Electric Traction

Traction System –introduction

a) Non-electric traction systems

- Steam engine drive used in railways and IC-engine drive used for road transport.

(b) Electric traction systems

- Self-contained vehicles or locomotives viz. battery elec-tric drive and diesel-electric drive, vehicles, gas turbine electric vehicles, etc.

- Receive electric power from grid network viz. railway electric locomotive fed from overhead ac supply, tramways and trolly buses supplied with dc supply.

Electric Traction System

- The locomotion in which the driving force is obtained from electric motor (traction motor – providing rotational motion) which enables to obtain linear motion for electric locomotive, trams, trollybuses, etc. This is known as electric traction system.

3

Locomotives & EMUs

- A **locomotive** or **engine** *is a rail transport vehicle that provides the motive power for a train.*
- **A steam locomotive** *is a locomotive whose primary power source is a steam engine.*
- **Internal combustion locomotives** *use an IC-engine, connected to the driving wheels by a transmission.*
- **Petrol locomotives** *use petrol as their fuel and provides mechanical transmission to deliver the power output of the engine to the driving wheels.*
- **A diesel locomotive** *is a type of railway locomotive in which the prime mover is a diesel engine.*
- **In a diesel–electric locomotive**, *the diesel engine drives either an electrical DC generator, or an AC alternator-rectifier , the output of which provides power to the traction motors that drive the locomotive. There is no mechanical connection between the diesel engine and the wheels. The vast majority of diesel locomotives today are diesel-electric.*

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- **An electric locomotive** is powered only by electricity. either direct current (DC) or alternating current (AC).
  - ✓ *Electricity is supplied with a (nearly) continuous conductor running along the track , usually by an overhead line, suspended from poles or towers along the track* ***or*** *from structure or tunnel ceilings* ***or*** *a third rail mounted at track level;*
  - ✓ *Both overhead wire and third-rail systems usually use the running rails as the return conductor.*
- **EMU:** An electric multiple unit is a multiple-unit train, using electricity as the motive power. An EMU requires no separate locomotive, as electric traction motors are incorporated within one or a number of the carriages . The great majority of EMUs are passenger trains.

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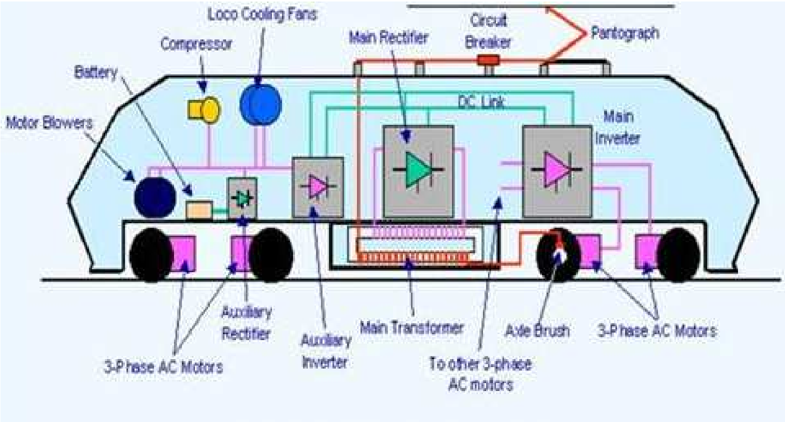
AC electric locomotive (Kando System) -In 1894, Hungarian engineer Kálmán **Kandó**

Developed the rotary phase converter, enabling electric locomotives to use 3-φ induction motors whilst supplied via a single O/H wire, carrying single phase AC (16kV 50 Hz) power of the high voltage national networks, which is then converted into 3-phase ac supply at the same frequency.

By using inverter, it is to get variable-frequency 3-phase supply at 1/2 to 9 Hz frequency. At this low frequency, 3-phase motors develop high starting torque.

6



Block Diagram of Modern AC Electric Locomotive

- Red Lines- 1-phase A.C. circuit
- Green Lines- D.C. circuit
- Purple Lines- 3-phase A.C. circuit
- The current passes directly from the pantograph (or shoe) to the main and auxiliary inverters.

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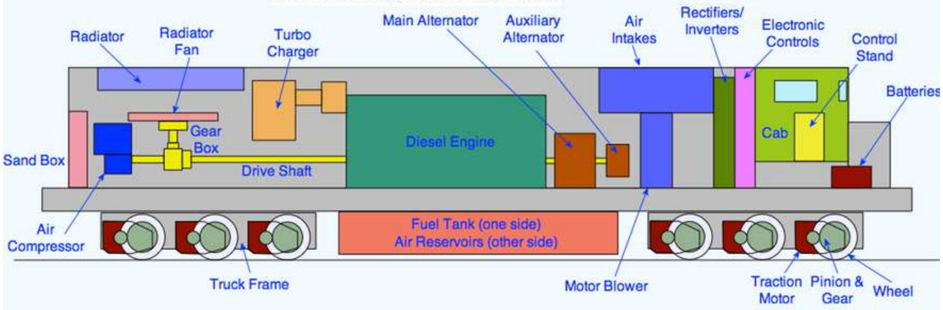
Schematic of diesel electric locomotive .



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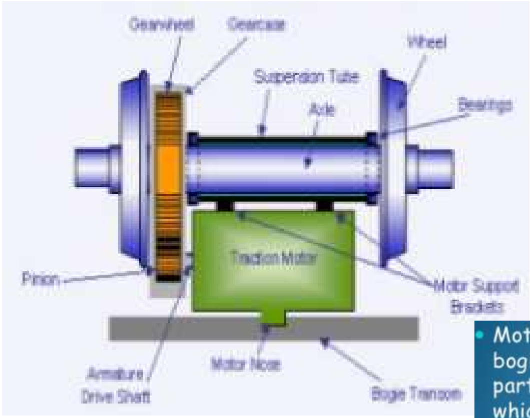
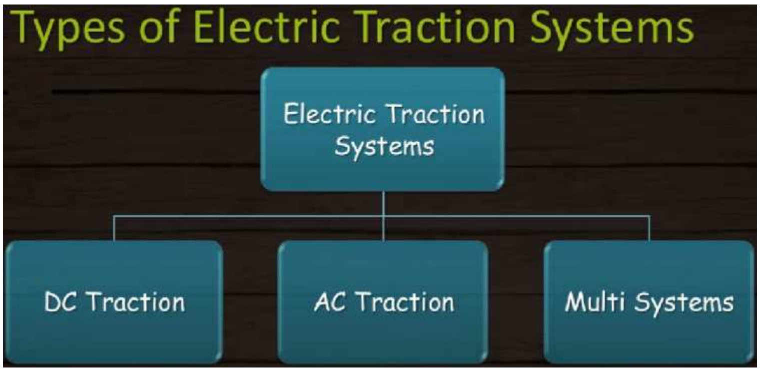


- Motor is mounted in the bogie frame supported partially by the axle which it drive and partially by the bogie frame.

