Electric locomotives for freight corridors

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1. State-of-the-art electric locomotive technology

1.1 Development of locomotive propulsion systems

Over the last 20 years there has been an impressive development of power electronics which led to the wide spread utilization of asynchronous traction motor (ac) propulsion on all types of locomotives. Delivered in the early 90'ies, the Swiss Loco 2000 were the first mainline locomotives to use high voltage 4'500V gate turn-off (GTO) power switching semiconductors. This enabled to install a power at the wheel of up to 7'000 kW (9'380 hp) on a 4-axle locomotive. The WAP-5 and WAG-9 locomotives were developed at this time and are equipped with this propulsion technology. The power conversion concepts and circuit topologies used on these Indian Railway locomotives are now an industry standard for locomotives running under AC catenaries (15 kV, 16.7Hz and 25 kV, 50Hz). In the mean time, the semiconductor switching devices were developed further and have changed from the GTO-thyristor to the IGBT-transistor. This new device allows more compact converter designs, lower weight and higher overall power efficiency. Today, ac propulsion technology is used on practically all new high power locomotives, even on multisystem locomotives which operate on all four major European catenaries, i.e. 25 kVAC, 15 kVAC, 1.5 kVDC and 3 kVDC.

1.2 Latest electric locomotive development – The TRAXX Platform

The TRAXX locomotive platform was developed as a standard locomotive family to meet the new requirements of train operators on today's liberalized trans-European rail network. The TRAXX platform is derived originally from the large series of >400 German freight locomotives BR 185. Today, more than 1040 TRAXX locomotives have been sold and more than 500 units are in revenue service. Adapted to the European infrastructure, the TRAXX locomotives are 4-axle with an axle load of 20 – 22 tons depending on their application. They operate on routes with typically 22.5t permissible axle loads and are used in freight and passenger services, hauling e.g. heavy 3'300 ton train loads from Germany over the Swiss Alps on 27‰ (1:37) to Italy, see photo 1.

The typical traction concept for freight in Europe is to use a single 4-axle electric locomotive with the heaviest possible train load. Due to congestion the mandatory line speeds given by the network are typically 80-120 km/h. This necessitates a high power at the wheel of 5'600 kW (7'500 hp). These freight trains connect important hubs and operate increasingly long-haul up to 1'000 km and more. They run typically with fixed times schedules. The shunting and distribution of the wagons (short-haul) to their final destination is done either by electric or diesel locomotives. The 4-axle TRAXX DE is designed for this short-haul operation on non-electrified lines within an operating radius of typically 50 – 100 km. The need for large 6-axle diesel locomotives is very much smaller in continental Europe (outside England) in comparison to electric locomotives. Over the last 6 years only approx 80 new 6-axle diesel locomotives in total were put into operation, mainly at small operators with niche services.

1.3 Newest electric locomotives for heavy haul freight

Electric locomotives are an effective solution to heavy-haul operations where high tractive effort and high traction power is needed. Typical examples are in South Africa

(Coal Link and OREX), Australia (Queensland Railways coal trains), Russia and China. In China there is a massive electrification with 25 kVAC catenary with heavy investments in new electric locomotives.

Responding to the specific needs of the LKAB iron ore mines in northern Sweden, a new 6-axle electric locomotive “IORE” was developed to haul 8’200 ton train loads on steep 10 ‰ (1:100) uphill grades at speeds of minimum 35 km/h. On downhill grades and when braking energy is regenerated back to the catenary. Energy consumption and regeneration values are monitored. Typically energy savings amount to 20% of the absorbed energy. This IORE locomotive has a double Co’Co’ configuration with a power at the wheel of 2x5’400 kW (14’470 hp) and is today the most powerful and most modern electric heavy-haul locomotive in operation worldwide, see photo 2. It is equipped with the same propulsion concepts as the TRAXX locomotives, however, adapted to the Co’Co’ configuration and to axle loads which can be ballasted from 25 to 30 tons.

Photo 1 (left): TRAXX AC locomotives (BR 185) of Railion Germany.

