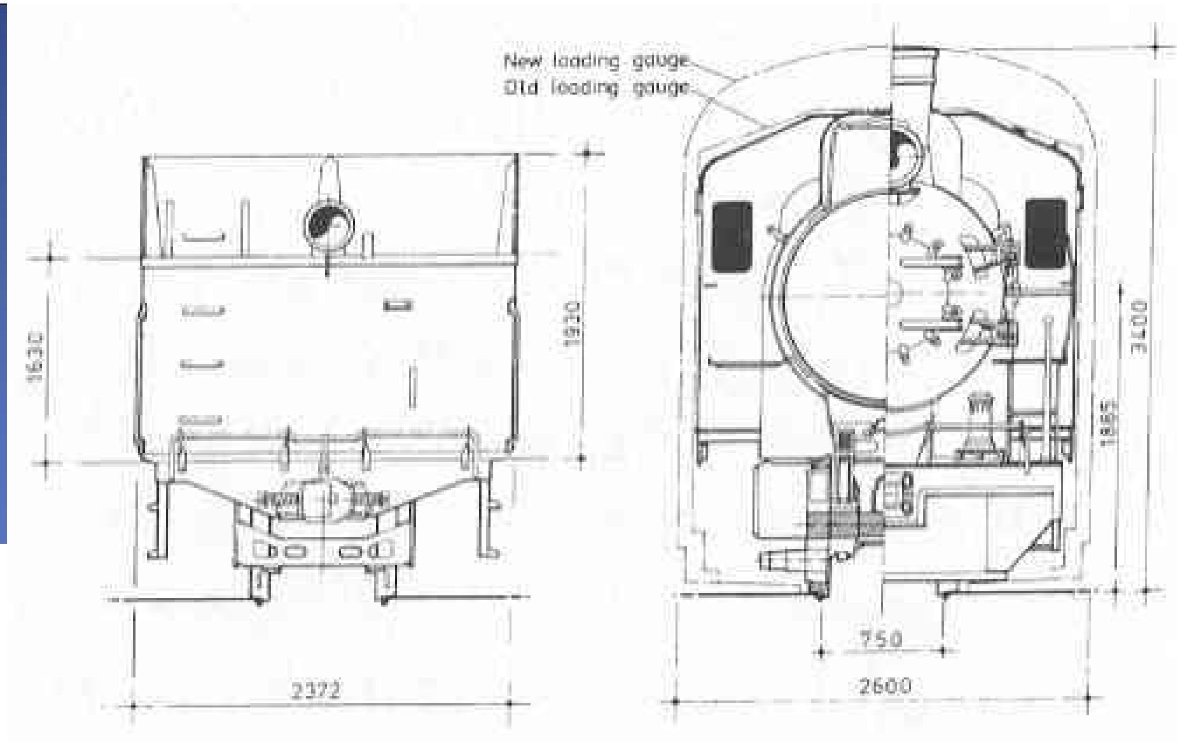
- Open cycle with water as the process fluid
- Fuel burned in firebox with air drawn in from underneath the fire
- Energy is added to the water in the boiler and extracted from the steam in the cylinders
- Spent steam & combustion gases mixed in the exhaust system
- Thermal efficiency <8%.

- Steam locos hauled prodigious loads in the USA (over 15,000t) in the pre-roller bearing era.
- As far as Australia is concerned, development of steam traction ended in the 1920s.
- Rotational speeds were about half of AAR design guidelines.

Porta's locos on the Rio Turbio Railway

- 48 tonne locos built by Mitsubishi in 1956 and 1963
- Power Output increased from 520 kW to 900 kW by Porta;
- Ash clinkering problems overcome by Gas Producer firebox;
- 1700 tonne trains routinely hauled (tested to 3000 tonnes);
- Very high mileage between overhauls.
- All-steam railway until 1997;
- Can sustain 28 dbhp/ton.




New loading gauge
Old loading gauge
1630
1910
3400
1865
750
2372
2600


RFLEP
117

Reliability Record for Rio Turbio Railway's Locos

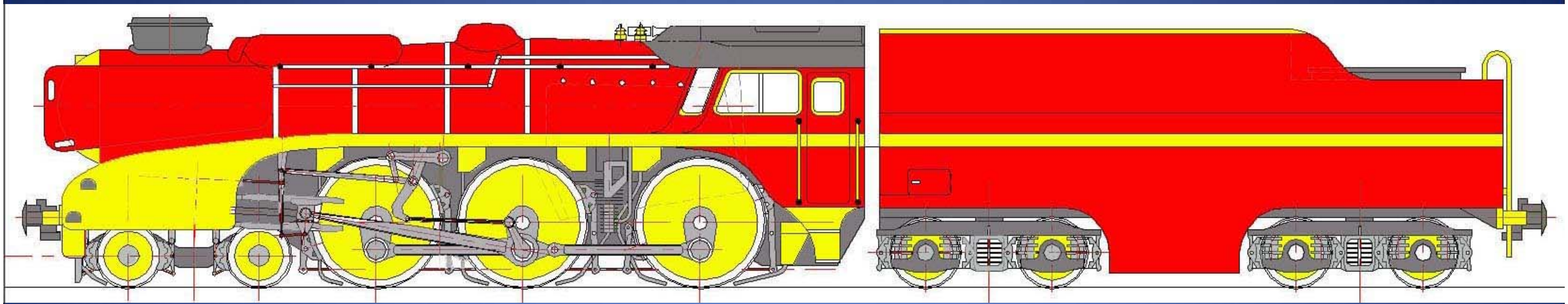
- 480,000 km before driving axlebox (white metal) bearings needed replacing = 180 million revolutions of the 850mm dia driving wheels;
- 70,000 km between tyre profiling = 26 million revolutions;
- No superheater replacements in 500,000 km despite high steam temperatures (>400^{o}C);
- No boiler tube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

David Wardale

Wardale's "Red Devil": rebuild of SAR 1950s Class 25.
Achieved 60% increase in power & 40% reduction in specific coal consumption.