SYNTAX USED IN LOCOS

- **The first letter (gauge)**
- W – Indian broad gauge (the "W" Stands for Wide Gauge - **1.676 m**)
- Y – metre gauge (the "Y" stands for Yard Gauge - **1 m**)
- Z – narrow gauge(**0.762 m**)
- N – narrow gauge (toy gauge **or light gauge - 0.610 m**)
- **The second letter (motive power)**
- D – diesel
- C – DC electric (can run under DC overhead line only)
- A – AC electric (can run under AC overhead line only)
- CA – both DC and AC (can run under both AC and DC overhead line); 'CA' is considered a single letter
- B – Battery electric locomotive (rare)
- **The third letter (job type)**
- G – goods
- P – passenger
- M – mixed; both goods and passenger
- S – shunting (also known as switching engines or switchers in the USA and some other countries)
- U – electric multiple unit (used to carry commuters in city suburbs)
- R – Railcars
- For example, in "**WDM 3A**":
- "W" means broad gauge
- "D" means diesel motive power
- "M" means suitable for both goods and passenger service
- "3A" means the locomotive's power is 3,100 hp ('3' stands for 3000 hp, 'A' denotes 100 hp more)
- Or, in "**WAP 5**":
- "W" means broad gauge
- "A" mean AC electric traction motive power
- "P" means suitable for Passenger service
- "5" denotes that this locomotive is **chronologically** the fifth electric locomotive model used by the railways for passenger service.



- **Single-phase ac**
  (16 2/3 and 25 Hz)
- **Three-phase ac**
  (16 2/3 and 25 Hz)

Composite system

- involving conversion of single-phase ac into 3-phase ac (also called Kando system)
- single-phase to DC system

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Merits of Electric Traction

- *High starting torque.*
- *Less maintenance cost*
- *Cheapest method of transport*
- *Rapid acceleration and braking*
- *Less vibration*
- *Free from smoke and flue gases hence used for underground and tubular railway.*
- *Catering greater volume of traffic*
- *Running in sections during the periods of light traffic*

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❑ Demerits of electric traction

- *High capital cost.*
- *Problem of supply failure.*
- *The electrically operated vehicles have to move on guided track only.*
- *Additional equipment is required for achieving electric braking and control.*

TYPES OF RAILWAY SERVICES

- Urban service or City service
- Suburban service
- Main line service

S.No.	Type of Service	Acceleration in kmphps	Retardation in kmphps	Maximum Speed in kmph	Distance between Stations in km	Special Remarks
1.	Urban	1.5 to 4.00	3 to 4	120	1	No free running period, coasting period—small
2.	Suburban	1.5 to 4.00	3 to 4	120	2 to 5 km	No free running period, coasting period—long
3.	Main Line	0.6 to 0.8	1.5	160	More than 10 km	Free running and coasting periods—long. Acceleration and braking periods—comparatively small.

Supply Systems for Electric Traction

- **D.C system**--- **600V,1500V to 3000V**
- **A.C system**
  - Single phase system--- **300V-400kV at 16 2/3 Hz,25 Hz**
    --- 15kV-25kV for 50Hz
  - Three phase system--- **300V-3.6kV at 16 2/3 Hz**
- **Composite system**
  - Single phase AC to DC
  - Single phase to three phase

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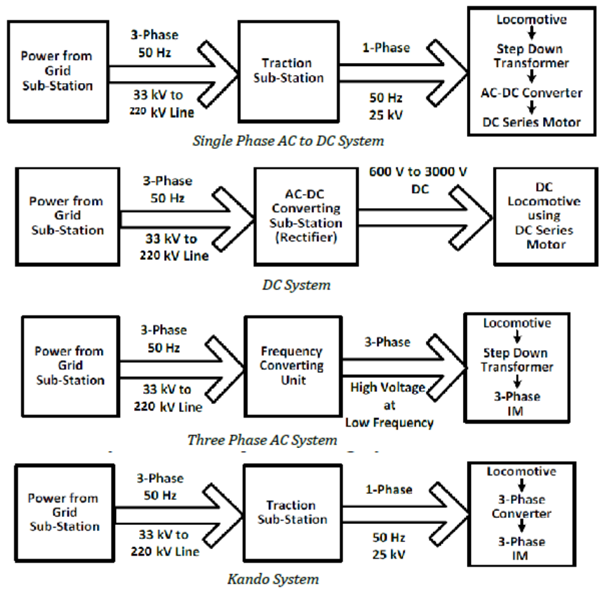
Layout of Supply systems



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Electric Traction in India…1

- Electric traction was introduced on Indian Railways in year 1925 on 1.5 KV DC and the first electric train ran between Bombay's Victoria Terminus and Kurla along the Harbour Line of CR, on February 3, 1925, a distance of 9.5 miles, flagged off the then Governor of Bombay Sir Leslie Orme Wilson.
- The first actual train run (apart from trial runs) using 25kV AC was on December 15, 1959, on the Kendposi-Rajkharswan section (SER).
- In the year 1957, Indian Railways decided to adopt 25 kV 50 Hz AC traction based on French Railway (SNCF) technology.
- The Mumbai region is the last bastion of 1500V DC (negative earth, positive catenary) electrified lines on Indian Railways. Soon, this region [redacted] converted to 25KV AC with overhead lines, which is the standard throughout the rest of the country.