Photo 2 (right): IORE locomotives of LKAB in northern Sweden

2. Comparison of electric and diesel traction

2.1 General considerations

Electric traction was developed to obtain higher traction power at the wheels compared to locomotives with thermal engines. Whilst in North America development ceased in the 70’ies, electric traction was pursed vigorously in Europe to this date. Today this technology is not available in North America and operators cover their needs of electric locomotives from abroad, e.g. with the recent deliveries of the ALP 46 to New Jersey Transit.

The power efficiencies along the power supply chain are shown in following Table 1:

Table 1. Power source and power efficiency	Electric traction	Diesel traction
Energy sources	Coal, gas, hydro, nuclear, oil, …	Oil
Thermal efficiency (approx): a) Combined cycle power plant	 a) 60%	 --

b) Combined cycle power plant with waste heat utilization	b) 85%	--
Electric generation and transmission	High efficiency	
Diesel engine thermal efficiency (approx)	--	40%
Loco power conversion efficiency (average)	85 – 87%	83-84%
Overall efficiency	**higher**	**Lower**
Energy savings by regeneration: a) Flat countries (average) b) Mountainous countries (average)	 a) 5 – 7% b) 20 – 30%	none

Power supply - electric locomotives. The power source for electric locomotives is many: hydro, nuclear and thermal (oil, coal, gas) power plants. The incremental need of additional electric power for electric locomotives on freight corridors must be compared to the incremental power efficiency to supply this power. Modern combined cycle plants have a high thermal efficiency of up to 60% and up to 85% when combined with waste heat utilization. Power plant electric generation and transmission for 25 kVAC catenaries have in general low power losses. The average power efficiency of the locomotive itself is typically 85-87% depending on its specific design. When braking the train, energy is fed back to the catenary (and grid) and can be used by other locomotives or other consumers on the grid. Energy savings by regeneration are typically in the range of 5 – 7% in a flat country (e.g. Finland) and 20 – 30% in a mountainous country (e.g. Switzerland).

Electrification. The cost of electrification is typically small compared to the total investment of new railway lines and is typically only 5% of the total investment costs. It is even much lower if complex infrastructure is required, e.g. bridges and tunnels. Catenary wires are very durable and can average 10 Mio locomotive passings or more for freight operations. The life of electrification infrastructure, e.g. substations, is in the range of 50 … 100 years. Also the maintenance costs of modern catenary systems are low. The amortization of new electrification on well frequented lines is thus short considering that diesel fuel costs are in average increasing and are already very much higher than electric energy per transported gross-ton-km. Also to be considered is the national security of energy supply.

Power supply – diesel locomotives. In contrast to the above, thermal efficiency of modern locomotive diesel engines is approx. 40%. This value is obtained by new technologies such as high power density (via high turbocharger boost), high turbocharger efficiencies, direct fuel injection with electronic timing control and high compression ratio and low thermal and mechanical losses. The resulting power at the shaft of the diesel engine is then converted to traction power at the wheels. On the TRAXX DE this conversion efficiency is approx 84%. In general, the conversion efficiency on a diesel-electric locomotive is lower compared to an electric locomotive due to the high cooling power needed to dissipate the diesel engine heat.

Diesel emissions. Additionally, the diesel engine has critical issues of noise, vibrations and exhaust emissions particularly when it operates in populated areas. For these reasons, national and international standards are specifying a massive reduction of their emissions of NOx, CO, HC and particle matter, e.g. in Europe with EU Stage IIIb requiring particle filters starting 2012. It is yet unclear how to fulfill these requirements within the same locomotive overall performance envelop. Particle filters are installed so far in Europe on the new diesel-hydraulic shunting locomotive Am 843 of the Swiss railways, adding significantly to cost and weight.

Double stack operation. To improve the efficiency of train operations locomotives must haul heavy trains and increasingly bulky intermodal trains. In the latter case, double stack trains greatly improve the competitiveness of the railway. Double stack trains are also possible with electric traction, see Fig. 3a. Double stack trains are operated under the catenaries of the North-East Corridor in USA. The pantographs of the modern ALP 46 of New Jersey Transit are adjusted to this high catenary, see Fig. 3b. Also in China, double stack container trains operate under 25 kVAC catenaries. The introduction of double stack trains on electrified dedicated freight corridors will depend on operational considerations, e.g. maximum speed and operation on feeder lines to the freight corridor. Potentially, the high reaching pantographs can also be installed on existing locomotives.