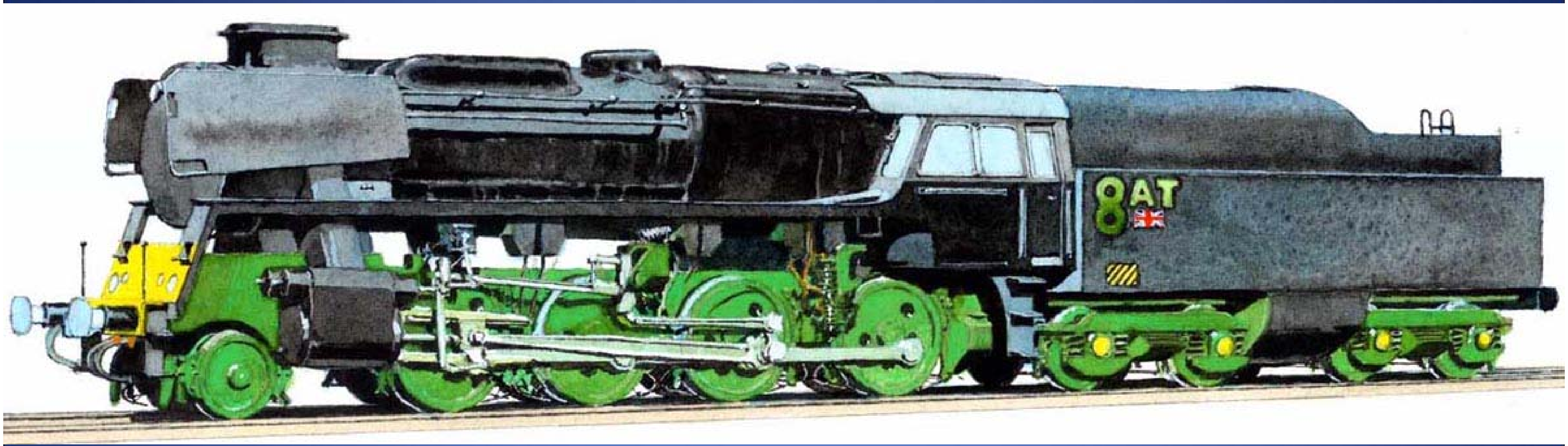
Wardale says that every part of the locomotive could be improved further.

The 5AT – “Second Generation Steam”



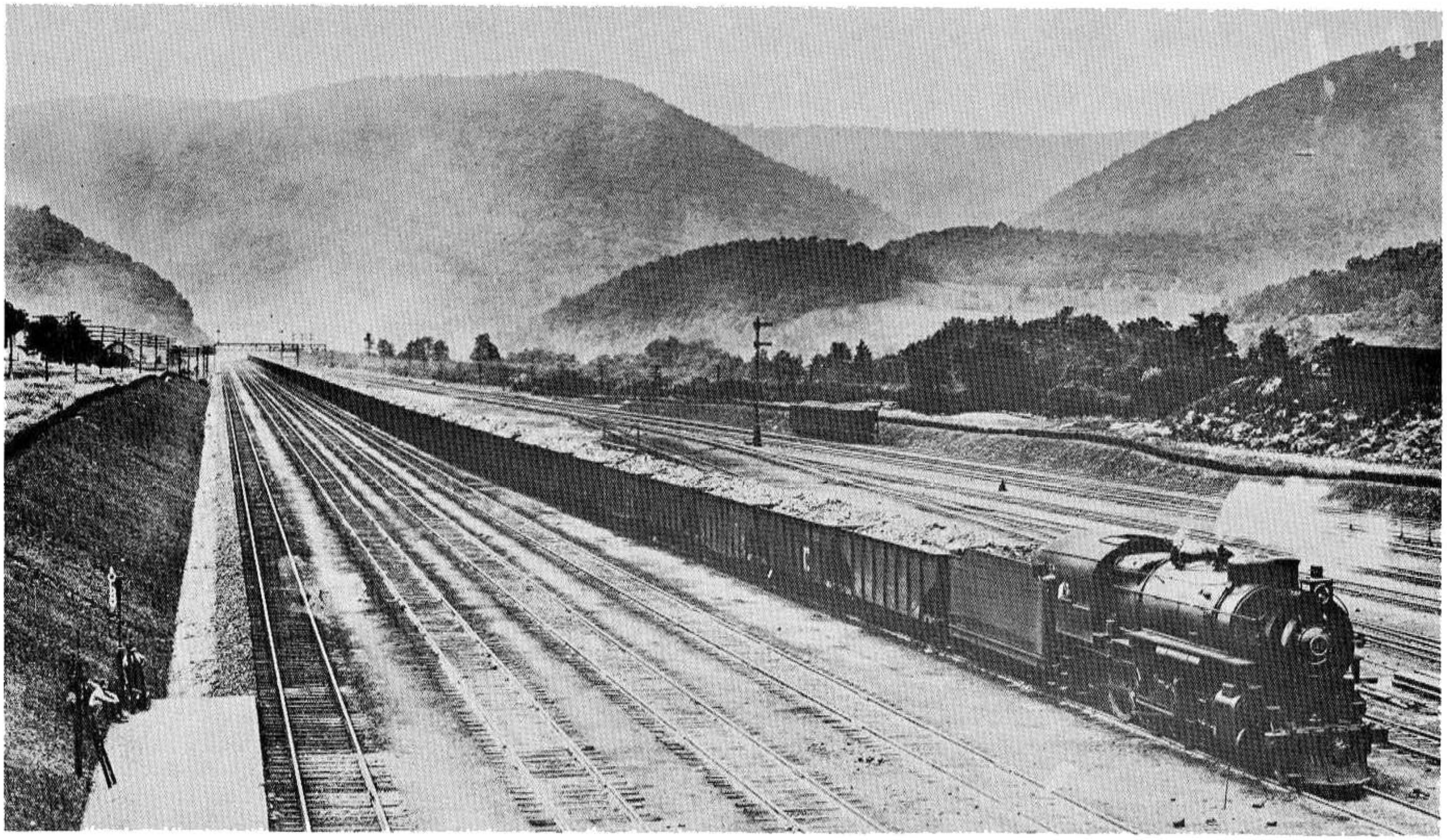
- Conceived by David Wardale;
- First <u>new</u> steam loco design to adopt Porta’s developments;
- Max design speed 200 km/h;
- Target – tour and cruise trains in UK and Europe;
- Fundamental Design Calculations completed;
- Can be modified for freight haulage (using smaller wheels).

The 8AT



- Uses same boiler, cylinders, cab, tender and motion as 5AT;
- 1.325 m dia. driving wheels give 192 kN drawbar tractive force;
- Max power - 2100 kW at drawbar at 120 km/h; 1800 kW at 80 km/h;
- Starting tractive force – 192 kN at the drawbar;
- 21 tonne axle load (including ballast) to control slipping;
- Able to haul 3000 tonne coal trains at 95 km/h on level track.

Is the 8AT Haulage Capacity realistic ??



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

American 2-8-0 locomotive of similar size and "tractive effort" to the 8AT, but with no superheat, low boiler pressure & plain bearings, hauling 6,450 US tons.

Hypothetical Railway Operation

- Single purpose railway for transporting 20 million tons of coal 100km from a mine site to an export terminal;
- Near-level terrain;
- Operates 24/7;
- Max speed 80 km/h, average speed 50 km/h (loaded & empty);
- Single line operation with passing loops;
- Trains loaded and unloaded as soon as they arrive at each end;
- Locomotives remain attached to their trains for servicing.