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Electric Traction in India…2

- Typical Voltages used for electric Traction are 1.5kV DC and 25kV AC for mainline trains.
- Calcutta had an overhead 3kV DC system until the '60s.
- The Calcutta Metro uses 750V DC traction with a third-rail mechanism for delivering the electricity to the EMUs (Electric Multiple Units).
- The Calcutta trams use 550V DC with an overhead line (catenary) system with underground return conductors. The catenary is at a negative potential.
- The Delhi Metro uses 25kV AC overhead traction with a catenary system on the ground-level and elevated routes, and uses a rather unusual 'rigid catenary' or overhead power rail in the underground tunnel sections.

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Electric Traction in India…3

DC Traction

- DC traction units use direct current drawn from either a conductor rail or an overhead line.
- The most popular line voltages for overhead wire supply systems – 1500V DC and 3000V DC.
- 600V DC–750V DC volt range used for third rail systems (a means of providing electric power to a railway train, through a semi-continuous rigid conductor placed alongside or between the rails of a railway track and that additional rail is called conductor rail)

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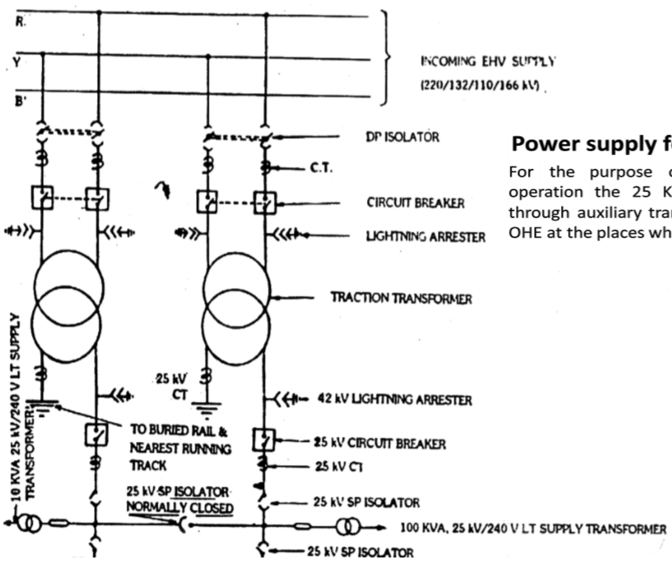
AC Supply from Traction sub-station



Power supply for signaling

For the purpose of signaling and reliable operation the 25 KV is converted to 240 V through auxiliary transformer by tapping 25 KV OHE at the places where needed.

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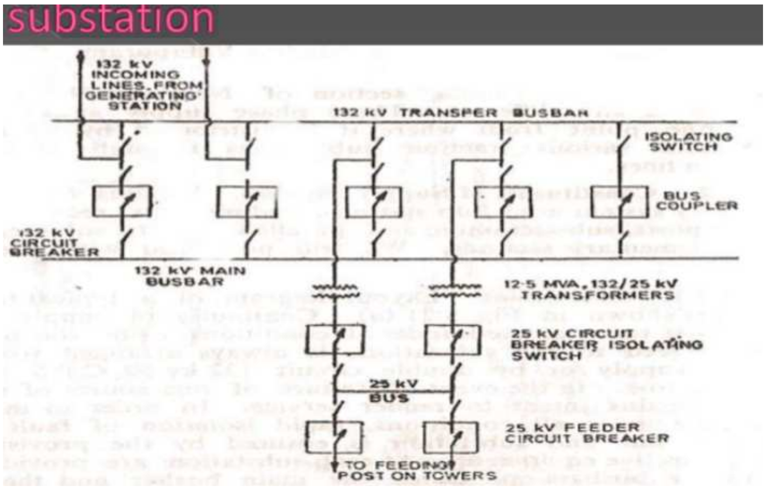
Power Supply from Grid sub-station



Supply System…1

- 25 kV, AC, 50 Hz, 1-ϕ traction power is supplied by the Utilities from their 220/132/110/66 kV EHV, 3-ϕ grid system to the traction sub-stations of Railways (at distance of 35-50 km apart) located along the route of the electrified sections

- The utilities supply from their EHV, 3-ϕ grid substation through step down single phase transformers i.e. high-voltage 3-phase supply is converted into low-voltage 1-phase supply. Scott-connected or V-connected 3-phase transformers is used.

Supply System…2

- All EHV and 25 kV equipment is owned, installed, operated and maintained by the Supply Authority except 25 kV feeder circuit breakers which are owned, installed, operated and maintained by the Railway.
- At each traction substation, normally two single phase transformers are installed, one which is in service and the other is 100% stand by. The present standard capacity is about 20 MVA (ONAN)/30 MVA (ONAF). These transformers step down the grid voltage to 25 kV for feeding the traction overhead equipment (OHE)
- *Traction transformers are usually provided with off-load changers (operated locally or by remote control with taps from + 10% to (-) 15% in steps of 5%.*
- *The tapings on the transformers are on the secondary winding and set to ensure the voltage is maintained as high as possible but not exceeding 27.5 kV at the feeding post at any time.*
- *one terminal of the 25 kV secondary winding is connected to the overhead equipment (OHE) and other terminal of the 25 kV secondary winding is solidly earthed and connected to the running rails.*

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Supply System…3

- On high traffic density routes transformers of 30 MVA rating are being tried.
- The permissible variation of the bus bar voltage on the busbars at the grid substations is +10% and -5% i.e. between 27.5kV and 23.75kV
- To keep the voltage unbalance on the 3 phase grid system within the above limits, power for ac single phase traction is tapped off the grid system across the different phases at adjacent substations in cyclic order.
- The load current flows through the OHE to the locomotive and return through the rails and earth to the traction sub-station.
- Traction transformers usually have the Overload rating: (a) 50% overload for 15 min and (b) 100% overload for a period of 5 min, after the transformer has attained steady temperature on continuous operation at full load.
- Auxiliary transformers 25kV/240V are provided at all the posts and also at certain intermediate points to supply ac at 240 V, 50Hz required for signaling and operationally essential lighting installations and level crossings.