Electric locomotives – high power capability. The biggest advantage of electric traction is the much higher available power at the wheels. Due to the heavy diesel combustion engine, the power for the diesel locomotive is much lower than on an electric locomotive for a given axle load. This is seen in the comparison of the diesel-electric TRAXX DE with the electric TRAXX AC locomotive. Hereby it is to be noted, that the TRAXX DE is the most powerful diesel 4-axle locomotive available in its weight class of 84 tons. It utilizes a “light” high-rpm MTU or CAT diesel engine which has a significantly higher output power per weight than typical American diesel engines. As seen in the table below, the electric TRAXX locomotive is three times more powerful than the diesel locomotive.

4-axle	Axle load	Length	Diesel engine	Power at wheel
TRAXX AC	21t	18.9m	----	5’600 kW / 7’500 hp
TRAXX DE	21t	18.9m	2’200 kW / 2’950 hp	1’840 kW / 2’465 hp

Note also, that electric locomotives are rated by their power at the wheel, whilst diesel locomotives are rated by the diesel engine power. Hence, the power at the wheels of diesel locomotives is much lower than the rated power.

Adhesion. The maximum possible tractive effort of both electric and diesel locomotives is dependent on many factors, e.g.

1. *Axle load and axle configuration (4- and 6-axle)*
2. *Wheel / rail running quality*
    - Wheel guidance, e.g. avoiding lateral slip
    - Load transfer, which can be minimized by appropriate bogie design
    - Wheel material, allowing optimal wheel surface conditioning
3. *Torque control schemes*
    - Bogie or single axle control
    - Control schemes, allowing wheel surface conditioning without excessive wheel slip
    - True speed measurement

Considering the above design influences, a very high adhesion coefficient of approx. 46% is reached at ideal conditions. More important, however, is to obtain a high adhesion at real operating track conditions, i.e. with contaminated track surfaces with rust, dampness, leaves and non-perfectly aligned track geometry. The Flexifloat bogies of the WAG9 and TRAXX locos allow axle loads of 20 – 30 tons and have excellent ride quality also on non-optimal track. Additionally, the TRAXX locomotives have novel control schemes that can clean contaminated track and thus raise the adhesion coefficient from one wheelset to the next. Considering the influence of the wheel-track interaction, the 4-axle locomotive has a slight advantage against the 6-axle locomotive with regards to adhesion.

Remote operation. Both electric and diesel locomotives are used today in remote operation with communication either by cable or radio. As reference, Locotrol is used on the electric trains at Queensland Railways. Also, the Loco 2000 was equipped with Locotrol for operation over the Swiss Alps. For various reasons, e.g. lower overall cost, Locotrol is now replaced by a second driver.

2.2 Characteristics of electric and diesel locomotives in comparison

In the below various electric and diesel locomotives are compared for the following train loads on the freight corridors

a) Train load of 6'000 tons on 5‰ (1:200)

b) Train load of 7'200 tons on 5‰ (1:200)

The locomotives types are:

a) TRAXX AC: This is the standard 4-axle locomotive as used in Europe for freight on 25 and 15 kVAC. It has 5'600 kW (7'500 hp) at the wheel, 300 kN starting TE and weighs 84 tons (21t/axle). This corresponds to an adhesion coefficient $\mu = 0.36$.

b) TRAXX AC-H: This is a potential derivative of the above 4-axle locomotive, however, ballasted to 30t/axle. Based on the same adhesion coefficient the starting TE is 429 kN.

c) IORE: This is the locomotive used on the iron ore line in northern Sweden. Each 6-axle section has a power at the wheels of 5'400 kW (7'235 hp), 600 kN starting TE and weighs 180 tons (30t/axle). It uses the same Flexifloat bogie concept as the WAG-9. In comparison to a 2-axle bogie, it attains on the average a slightly lower adhesion coefficient due to increased load transfer and increased lateral wheel slip in curves due to the longer wheel base. The adhesion coefficient used is $\mu = 0.34$.

d) WAG-9: This is the 6-axle freight locomotive of Indian Railways. It has a power at the wheels of 4'500 kW (6'000 hp), 460 kN starting TE and weighs 123 tons (20.5t/axle). This results to a maximum adhesion coefficient of $\mu = 0.38$.