Haulage Capabilities
Alternative Traction Types

Chinese SS-3 4320 kW Electric Loco

Chinese DF4-D 2940 kW Diesel Loco

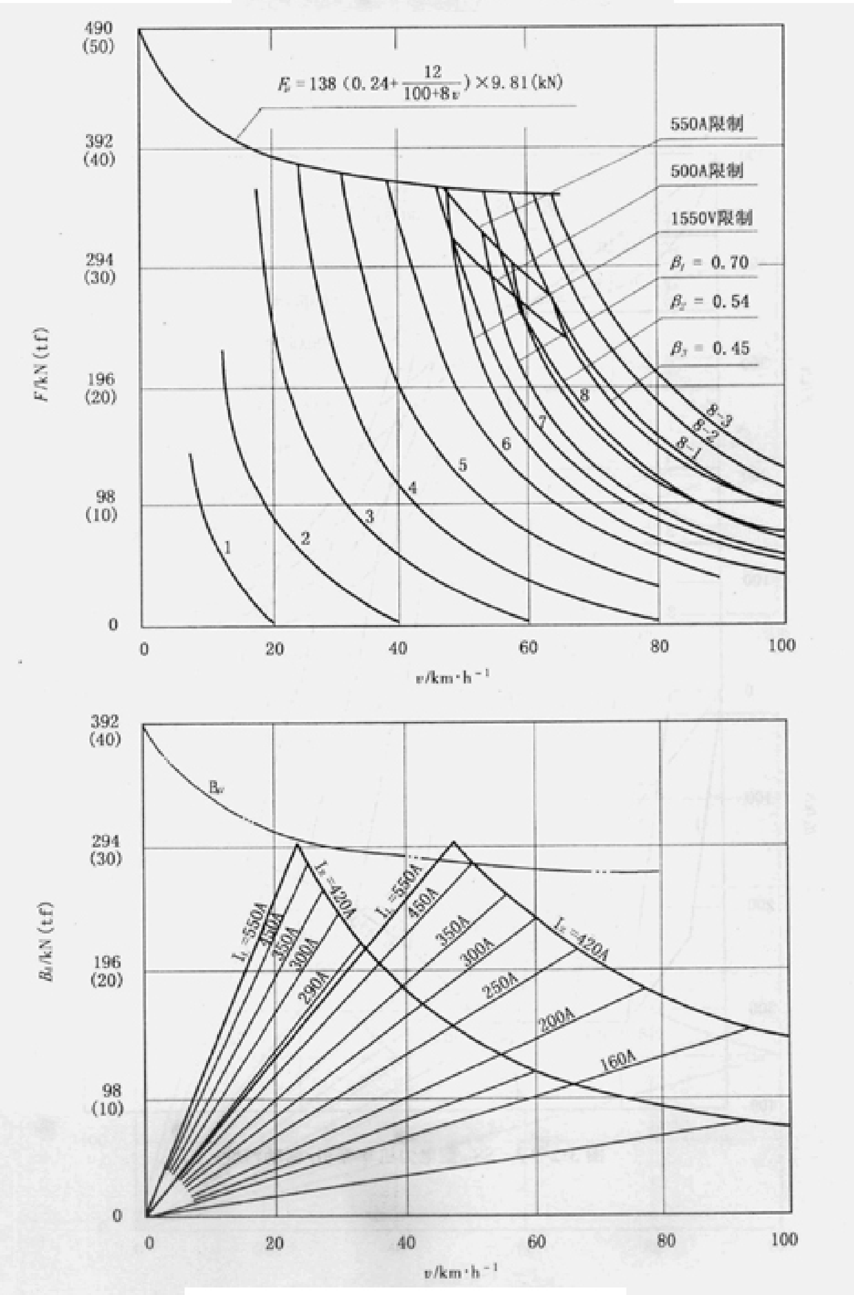
Chinese QJ 2600 kW Steam Loco

8AT 2100 kW Modern Steam Loco

Loco Type	QJ Old Steam	8AT New Steam	Diesel DF4-D	Electric SS-3
Wheel Arrangement	2-10-2	2-8-0	Co-Co	Co-Co
Max Power Output kW (wheel rim)	2600	2100	2430	4320
Max Speed (km/h)	80	100	100	100
Loco Weight excluding tender (tonnes)	134	96	138	138
Axle Loading (tonnes)	20.5	21	23	23
Adhesive Weight (tonnes)	100.5	84	138	138
Starting Wheel Rim Tractive Effort (kN)	287	206	480	487
Continuous Wheel Rim TE at 20km/h	244	163	385	385
Reqd. Starting Friction Coeff.	0.29	0.25	0.36	0.36

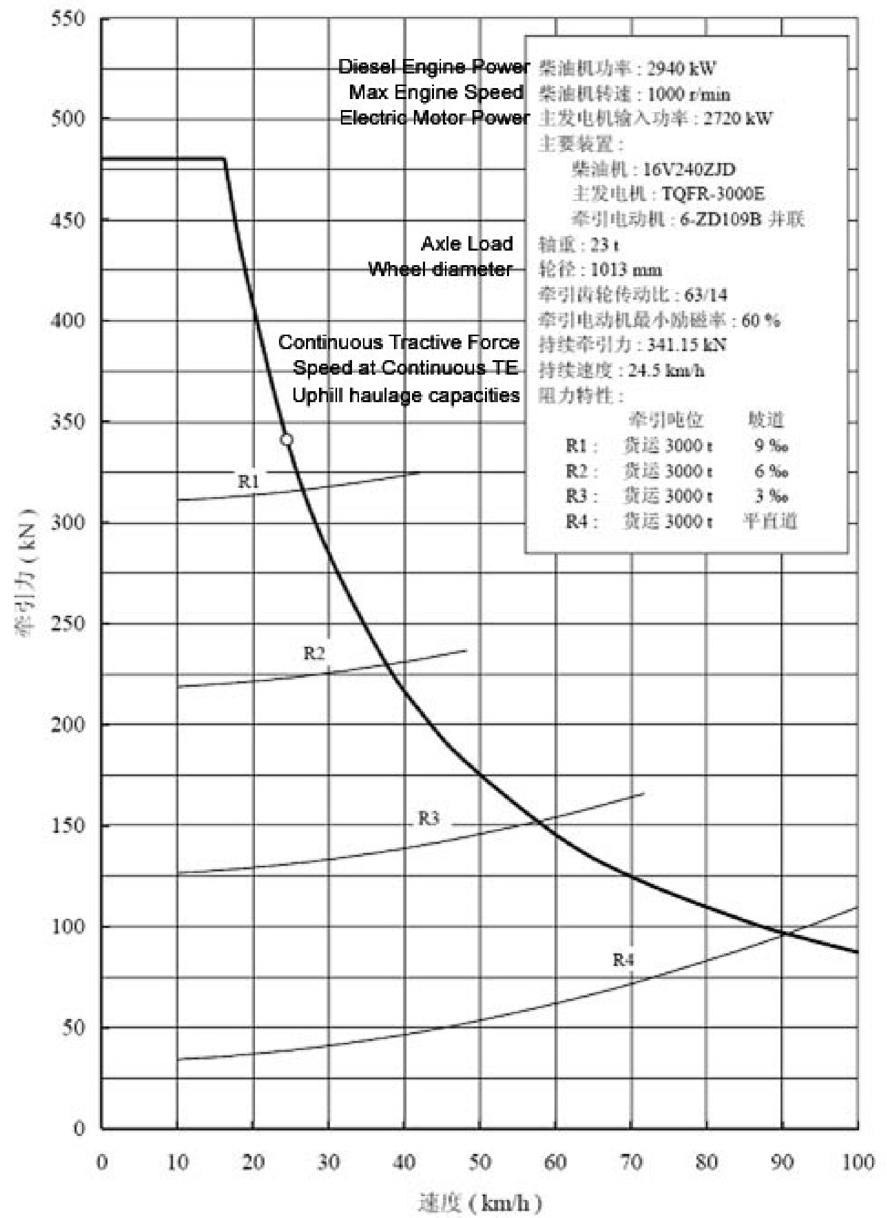
SS-3 and DF4-D - Tractive Force vs Speed Graphs