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Supply System…4

- The approach to reduce the voltage unbalance in AC traction is the arrangement of the traction transformer in a way that the traction transformers located next to each other receive the power from alternate pairs of phases.
- To further reduce the voltage unbalance, specially-connected transformers were developed such as **V-connected, Scott, Modified-Woodbridge, and Roof-Delta transformer**, most of which are capable of decreasing the voltage unbalance down to zero in theory as long as both tractive loads of the secondary supply arms are equal.
- Since traction loads inherently fluctuates, the specially-connected transformers will not reach their optimal operation points at all time; this leads to the development of compensators or power quality conditioners.

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Supply System-5 : Phase distribution

Phase distribution: To balance the power drawn on different phases of the 3-phase 132kV or 220kV grid supply, typically different sections of track are provided with power from different phases.

It is often set up so that adjacent substations are supplied by different phases.

Consecutive AC substations, therefore, are electrically not connected in parallel;

This is very different from DC traction systems where all substations are always in parallel.

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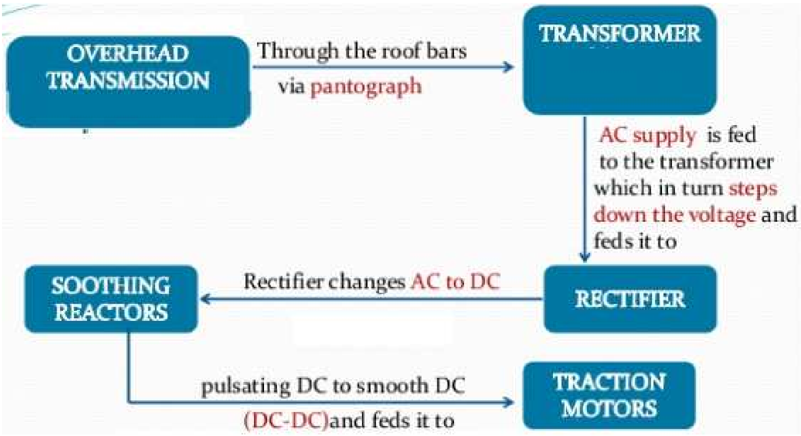
Traction System topology



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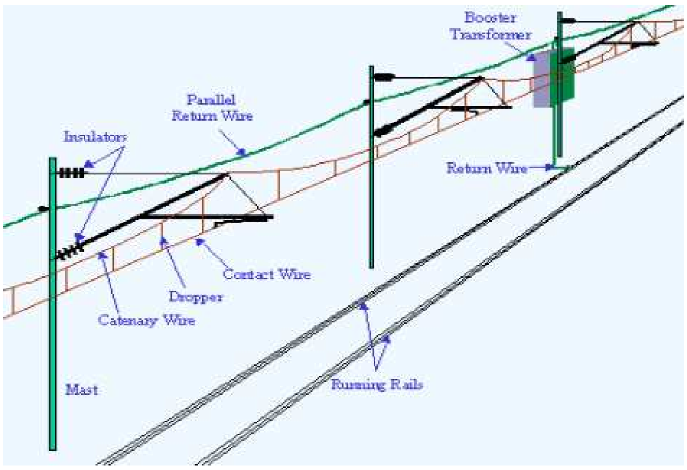
Traction System



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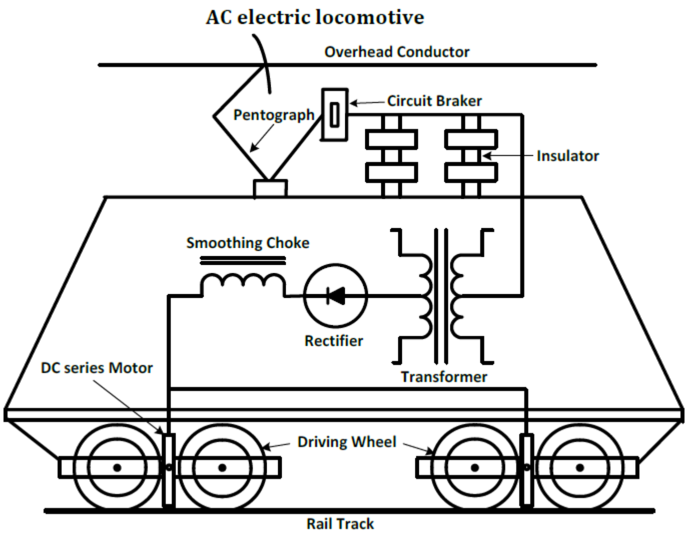
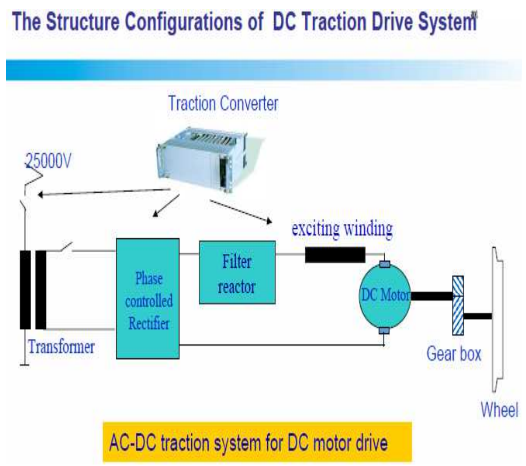
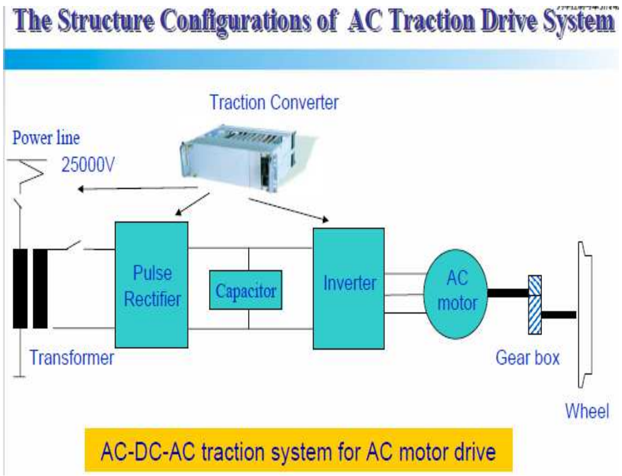

AC electric locomotive
Overhead Conductor
Circuit Braker
Pentograph
Insulator
Smoothing Choke
Rectifier
Transformer
DC series Motor
Driving Wheel
Rail Track

29


The Structure Configurations of DC Traction Drive System
Traction Converter
25000V
exciting winding
Phase controlled Rectifier
Filter reactor
DC Motor
Transformer
Gear box
Wheel
AC-DC traction system for DC motor drive

30



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Pantograph Collector

- The pantograph is employed in railways for collection of current where the operating speed is as high as 100 or 130 kmph and the currents to be collected are as large as 2000 or 3000 A.
- Pantographs are mounted on the roof of the vehicles and usually carry sliding shoe for contact with the overhead trolley wire.
- The contact shoes are usually about 1.2 meter long. There may be a single shoe or two shoes on each pantograph.
- Material used for pantograph is often steel with sometimes, wearing used plates of copper or bronze inserted.