e) TRAXX DE: This is the 4-axle diesel-electric locomotive of the TRAXX platform with a 2'200 hp engine. It has 1'840 kW (2'465 hp) at the wheel, 270 kN starting TE and weighs 84 tons (21t/axle). This corresponds to an adhesion coefficient $\mu = 0.33$. Principally, this locomotive has the same adhesion capability as the electric TRAXX locomotives; however, an overall design optimum was found with a slightly lower TE.

f) DE-4400 hp: This is a potential 6-axle diesel locomotive with a 4'400 hp engine based on the design concepts of the TRAXX DE, however, extended to a Co'Co' locomotive. It has 2'750 kW (3'685 hp) at the wheel, 500 kN starting TE and weighs 150 tons (25t/axle). For comparison, the same Flexiloat bogie is assumed as the IORE locomotive, thus the adhesion coefficient is $\mu = 0.34$. This locomotive overall performance is slightly higher than the new Euro 4000 of Vossloh which has a 4'258 hp engine.

g) DE-6000 hp: This is a potential 6-axle diesel locomotive similar to the above DE-4'400 hp, however, with a 6'000 hp engine. It has 3'745 kW (5'029 hp) at the wheel, 600 kN starting TE and weighs 180 tons (30t/axle).

The locomotive data is listed in the below Table 2.

Table 2.		**TRAXX AC**	**TRAXX AC-H**	**IORE**	**WAG-9**	**TRAXX DE**	**DE-4400hp**	**DE-6000hp**
Configuration		Bo'Bo'	Bo'Bo'	Co'Co'	Co'Co'	Bo'Bo'	Co'Co'	Co'Co'
Axles		4	4	6	6	4	6	6
Axle load	tons	21	30	30	20.5	21	25	30
Mass	tons	84	120	180	123	84	150	180
Diesel power	kW hp	-- --	-- --	-- --	-- --	2'200 2'950	3'285 4'400	4'478 6'000
Length	m	18.9	18.9	22.9	20.562	18.9	~ 22	~ 23
Power at wheel rim	kW hp	5'600 7'500	5'600 7'500	5'400 7'235	4'500 6'000	1'840 2'465	2'750 3'685	3'745 5'029
Power at wheel per axle	kW hp	1'400 1'876	1'400 1'876	900 1'206	750 1'005	460 616	458 614	624 836
Power at wheel per locomotive weight	kW/t hp/t	67 89	47 63	30 40	37 49	22 29	18 25	21 28
Starting tractive effort	kN	300	429	600	460	270	500	600
Max. adhesion coefficient	μ	0.36	0.36	0.34	0.38	0.33	0.34	0.34

In the following chapter the performance of these locomotives for the above defined trains is shown and compared.

3. Locomotive hauling performance in comparison

The tractive effort diagrams of all types are shown in figure 1 together with the train resistance curves for the loads of 6'000 and 7'200 tons respectively. These train resistance curves can be considered to be an average; mixed freight trains could have higher values and dedicated high performance freight cars (e.g. with Scheffel bogies in South Africa) have lower values. It is evident that only the electric and diesel locomotives with high TE can haul the trains. However, using two locomotives in multiple operations, see figure 2, all of the above locomotives can haul the trains, however, at different maximum speeds. This depends on the available power at the wheels. The highest speed is obtained by the electric locomotives due to their high power capability.