图 3·2·9·2 SS_3 型电力机车牵引/制动特性



DF4D 货运机车牵引曲线

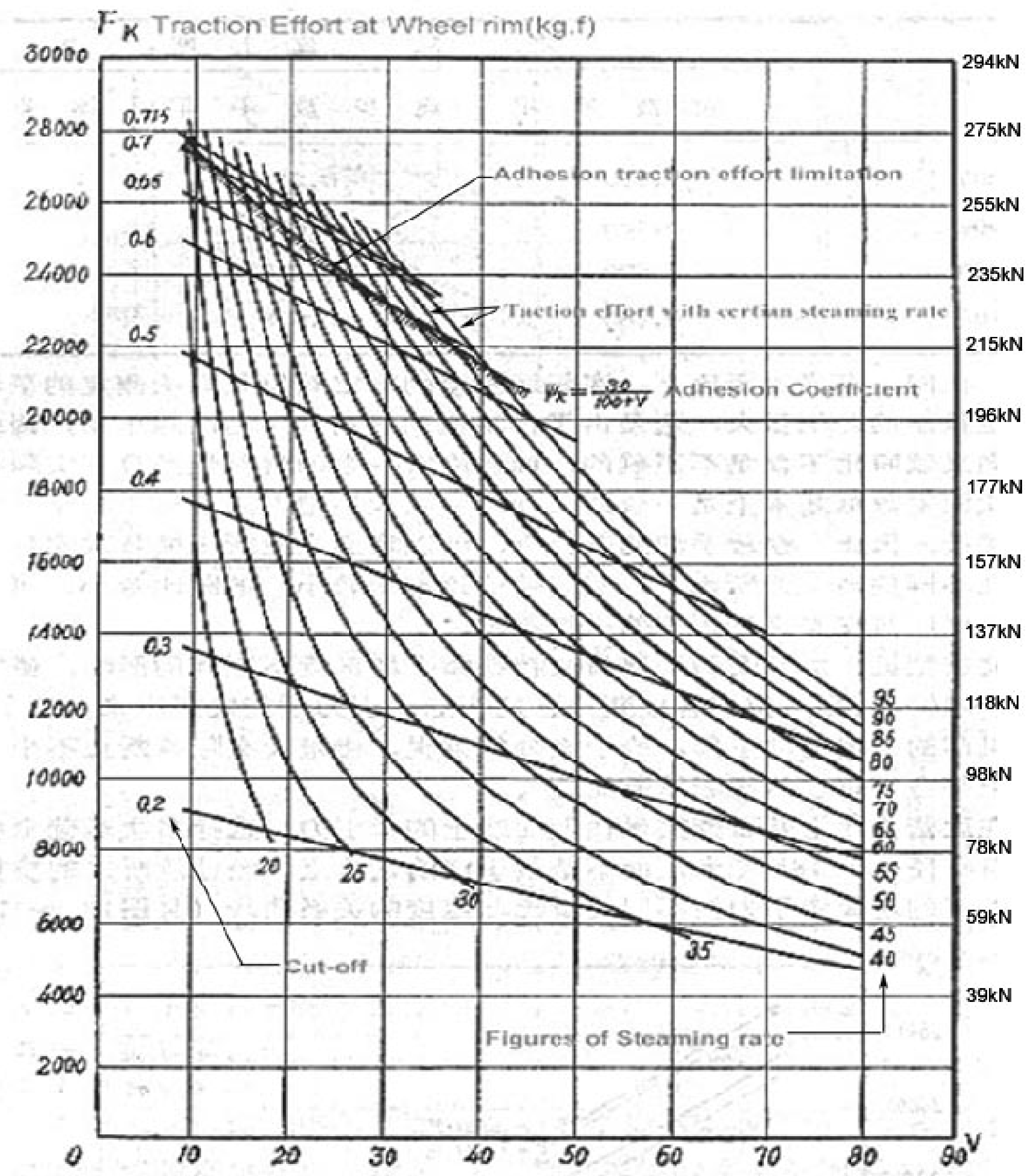
DF4-D Freight Haulage Diagram



QJ Performance Graphs

Tractive Force vs. Speed

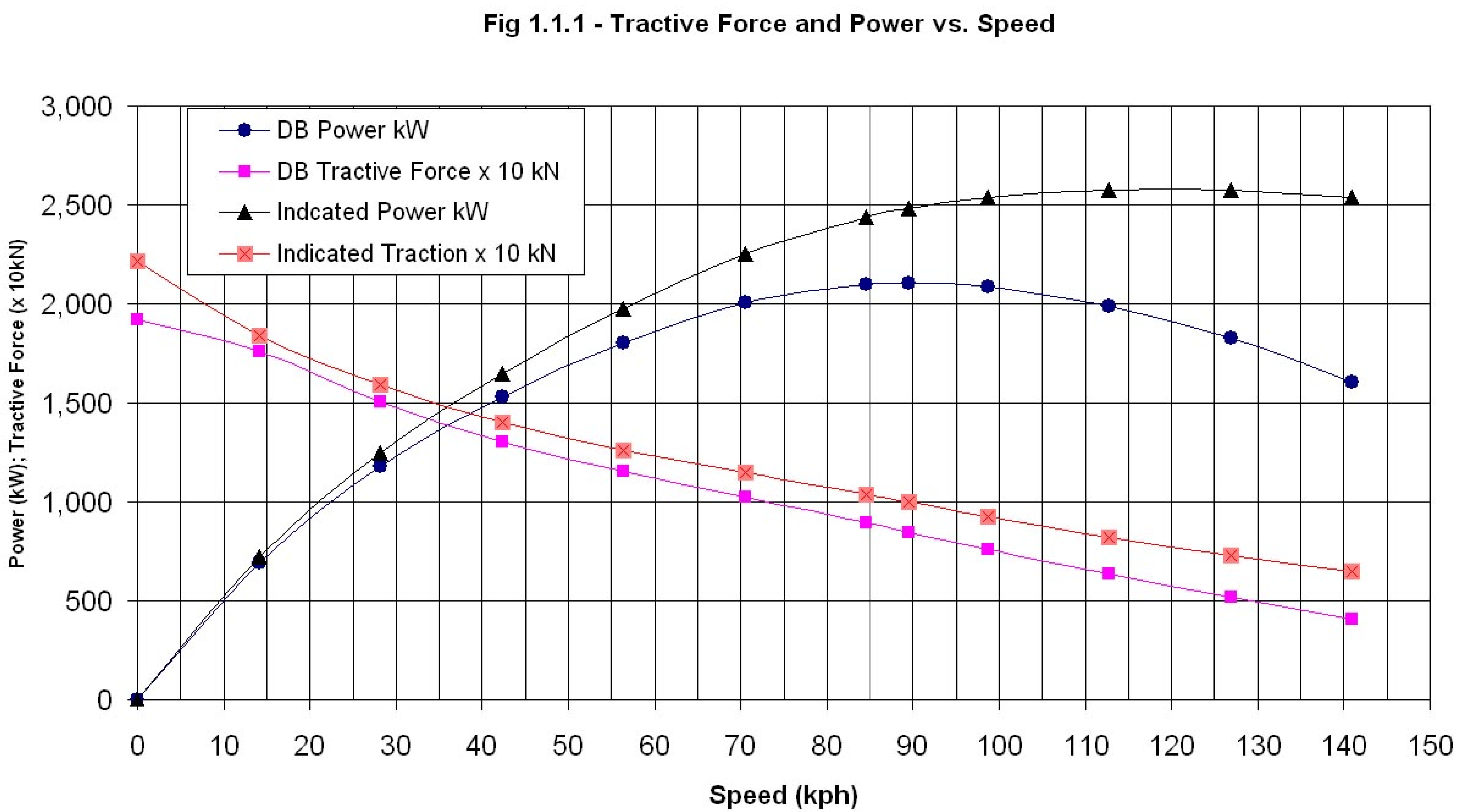
over a range of cut-offs and steaming rates



The curves of traction effort at wheel rim to different steaming rate, cutoff and speed (V)

图17　轮周牵引力F_K按不同遮断比、不同供汽率与速度的关系曲线

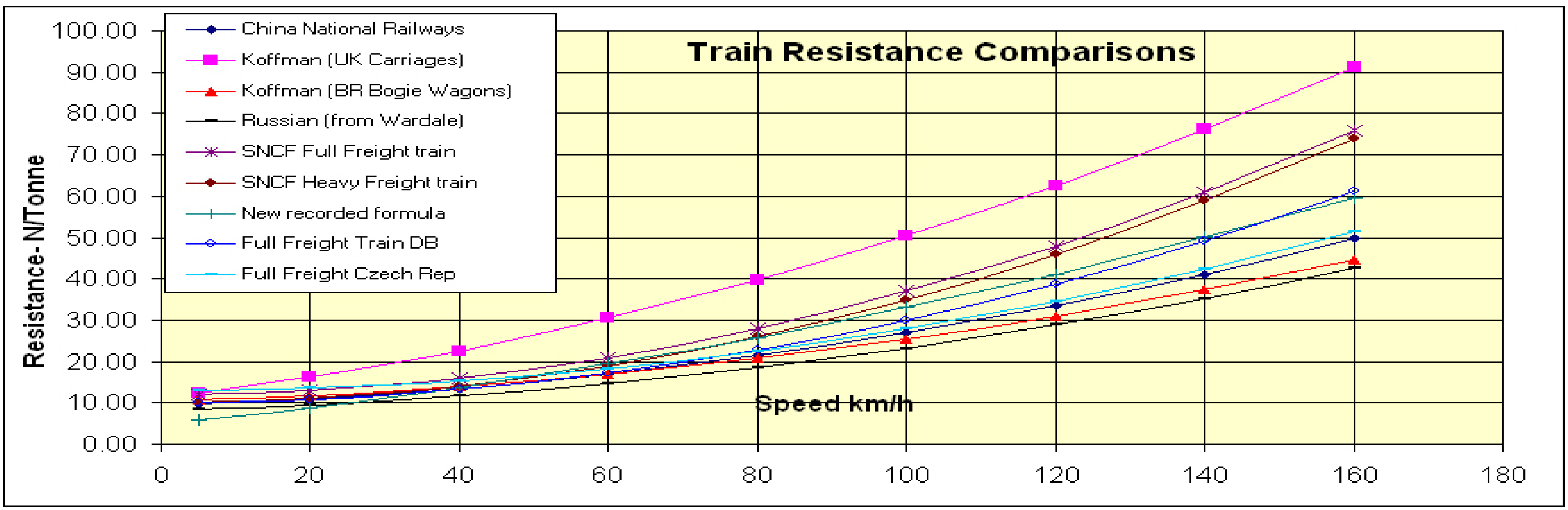
8AT Performance Graphs
Maximum Tractive Force and Power vs. Speed



Comparison of Formulae for Determining Specific Rolling Resistance of Freight 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	$R = 1 + 0.1 \times 0.2 \times (V/10)^2$ 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	



Train Haulage Estimates for Steam, Diesel and Electric Traction

	Old Steam	Modern Steam	Diesel	Electric
Loco Type	QJ	8AT	DF4-D	SS-3
Loco Weight (including tender)	200	170	138	138
Power Rating kW (wheel rim)	2200	1700	2940	4320
Max Design Speed (km/h)	85	100	100	100
Max Continuous Speed with 3,000 t train	85	85	100	100
Max Continuous Speed with 3,500 t train	85	**80**	100	100
Max Continuous Speed with 4,000 t train	**80**	70	95	100
Max Continuous Speed with 5,000 t train	70	60	**75**	100
Max Continuous Speed with 6,000 t train	65		70	100
Max Continuous Speed with 7,000 t train	60	-	65	100
Max Continuous Speed with 8,000 t train		-	60	90
Max Continuous Speed with 9,000 t train	-	-	55	**78**
Max train weight for 80km/h on level track	4,100	3,200+	4,700	8,700
Stalling (5 km/h) Grade for Max Train Size	0.56%	0.48%	0.91%	0.41%
Train (inc loco weight) / Loco Weight Ratio	21.5	19.8	36.5	66.2

Estimating Ideal Train Capacities

We have minimum train capacity $W_t = T_h \times 2 \times d_L / V$

If target annual throughput = 20 million tonnes per year, this equates to 62,500 tonnes per day over a 320 day year.