Traction motor : DC series motor, AC series motor , Induction motor, etc

Traction transformer

There are two traction transformer connected in parallel of same rating for the purpose of reliability the rating of transformer are

Capacity: 20,000 KVA. Frequency: 50 Hz

Full load: 25 KV Preferred: 0.9

Zero load: 27 KV

Circuit Breaker

The high voltage circuit breaker is special type of electro pneumatic contactor mounted on the roof of the loco. The electrical equipment of the loco is connected to or disconnected from the OHE by means of the circuit breaker.

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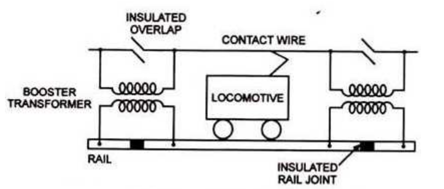
BOOSTER TRANSFORMERS

- In ac traction system return current mainly flows to the substation through track leaving a small portion, which flows through ground because of leakage of current from track to the ground. This leakage current or stray current causes an interference with communication lines which are running near the track. **To avoid flow of leakage current through ground, booster transformer is used.**

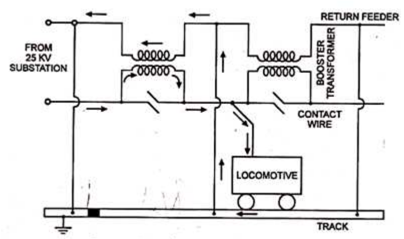
- Booster transformer consists of the windings of unity turn-ratio.

- Primary winding is in series with the contact wire and the secondary is in series with the return current circuit. Current flowing through contact wire passes through the primary winding which induces current in the secondary in equal amount. This induced current in secondary forces the return current to flow through only return circuit, and so avoids leakage current.

BOOSTER TRANSFORMERS



Rail-Connected Booster Transformer



Booster Transformer Using Return Feeder

Crest Speed, Average Speed and Schedule Speed of Train:

- **Crest Speed:** The maximum speed attained by the vehicle during the run is known as crest speed.
- **Average Speed:** The mean of the speeds from start to stop i.e., the distance covered between two stops divided by the actual time of run is the average speed.

  Average speed = Distance between stops/Actual time of run, T
- **Schedule Speed:** The ratio of distance covered between two stops and total time of run including time of stop is known as schedule speed. Mathematically,

  Schedule speed = Distance between stops/ (Actual time of run + stop time)

The schedule speed is always less than the average speed. The difference is large in case of urban and suburban services and is negligibly small in case of main line service.

The schedule speed is affected by the following factors:

1. Acceleration and braking retardation.
2. Maximum or crest speed.
3. Duration of stop.

Dead Weight, Accelerating Weight and Adhesive Weight

- **Dead Weight:** The total weight of locomotive and train to be pulled by the locomotive is known as dead weight.
- **Accelerating Weight:** The effective weight of entire train can be considered to be divided into two parts:

  (i) The weight, which requires angular acceleration such as weight of wheels, axles, gears etc. and

  (ii) The weight, which requires linear acceleration.

Hence the effective weight, which is greater than dead weight is called the accelerating weight. Accelerating weight is taken 10-12% more than dead weight.

- **Adhesive Weight:**

The total weight to be carried on the driving wheels is known as the adhesive weight.

Traction Effort

- The tractive effort of a locomotive (whether AC or DC) is defined as,

  Tractive effort = Weight on drivers x Adhesion

  Adhesion = Coefficient of friction x Locomotive adhesion variable

- **The friction coefficient** between wheel and rail is usually in the range of .40 to .45 for relatively clean, dry rail in reasonable condition and is essentially the same for all locomotives.

- The locomotive adhesion variable represents the ability of the locomotive to convert the available friction into usable friction at the wheel rail interface. **It varies dramatically from about .45 for old DC units to about .90 for modern AC units.** This variable incorporates many factors including electrical design, control systems, truck type and wheel conditions.

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Typical Speed-Time Characteristics of Electric Trains

(i) Initial Constant acceleration (rheostatic acceleration)

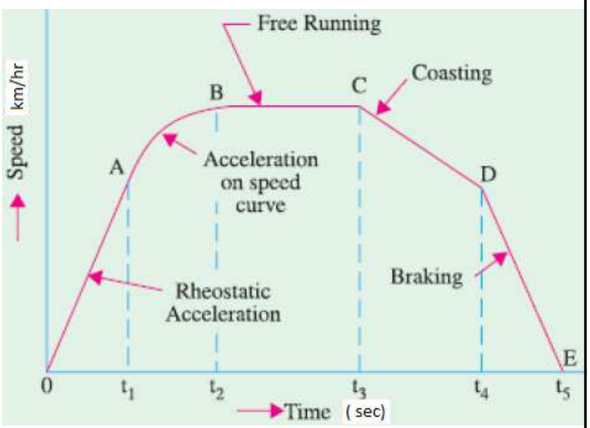
(ii) Acceleration on speed

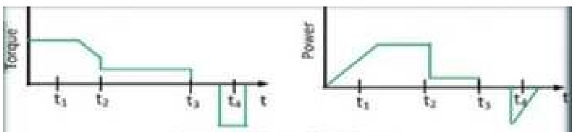
(i) Constant speed run or free running

(iv) Coasting i.e. running with power switched off

(v) Retardation(due to braking).