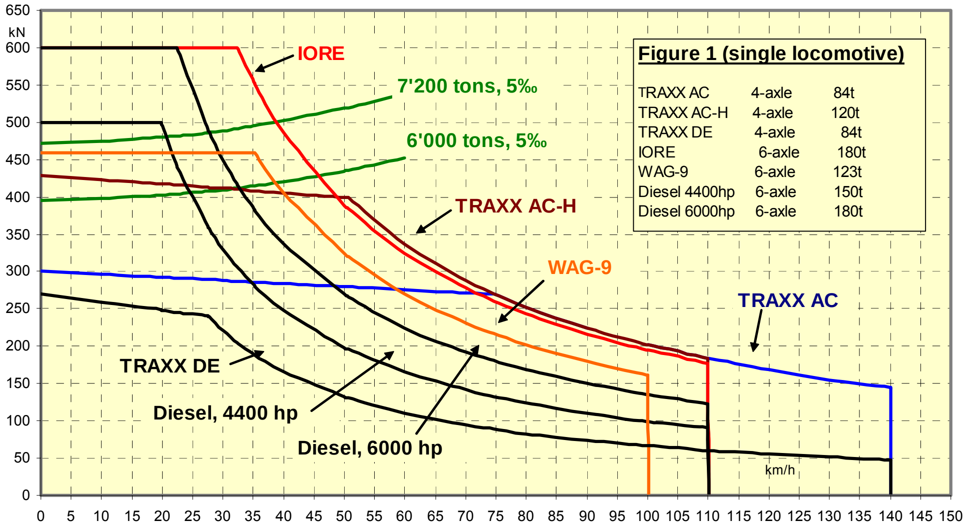

Figure 1: Tractive effort versus speed for a single locomotive.

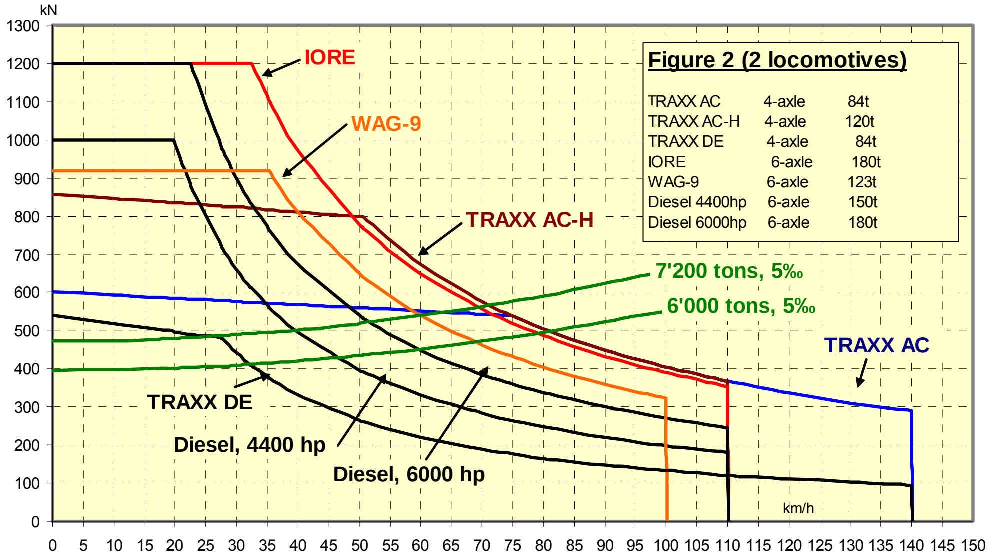

Figure 2: Tractive effort versus speed for two locomotives in multiple.

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The situation changes significantly, when the specified trains must operate at a high speed of e.g. 100 km/h. Here at high power at the wheel is needed, i.e. minimum 16 MW and 19 MW for the train loads of 6'000 and 7'200 tons respectively. Correspondingly, for the 7'200t train the smallest number of locomotives, i.e. 4 units, is obtained with electric TRAXX AC (and IORE) locomotives see figure 3. The DE-6000 hp locomotive requires minimum 6 units, see figure 4.