Assume the railway operation is only **75% efficient**, then target daily throughput = 83,333 tonnes per day or T_h = 3472 t/h x 24 hours.

Thus if the railway length is 100 km, V = 50 km/h and there are 4 passing loops, the distance between loops, d_L = 20 km from which can be calculated the minimum train capacity $W_t = 3472 \times 2 \times 20 / 50 = 2778$ tonnes.

If we assume the use of Chinese C70 wagons with a gross weight of 93 tonnes and tare weight of 23 tonnes, we can deduct that the train needs 40 wagons with a gross weight of 3720 tonnes and net weight of 2800 tonnes.

We can thus use the maximum train loads for each locomotive type to determine the number of passing loops required for each type.

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

Item	units	QJ	8AT	DF4	SS3
Max Haulage Capacity for 80 km/h (loaded)	tonne	**4,100**	**3,200***	**4,700**	**8,700**
Equiv net capacity with 70t net 23t tare wagons	tonne	3,086	2,409	3,538	6,548
Minimum required trains per day	No.	27	34.6	23.6	12.7
Max distance between trains at 50km/h	Km	44.4	34.7	50.9	94.3
Max distance between passing loops	Km	22.2	17.3	25.5	47.1
Theoretical No. of passing loops in 100 km	No.	3.50	4.77	2.93	1.12
Actual minimum number of passing loops	No.	4	5	3	2
Minimum number of trains in transit	No.	5	6	4	3
Distance 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	Tonne	2,778	2,315	3,472	4,630
Minimum number of 70 t wagons	No.	40	34	50	67
Actual train load (net)	Tonne	2,800	2,380	3,500	4,690
Actual train weight (gross)	**Tonne**	**3,720**	**3,162**	**4,650**	**6,231**
Percentage of loco capacity required	%	91%	99%	99%	72%

Estimating Target Train Loading Rates

Activity	units	QJ	8AT	DF4	SS3
Net Train Capacity	tonne	2,800	2,380	3,500	4,690
Train Arrival Frequency	mins	48	40	60	80
Arrival checks and documentation	mins	3	3	3	3
Travel round 1.6 km balloon loop @ 20km/h	mins	5	5	5	5
Position train under loading chute	mins	1	1	1	1
Time to move train clear of loading chute	mins	1	1	1	1
Refill tender water tank	mins	8	6	-	-
Dispatch checks and documentation	mins	inc	inc	3	3
Time available for train filling	mins	30	24	47	67
Required Coal Loading Rate	**t/h**	**5,600**	**6,000**	**4,450**	**4,200**

Unloading Station

More complex than loading system because of the need to take account of the unloading method (rotary or bottom dump) and also locomotive servicing requirements.

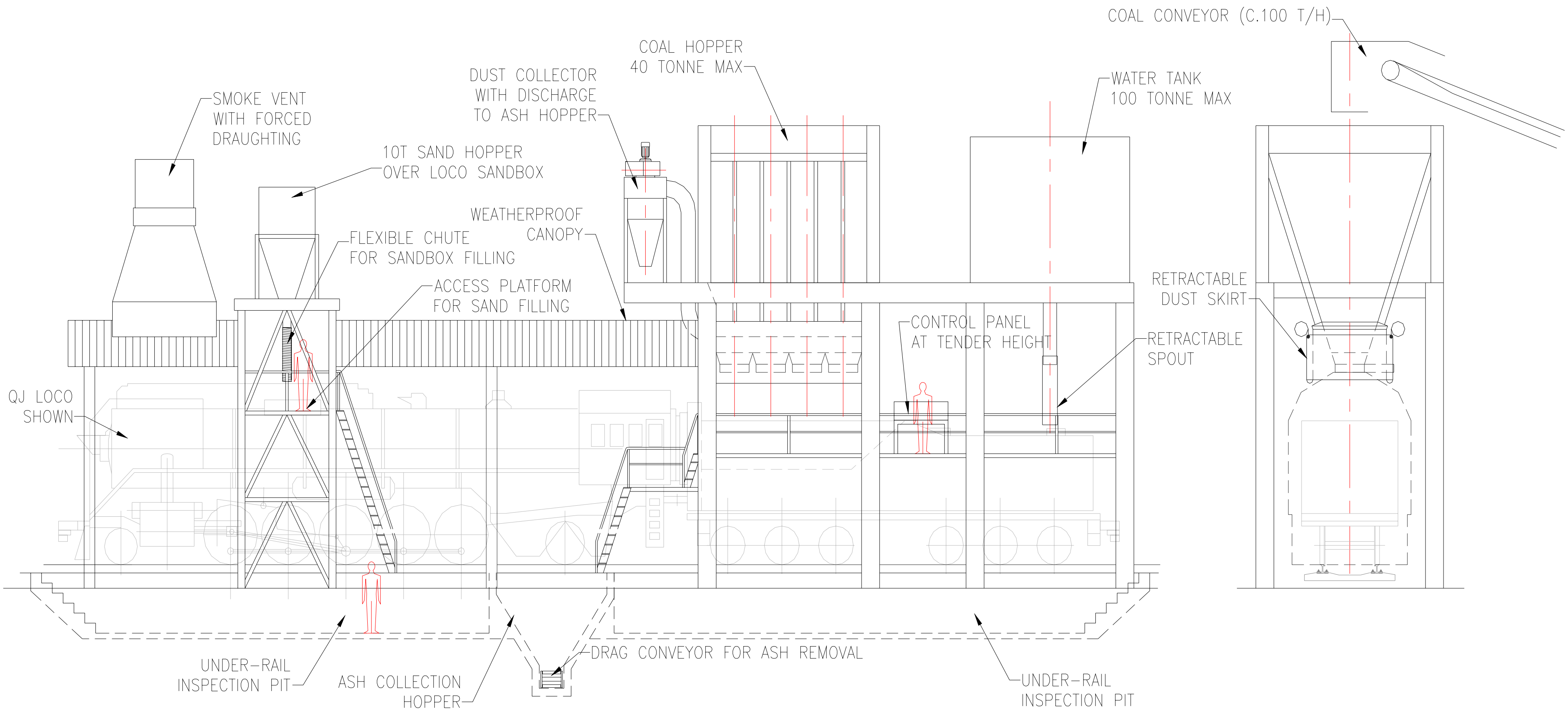
- Steam traction will require ash removal, lubrication, sand refilling etc. at least once per 200 km round trip, and may need refuelling, watering and ash removal at each end of the line.
- Diesels will need refuelling and servicing every 2 or 3 round trips.