- *The area covered by the Speed-time curve, represents the distance covered in the corresponding time.*





Torque and Power Time Curve

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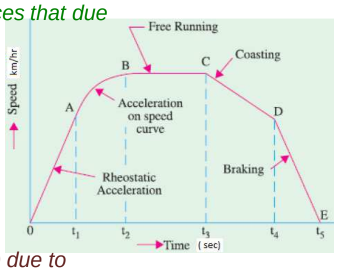
Various Stages of Speed-Time Characteristics

(i) Initial Constant acceleration or Rheostatic acceleration) (O-A):

- *Notching up or starting period*
- *Starting resistance of the motor gradually cut-off so that*
- *Motor current & Tractive effort are nearly constant*
- *Produces constant acceleration*

(ii) Acceleration on speed (A-B):

- *Starting resistance totally cut out*
- *Full supply voltage applied to the motors*
- *Motor currents & Torque decrease as speed increases*
- *Acceleration gradually decreases till torque exactly balances that due to resistance to the motion*
- *Finally current taken by motor is constant*



(iii) Constant speed / free running (B-C)

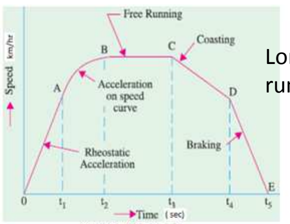
- *Train runs at a const speed (acceleration is zero)*

(iv) Coasting (C-D)

- *.Running with power switched off*
- *Utilizing some of the KE, otherwise energy gets wasted.*
- *Speed is gradually falling (retardation practically constant) due to friction,windage, etc.*

(v) Braking (D-E) : Breaks are applied to bring the train at halt.

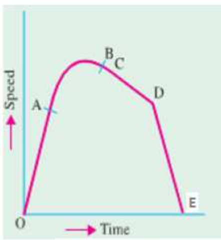
Speed-Time Characteristics for main,city and suburban services



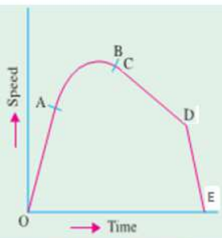
(Main-Service)

Long periods of free-running at high speeds

- ✓ No free running period
- ✓ Relative values of acceleration and retardation are high to achieve moderately average speed between stops.
- ✓ Due to short distances between stops, there is no possibility of free-running period but a short coasting period to save on energy consumption.



(City service)

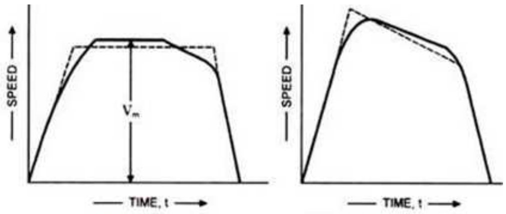


(Suburban service)

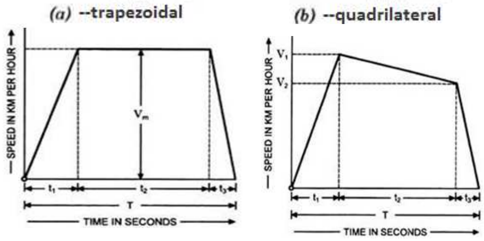
- ✓ No free running period
- ✓ Relatively longer coasting due to longer distances between stops,
- ✓ Relatively high values of acceleration and retardation to achieve moderately average speed between stops.

Simple Geometric Speed-Time Characteristic Curves

- ***In order to study the performance of a service at different schedule speeds, the actual speed-time curves are replaced by simple geometric shaped curves, either quadrilateral or trapezoidal shape, which do not involve a knowledge of the motor characteristics.***



(a) --trapezoidal (b) --quadrilateral



- The acceleration and free-running periods are governed by the speed-torque characteristics of the electric traction motors.
- Coasting and braking are governed by the train resistance and the allowable braking retardation respectively

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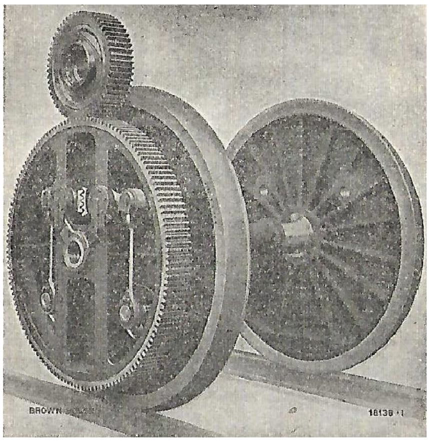
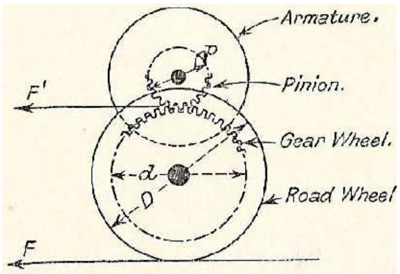
Mechanics of Train Movement...1





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Mechanics of Train Movement...2

- **Tractive Effort for Propulsion of Train:**

Total tractive effort required to run a train on track = Tractive effort required for linear and angular acceleration ± tractive effort to overcome the effect of gravity + tractive effort to overcome the train resistance.

or $\boxed{F_t = F_a \pm F_g + F_r}$

(i) **Tractive Effort for Acceleration:** In order to accelerate the train, force applied is :

Fore = Mass * acceleration

Consider a train of weight = **W tonnes = 1,000 W kgf and Acceleration = α kmphps**

Mass of train, M= 1,000 W kg

= α * 1,000/3,600 m/s² = 0.2778 *α m/s²

Tractive effort required for linear acceleration:

$$\boxed{\mathbf{F_a = m\alpha == 1000\,W \times 0.2778 * \alpha = 277.8 * W * \alpha \text{ newtons}}}$$

With the linear acceleration of the train, the rotating parts of the train such as wheels and motors also accelerate in an angular direction.

Therefore, the tractive effort required is equal to the arithmetic sum of tractive effort required to have the angular acceleration of rotating parts and tractive effort required to have the linear acceleration.