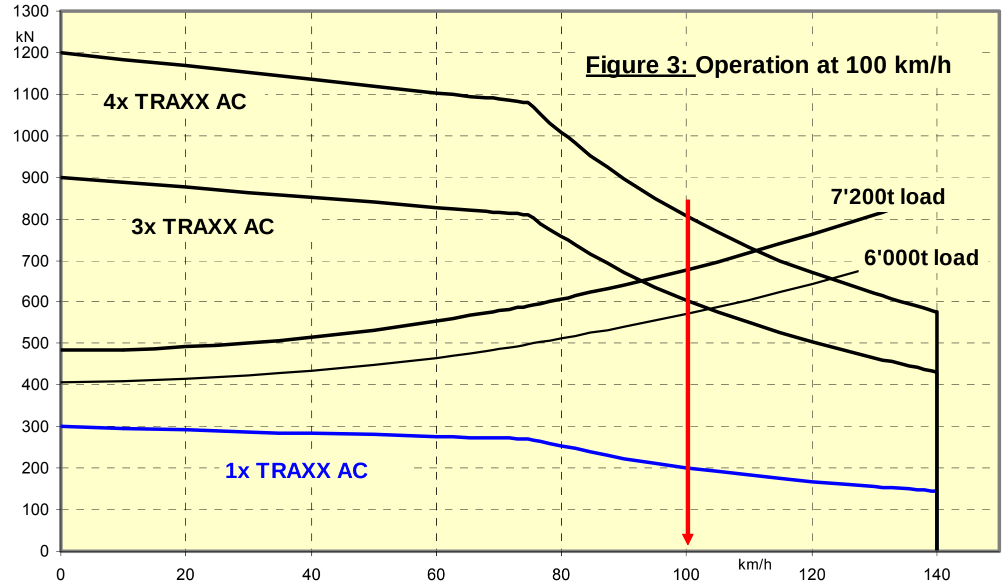

Figure 3: Three TRAXX AC locos can haul the 6'000 ton train load on 5‰ (1:200) at 100 km/h. Four TRAXX AC locos are ample for the 7'200 ton train load.

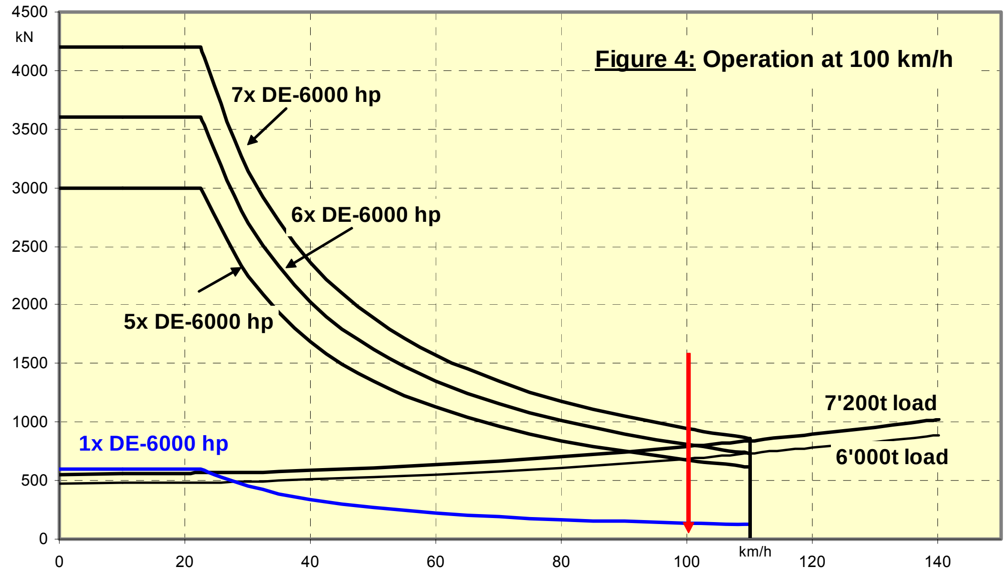

Figure 4: A minimum of 5 DE-6000 hp are needed for the 6'000 ton and minimum 6 DE-6000 hp are needed for the 7'200 ton train load on 5‰ (1:200) at 100 km/h.

Electric locomotives for freight corridors

The results of the analysis are given in the following Table 3:

Table 3.		TRAXX AC	TRAXX AC-H	IORE	WAG-9	TRAXX DE	DE-4400hp	DE-6000hp
Maximum speed with a single locomotive on 5‰								
Max speed with 6'000t	Km/h	--	(30)	45	38	--	25	32
Max speed with 7'200t	Km/h	--	--	38	--	--	(20)	28
Maximum speed with two locomotive on 5‰								
Max speed with 6'000t	Km/h	80	80	78	68	32	46	59
Max speed with 7'200t	Km/h	60	70	68	60	25	39	52
Operation at 100 km/h on 5‰								
6'000t	**locos**	**3**	**3**	**4**	**4**	**10**	**7**	**5**
Mass locos/train load	ratio	4.2%	6%	12%	8.2%	14%	18%	15%
Length locos/length load	ratio	6%	6%	9%	8%	19%	15%	12%
Powered axles	axles	12	12	24	24	40	42	30
7'200t	**locos**	**4**	**4**	**4**	**5**	**11**	**8**	**6**
Mass locos/train	ratio	4.7%	6.7%	10%	8.5%	13%	17%	15%
Length locos/length load	ratio	8%	8%	9%	10%	21%	18%	14%
Powered axles	axles	16	16	24	30	44	48	36