Time available for unloading wagons may thus be very short, requiring high unloading rates that may be unachievable with a rotary unloader (limited to ~7,000 t/h max).

Thus it may be necessary to have two (or more) trains at the unloading station at any time.

Loco Servicing Facility

- Loco is serviced, coaled & watered while still connected to train.
- Locomotive coal should be the best available from mine.
- Mechanised coal, sand and ash handling, dust capture, etc.



SCHEMATIC ARRANGEMENT FOR
LOCOMOTIVE SERVICING TOWER

Estimating Rolling Stock Requirements - 1

Minimum Number of Locos and Trains Required to Operate Railway					
Item	**Units**	**QJ**	**8AT**	**DF4**	**SS3**
Reqd. No. of passing loops	unit	4	5	3	2
Number of trains in transit	unit	**5**	**6**	**4**	**3**
Required train mass (net)	tonne	2,800	2,380	3,500	4,690
Required train mass (gross)	tonne	3,720	3,162	4,650	6,231
Number of trains at loader	unit	**1**	**1**	**1**	**1**
Minimum train loading rate	t/h	5,600	6,000	4,450	4,200
Reqd. rotary unloader capacity	t/h	1x5000	1x5000	1x5000	1x7000
Number of trains at unloader	unit	**2**	**2**	**2**	**1**
Available time for loco servicing	mins	43	35	50	25

Estimating Rolling Stock Requirements - 2

Annual Distance Operated

Additional locomotive requirements to cover maintenance can be estimated from maintenance frequency, maintenance downtime, and annual mileage of locomotives. Annual mileage is calculated as follows:

	Units	QJ	8AT	DF4	SS3
Number of wagons per train	Unit	40	34	50	67
Loco standing time at loading station	Mins	48	40	60	80
Number of locos at unloading station	unit	2	2	1	1
Loco standing time at unloading station	Mins	96	80	60	80
Travel time on line (both ways)	Mins	120	120	120	120
Total turnaround time for each loco	hours	6.4	6.0	6.5	7.1
Number of round trips per day per loco	unit	3.8	4.0	3.7	3.4
Distance traveled by each loco per day	km	750	800	738	675
Annual distance per locomotive	km	240,000	256,000	236,000	216,000

Estimating Rolling Stock Requirements - 3

Servicing requirements (from Chinese data):

		QJ	8AT	DF4	SS3
Annual mileage for each locomotive	km	240,000	256,000	236,000	216,000
Major overhaul period	km	250,000	500,000	700,000	1,200,000
Time to complete major overhaul	days	15	15	15	15
Intermediate overhaul period	km	83,333	125,000	233,333	400,000
Time to complete major overhaul	days	6	6	6	6
Scheduled maintenance period	km	22,500	24,000	30,000	40,000
Time to complete scheduled maint.	days	2	2	2	2
No. of major overhauls per year	unit	0.96	0.51	0.34	0.18
Time for major overhauls per year	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 overhauls	days	11.5	9.2	3.5	2.2
Scheduled maintenances per year	unit	10.67	10.67	6.86	4.86
Time under scheduled maint.	days	21.3	21.3	11.9	9.7
Total maintenance time per year	days	47.3	38.2	19.8	14.6
%age of loco fleet under maint.	%	15%	12%	6%	5%
Number of locos to cover maint.	theory	1.18	1.08	0.43	0.23
Number of locos to cover maint.	actual	2	2	1	1

Estimating Rolling Stock Requirements – 4

Summary of Loco Requirements

Minimum number of trains in transit	unit	5	6	4	3
Minimum number of locos/trains at loading station	unit	1	1	1	1
Number of locos at unloading station	unit	2	2	2	1
Number of locos to cover maintenance	actual	2	2	1	1
Stand-by locos to cover breakdown etc	est'd	3	3	2	1
Total Loco Fleet Required	**unit**	**13**	**14**	**10**	**7**

NB The number of standby locomotives takes into account the difference between the actual number of locos provided to cover maintenance & the theoretical number required.

Summary of Wagon Requirements

		QJ	8AT	DF4	SS3
Number of trains in transit	unit	5	6	4	3
Number of trains at loading station	unit	1	1	1	1
Number of trains at unloading station	unit	2	2	2	1
Number of trains to cover maintenance	est'd	1	1	1	1
Total number of trains required	unit	9	10	8	6
Number of wagons per train	unit	40	34	50	67
Total Wagon Fleet Required	**unit**	**360**	**340**	**400**	**402**

Locomotive Cost Comparisons

- Estimate capital cost (including locomotive infrastructure requirements), and amortization period;
- Estimate annual maintenance costs;
- Estimate labour costs associated with loco operation & servicing;
- Estimate water costs for steam locos, including treatment chemicals;
- Estimate fuel consumption and compare with recorded data;
- Estimate fuel costs.

Estimating Capital Costs

- Steam loco fuelling and servicing facilities –
  estimated price $4 million;
- Diesel loco fuelling and servicing facilities –
  estimated price $2 million;
- Electric loco servicing facilities – estimated price $1 million;
- Electrical infrastructure - $530,000 per km (from Chinese data)
- DF4-D and SS-3 cost including shipping ~ $1.25 million (quoted)
- QJ cost including reconditioning and shipping ~ $0.4 million (quoted)
- 8AT steam loco (built in China or similar) ~ $2.5 million (estimated)

Note: Unit cost of 8AT locomotives includes a margin to cover the cost of design, building and testing of a prototype loco.