Mechanics of Train Movement...3

- **Tractive Effort for Propulsion of Train:**

For the angular acceleration, the tractive effort required depends upon **the individual weight, radius of gyration etc. of the rotating parts requiring angular acceleration. Thus, the effective value of mass of the train is**

$$\mathbf{W_e = W + m}$$

Where, m is the mass of the rotating part.

Hence the equivalent or accelerating weight of the train is taken as W_e, which is higher than the dead weight W requiring linear acceleration to consider the tractive effort for the angular acceleration.

In practice m is from 8 to 15%. The normal value lies between 10 and 12 per cent.

Hence the total tractive effort required for acceleration,

$$\boxed{\mathbf{F_a = 277.8 * W_e * \alpha \text{ newtons}} \ldots\ldots(1)}$$

Mechanics of Train Movement...4

• **Tractive Effort for Propulsion of Train:**

(ii) Tractive Effort for Overcoming the Effect of Gravity:

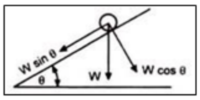
When a train is on a slope, a force of gravity equal to the component of the dead weight along the slope acts on the train and tends to cause its motion down the gradient or slope.

Force due to gradient, F_g = 1000 W sin θ kg

In railway, gradient is expressed as rise in metres in a track distance of 100 metres and is denoted as 'percentage gradient' **(G%).**

i.e. G = Sin θ × 100

or, sin θ = G/100 (2)



Substituting in F_g,

$\boxed{F_g = 1{,}000\ W * G/100 * 9.81 = 98.1\ W*G\ \text{newtons (here, W is in Kg)}......(3)}$

When the train is going up a gradient, the tractive effort will be required to balance this force due to gradient but while going down the gradient, the force will add to the tractive effort. **So, it is (+)ve for the motion up-gradient and (-ve) for the motion down-gradient.**

Mechanics of Train Movement...5

• **Tractive Effort for Propulsion of Train:**

(iii) Tractive Effort for Overcoming Train Resistance:

➢ All the forces resisting the motion of a train are due to:
1) ***The friction at the various parts of the rolling stock***
2) ***Friction at the track and***
3) ***Air resistance.***

The train resistance (first two components comprising of the mechanical resistance and the last term represents air resistance) depends upon shape, size and condition of track etc., and is expressed by ***'r' as the specific resistance in newtons per tonne of the dead weight***. The equation for train resistance is,

$$r = k_1 + k_2*V + k_3*V^2$$

where, k_1, k_2 and k_3 are constants depending upon the train and the track and V is the speed in kmph. For a normal train the value of specific resistance (r) is 40 to 70 newtons/tonne.

Tractive effort to overcome the train resistance, $\boxed{F_r = W * r\ \text{Newton}....(4)}$

Total net tractive effort required for propulsion of a Train:

$\boxed{F_t = F_a \pm F_g + F_r = 277.8 * W * \alpha \pm 98.1\ W*G + W*r\ \text{Newtons}.........(5)}$

Mechanics of Train Movement...6

Total Torque developed by all the traction motors:

Tractive effort transferred to the driving wheels, $F_t = \eta * T * \left(\frac{2*\gamma}{D}\right)$ **Newton**

Where, **T= torque** from armature of the motor(s) **Nm** attached to it a pinion of diameter d' in meters , tractive effort ' **F_t' in Newton** at the edge of the pinion , d is diameter of gearwheel in metres, D is diameter of driving wheel in metres, η is the efficiency of transmission, and γ is the gear ratio (d/d'=motor speed/wheel speed).

If there are N no. of identical traction motors in the train, **Torque developed by each motor = T/N Nm**

Specific Energy Output from Driving Wheels....1

Power Output from the Driving Axles:

Power, P =Rate of doing work

=Tractive effort * (distance/time)= Tractive effort * speed

= F_t * v where F_t is in newtons and v is in m/s

$$\text{or } P = F_t \times V \times \frac{1{,}000}{3{,}600} \text{ watts} = \frac{F_t \times V}{3{,}600} \text{ kW} \quad ...(6)$$

where V is in kmph.

Total energy required for the run (assume run on trapezoidal speed-time curve)

= Energy required during acceleration + energy required during free run

= (Average power during acceleration) x (acceleration period) + (average power during free run) x (duration of free run)

$$= \frac{1}{2}\frac{F_t V_m}{3{,}600} \times \frac{t_1}{3{,}600} + \frac{F_t' V_m}{3{,}600} \times \frac{t_2}{3{,}600} \text{ kWh} \quad ...(7)$$

where, V_m is the maximum speed in kmph, t_1, is the time of acceleration in seconds, t_2 is the time of free run in seconds, F_t is the tractive effort required during acceleration in newtons and F_t' is the tractive effort required during free run in newtons.

Instead of expressing the energy in kWh, it is more convenient for the purpose of comparison to introduce the weight of the train and the distance of run and to **express the energy in watt-hours per tonne-km**.

Specific Energy Output from Driving Wheels...2

$$i.e., \frac{\text{Energy output in watt - hours}}{\text{Weight of the train in tonnes} \times \text{distance of run in km}} \quad ...(8')$$

- The above quantity is known as specific energy output, and is used for comparing the dynamical performances of trains operating to different schedules.
- The energy input to the motors is called the energy consumption of the train.
- The total energy drawn from the distribution system will be greater than this by the quantity required for lighting, heating, control and braking.

Thus the specific energy consumption can be expressed in watt-hours per tonne-km:

$$i.e., \frac{\text{Energy consumption of train in watt-hours}}{\text{Weight of train in tonnes} \times \text{distance of run in km}} \quad ...(9)$$

Specific Energy Output from Driving Wheels...3

(i) Let the track have a gradient of **G%** throughout its run.