From the above it is visible that there are substantial advantages of electric versus diesel traction. Below are the key results:

1. **Higher speed:** Both the TRAXX AC with 21t axle load and the IORE locomotives with 30t axle load haul the 6'000 and 7'200 ton train loads at significantly higher speeds in double traction than two DE-6000 hp locomotives.
2. **Smaller number of locomotives for 100 km/h:** The TRAXX AC locomotive requires only 3 units for the 6'000 ton loads and 4 units for the 7'200 tons. The IORE requires 4 units. The DE-6000 hp needs 5 and 6 units respectively.
3. **Power utilization at 100 km/h:** The locomotive weight is non-productive mass and should be as low as possible. For the TRAXX AC locomotives the total locomotive weight is less than 5% of the train load. The DE-6000 hp locomotives have a much higher weight of 15% of the train load. Hence, the power needed at the wheel of the DE-6000 hp to run the train (and pull its own unproductive weight) is approx 10% higher than the TRAXX AC.
4. **Train length utilization at 100 km/h:** In the same way as above, the TRAXX AC locomotives add up to a train length of 6-8% of the train load (assumed 1'000m length of train load). The DE-6000 hp locomotives add up to 12-14% of the train load length. Hence, with a train length limited by the sidings, the TRAXX AC can haul approx 6% longer train loads than the DE-6000 hp.
5. **Service and maintenance:** On a modern locomotive service and maintenance are to a large extent determined by the mechanical parts subjected to wear and tear. The state-of-the-art electric locomotive is a "solid-state" machine and has only few moving parts and these are primarily in the bogie. Hence, the number of powered axles is an important indicator of required maintenance costs. The TRAXX AC needs only 12 and 16 powered axles to pull the 6'000 and 7'200 ton train loads at 100 km/h respectively. The IORE needs 24 powered axles. The DE-6000 hp needs 30 and 36 powered axles respectively.

6. **Wheel life:** There are no inherent weight restrictions on the electric locomotives. Therefore, these locomotives are equipped with large wheels of 1250mm diameter. In this way a long wheel life of more than 1’000’000 km is obtained at typical operations in Germany. On the other hand, diesel locomotives are critical in weight and size. This is one of the reasons why smaller wheels are used, which must be replaced more often. Wheel replacement adds significantly to maintenance costs.
7. **Track forces:** Whilst the TRAXX AC requires much fewer locomotives than the diesel alternatives, they also have a much lower axle load of 21t compared to the 30t with the DE-6000 hp. This greatly reduces wear and tear on wheels and tracks.
8. **WAG-9 versus the DE 4400/6000 hp:** As seen from table 2, also the WAG-9 is more advantageous than the DE-4400 hp and the DE-6000 hp.
9. **High tractive effort:** If the objective is to have locomotives with high tractive effort, then a high axle load is needed. The electric locomotives TRAXX AC-H and IORE provide a high tractive effort with least amount of powered axles at a given speed.

4. Summary

Based on the state-of-the-art technologies of electric and diesel locomotives various locomotive types are compared for operation on the DFC with train loads of 6’000 and 7’200 tons. In overall, many features speak for electric traction. It is evident that a high axle load is not necessary to haul the trains; 21 – 22.5t axle load is absolutely adequate even with 4-axle locos. Such locomotives provide a much higher power at the wheels and can haul the trains faster with much fewer powered axles. Also, such new freight locomotives can be sued universally on the whole network of IR.

It is evident that the choice of new locomotive is primarily a question of overall system optimization taking all aspects of the railway system into account. Equally important is the perception of future developments as rolling stock and infrastructure are long-term investments. Hence, a view on total cost of operation is equally important as achieving the targets of energy and environmental policies. As ac locomotive propulsion technology is now well established in India with the transfer of technology for the WAP-5 and WAG-9 locomotives in 1995, there is now an opportunity to migrate these locomotives or to add new locomotives with a higher performance level, well matching the needs of the new dedicated freight corridors.