Estimating Capital Costs

Capital Cost and Depreciation Estimates					
	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 required	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
Depreciation period for infrastructure	years	25	25	25	25
Depreciation period for locos	years	10	25	25	25
Amortized cost of infrastructure	$m/year	0.160	0.160	0.080	2.493
Amortized cost of locomotives	$m/year	0.520	1.400	0.480	0.360
Total Amortization Cost of Traction	**$m/year**	**0.680**	**1.560**	**0.560**	**2.829**

Estimating Loco Maintenance Costs

	Units	QJ	8AT	DF4	SS3
Major overhaul frequency	Km	250,000	500,000	700,000	1.2m
Major overhaul cost	$	45,000	50,000	230,000	287,500
Intermediate overhaul frequency	Km	83,000	125,000	233,000	400,000
Intermediate overhaul cost	$	25,000	25,000	57,500	74,750
Regular maintenance frequency	Km	22,500	24,000	30,000	40,000
Regular maintenance cost	$	5,000	5,000	11,500	13,800
Average loco km per year	Km	111,000	123,000	115,200	123,400
Major maint cost / loco / year	$	19,900	12,300	37,800	29,600
Intermediate maint cost / loco / year	$	16,600	16,500	14,200	11,500
Regular maint cost / loco/ year	$	24,600	25,700	44,100	42,600
Total maint cost / loco / year	$	61,100	54,500	96,200	83,700
Number of locos in fleet	Unit	13	14	10	7
Total cost of maint. per year	**$m**	**0.795**	**0.763**	**0.962**	**0.586**

Estimating Labour Costs

(locomotive operation and servicing)

- Each operating steam loco will require 2 operators;
- Each operating diesel and electric loco will require 1 operator;
- "Old steam" traction will require 8 people for locomotive servicing duties;
- "Modern steam" traction will require 4 people for locomotive servicing duties;
- Diesel traction will require only 2 servicemen at the servicing depot;
- Electric traction will require 6 servicemen, including 2 at the servicing depot and one linesman in each section of track between passing loops;
- Operating & servicing personnel will cost $5,000 per annum.

Estimating Labour Costs

(for locomotive operation and servicing)

	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 ($)	5,000	5,000	5,000	5,000
Labour cost per annum ($M)	**0.360**	**0.330**	**0.135**	**0.165**

Estimating Annual Water Costs - Summary

Item	Units	QJ	8AT
Water consumption Loaded Journey	tonne	30	22
Water consumption Empty Journey	tonne	22	16
Total water consumption per round trip	**tonne**	**52**	**38**
Number of round trips per year	unit	7,143	8,403
Total Water Consumed	tonne	371,863	320,753
Water cost including treatment	$/t	1.30	1.30
Total Water Cost including treatment	**$m**	**0.483**	**0.417**

Estimating cost per kWh of energy output
for each traction type

- Coal has a NAR calorific value of 6500 kcal/kg;
- Calorific value for diesel is the standard 10,200 kcal/kg;
- Representative drawbar thermal efficiencies used for each traction type;
- "Fuel consumption" of electric loco = kWh consumed / kWh supplied;
- Electrical losses from the point of supply to the loco drawbar = 20%;
- Unit cost for electric power $0.08 per kWh and $1000 per tonne for diesel fuel;
- Ex-mine coal price = $30 per tonne.

Note: Export coal price is not used because it includes costs of loading, transportation, storage, blending, loading onto ship, plus profit, which do not apply to coal used for locomotive fuel.

Estimating cost per kWh of energy output for each traction type

	Units	QJ	8AT	DF4	SS3
Energy Conversion Factor	kcal/kW-h	860	860	860	-
Max Drawbar Thermal Efficiency	%	8%	15%	30%	-
Assumed Drawbar 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	$1000	$0.08
Cost of Fuel per kW-h of loco's output	**US cents**	**4.41**	**2.65**	**23.61**	**10.00**

Estimating Fuel Costs per Annum

	Units	QJ	8AT	DF4	SS3
Annual Tonnage Throughput	m.t	20	20	20	20
Distance hauled	km	100	100	100	100
Total net million tonne-km per year	m.t-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
Ratio gross to net tonnes	-	1.33	1.33	1.33	1.33
Total million tonne-km per year (full)	m.t-km/y	2,657	2,657	2,657	2,657
Fuel consumption per million tonne-km	t or kWh	18.39	11.04	2.81	10,426
Total fuel consumed hauling full trains	t or kWh	48,871	29,322	7,474	27.7m
Total million tonne-km per year (empty)	m.t-km/y	657	657	657	657
Fuel consumption per million tonne-km	t or kWh	52.24	31.34	7.99	29,614
Total fuel consumed hauling empty trains	t or kWh	34,330	20,598	5,250	19.5m
Total fuel consumed-full & empty trains	t or kWh	83,201	49,921	12,725	47.2m
Cost of Fuel per tonne or kWh	$	30	30	1000	0.08
Cost of Fuel per year of operation	**$m**	**2.496**	**1.498**	**12.725**	**3.773**

Comparison of Overall Costs per Annum

Notes: 1: Electrical costs exclude maintenance of electrical infrastructure;
2: Extra capital cost of 8AT vs. diesel will be recovered within 3½ years.
3: 8AT costs are likely to be lower than those assumed in this study

	Units	QJ	8AT	DF4	SS3
Amortized Cost of Locos and servicing infrastructure:	$m	0.680	1.560	0.560	2.829
Total cost of maintenance	$m	0.795	0.763	0.962	0.586
Labour cost	$m	0.360	0.330	0.135	0.165
Total water cost incl. treatment	$m	0.483	0.417	nil	nil
Total fuel cost	$m	2.496	1.498	12.725	3.773
Total Operating Cost per Year	**$m**	**4.815**	**4.568**	**14.382**	**7.353**
Cost per tonne of freight hauled	$/t	0.24	0.23	0.72	0.37
Cost per million-net-tonne-km	$/mt-km	2.407	2.284	7.191	3,677
Cost ratio compared to 8AT option	%	105%	-	315%	161%
Cost difference compared to 8AT	$m	0.246	-	9.814	2.785

Sensitivity of Cost Assumptions on Cost Comparisons

Annual costs in $ million.

1: Even with $25 per tonne “carbon tax”, the 8AT would remain cheaper than other options.

2: Diesel costs are very sensitive to fuel prices, because they are largest component. Diesel traction costs are likely to escalate much more rapidly than steam’s.

	QJ	8AT	DF4	SS3
Calculated Operating Cost per annum	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

Conclusions

1. Steam traction is a technically viable option for coal haulage, especially where gradients are not steep;
2. Steam traction is (by a substantial margin) the most cost-competitive option for haulage of coal where coal and labour costs are low;
3. Steam's cost advantage is insensitive to large changes in cost assumptions;
4. Diesel's costs are <u>highly</u> sensitive to increases in fuel costs which are likely to occur in the future;
5. Modern steam offers the lowest operating costs, and its cost advantage will increase as fuel and labour costs rise.
6. Steam's cost advantage is enhanced by the smaller wagon fleet that is needed, and by haulage of shorter trains;
7. Further study is needed in some areas.

New Steam Locos <u>can</u> be built in 21st Century

Switzerland

UK

South Africa

Sincere thanks to:

- Railway Technical Society of Australasia
- EECW Pty Ltd
- Brian McCammon (New Zealand)
- Alan Fozard and John Hind (UK)
- Hugh Odom (USA)

Please contact me for further information.
www.5at.co.uk