(ii) Energy output to accelerate the train **from rest to a speed V_m as given in equⁿ (7)**

$$= \frac{1}{2}\frac{F_t V_m}{3{,}600} \times \frac{t_1}{3{,}600} \text{ kWh} = \frac{1}{2}\frac{F_t V_m}{3{,}600} \times \frac{V_m}{3{,}600\alpha} \text{ kWh}$$

$$\text{since } t_1 = \frac{V_m}{\alpha}$$

$$= \frac{1}{2}\frac{V_m^2}{(3{,}600)^2\alpha}[277.8\, W_e\alpha + 98.1\, WG + Wr] \text{ kWh} \quad ..(10)$$

$$\text{since } F_t = 277.8 W_e\alpha + 98.1 WG + Wr$$

(iii) Energy output **during free train** at the speed V_m against the gradient and resistance to motion **as given in equⁿ (7)**

$$= \frac{F_t' V_m}{3{,}600} \times \frac{t_2}{3{,}600} \text{ kWh} = \frac{F_t' \times S'}{3{,}600} \text{ kWh}$$

$$= [Wr + 98.1 WG] \times \frac{S'}{3{,}600} \text{ kWh} \quad .. (11)$$

$$\text{since } \frac{V_m t_2}{3{,}600} = S', \text{ the distance travelled during free run}$$

Specific Energy Output from Driving Wheels...4

Total energy output for the run

$$= \frac{V_m^2}{2\alpha(3{,}600)^2}[277.8W_e\alpha + 98.1WG + Wr] + [Wr + 98.1WG] \times \frac{S'}{3{,}600} \text{ kWh}$$

$$= \frac{V_m^2 \times 1{,}000}{2\alpha \times (3{,}600)^2}[277.8W_e\alpha + 98.1WG + Wr]$$

$$+ [Wr + 98.1WG] \times \frac{S' \times 1{,}000}{3{,}600} \text{ Wh}$$

$$= \frac{V_m^2}{2\alpha} \times \frac{1{,}000}{(3{,}600)^2} \times 277.8W_e\alpha + \frac{V_m^2}{2\alpha} \times \frac{1{,}000}{(3{,}600)^2}[98.1WG + Wr]$$

$$+ \frac{1{,}000S'}{3{,}600}[Wr + 98.1WG]$$

$$= 0.01072V_m^2W_e + [98.1WG + Wr]\left[\frac{V_m^2}{2\alpha \times 3{,}600} + S'\right] \times \frac{1{,}000}{3{,}600}$$

$$= 0.01072V_m^2W_e + \frac{1{,}000}{3{,}600}[98.1WG + Wr][S'' + S']$$

where $\frac{V_m^2}{2\alpha \times 3{,}600} = S''$, distance travelled during accelerating period

$$= 0.01072V_m^2W_e + 0.2778(98.1WG + Wr)S_1 \quad \cdot\ (12)$$

where S_1 is the distance travelled during acceleration and free run in km

Specific Energy Output from Driving Wheels...5

Specific energy output

$$= \frac{\text{Energy output for the run in watt-hours}}{\text{Weight of train in tonnes} \times \text{distance of run in km}}$$

$$= \frac{0.01072V_m^2W_e + 0.2778(98.1WG + Wr)S_1}{W \times S}$$

$$= \frac{0.01072V_m^2}{S} \times \frac{W_e}{W} + 0.2778\frac{S_1}{S}(98.1G + r) \text{ watt-hours per tonne-km} \quad \cdots (13)$$

If the track is level one, G = 0

then specific energy output

$$= \frac{0.01072V_m^2}{S} \times \frac{W_e}{W} + 0.2778\frac{S_1}{S}r \text{ watt-hours/tonne-km} \quad \cdots (14)$$

Specific energy consumption

$$= \frac{\text{Specific energy output at driving wheels}}{\text{Overall efficiency of the motors and gearing}}$$

$$= \frac{0.01072V_m^2}{S\eta} \times \frac{W_e}{W} + 0.2778\frac{S_1}{S} \times \frac{r}{\eta} \text{ watt-hours/tonne-km} \quad \cdots (15)$$

Specific Energy Output and Specific Energy Consumption

✓ Specific energy output is given by

$$= \frac{0.01072\, V_m^2 W_e}{SW} + \frac{0.2778\,(98.1\,G + r)S_1}{S}$$

watt-hours/tonne-km

However, the Energy consumption in propelling the train is required for:

- Linear and angular acceleration (initial acceleration/notching period)
- Working against gravity while moving up the gradient;
- Working against the resistance to motion;
- Overcoming the losses due to gearing system and
- Supplying losses in motors and other electrical system.

The specific energy consumption in watt-hours per tonne-km:

$$i.e.,\quad \frac{\text{Energy consumption of train in watt-hours}}{\text{Weight of train in tonnes} \times \text{distance of run in km}} \qquad (16)$$

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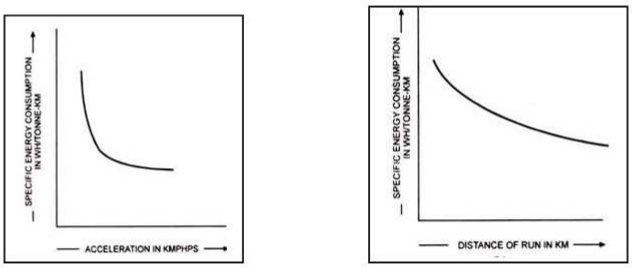
Specific Energy Consumption



(**Figs.** Specific energy consumption falls with the increase in value of acceleration (retardation) and distance of run)

Typical values of specific energy consumption:

(i) 50 – 75 watt-hours per tonne-km for suburban services and
(ii) 20 – 30 watt-hours per tonne-km for main line service.

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Factors Affecting Specific Energy Consumption of an Electric Train Operating on a Schedule Speed

- Specific energy output at axles is independent of locomotive overall efficiency.
- However, the specific energy consumption being equal to specific energy output divided by locomotive overall efficiency depends upon the overall efficiency of the locomotive.
- Greater the overall efficiency lesser will be the specific energy consumption for a given specific energy output at axles.
- Further, eq. (16) shows that specific energy con-sumption depends upon
  - *Maximum speed , Acceleration and Retardation*
  - *Distance travelled by the train while power is on, S_1,*
  - *Specific resist-ance r - more the train resistance, greater the specific energy consumption*
  - *Gradient G -- Steep gradient will involve more en-ergy consumption even if regenerative braking is used.*
  - *Distance between stops - Greater the dis-tance between stops lesser is the specific energy consump-tion.*
  - *For a given run at a given schedule speed, greater the value of acceleration and retardation, more will be the period of coast-ing and, therefore, lesser the period during which power is on. So specific energy consumption will less.*

NEXT