Unit-IV: Electric Traction

System of electric traction and track electrification - Mechanics of train movement, Speed-time curves for different services – trapezoidal and quadrilateral speed time curves, problems. Calculations of tractive effort – power - specific energy consumption for given run, effect of varying acceleration and braking retardation - adhesive weight and Coefficient of adhesion, problems

Electric Traction: The locomotive in which the driving or tractive force is obtained from electric motors is called electric traction.

Traction systems:

All traction systems are classified as

i) **Non electrical traction systems** – These traction systems does not consumes electrical energy.
Ex. Steam Engine drives, Internal combustion (IC) Engine drives

ii) **Electrical traction systems** – These traction systems uses electrical energy at some stages.
Ex. Battery electric drives, Diesel electric drives, Railway electric locomotive fed from overhead transmission.

Advantages of Electric Traction:

- It is cheapest method of all other methods of traction.
- It is free from smoke and flue gasses; hence it is very clean and neat.
- Well suitable for underground and tube railways due to the absence of smoke.
- More comfort and healthier to the passengers, since it is free from smoke and flue gasses
- It can start without loss of time.
- Maintenance and repair cost is low i.e about 50% of steam traction system.
- High starting torque. This system uses of d.c. & a.c. series motors, which has a very high starting torque.
- In electric traction, regenerative breaking is used which feeds back 40%of the energy.
- Electric braking is superior to mechanical braking.
- The electric locomotive can run safely with high speeds at curves.
- Electric motor produces uniform torque and reduces jerking action to the passengers.
- The **electric traction system** is the most efficient of all other traction system
- More economical for high traffic density.
- Saving in high grade coal.
- Electric traction provides base load to the power stations.
- Electric motors occupy less area compared to steam and diesel traction systems.
- Railway electrification encourages rural electrification as no special transmission lines have to be erected.
- No coal is required for electric traction.

Disadvantages of Electric Traction:

- Initial cost is high.
- Failure of supply is a problem
- The electric traction system is tied up to only electrified track.
- For braking & control, additional equipments required.

- Interference with telegraphs and telephone lines. To overcome this problem negative boosters are required.

System of Track Electrification:

i. D.C. Systems – uses 600v, 750v, 1500v, 3000v.
ii. Single phase A.C. System:– uses 15 to 25KV at 25Hz or 50 or 16 2/3Hz.
iii. Three phase A.C. System:- uses 3.3 to 3.6KV voltage, at 16 2/3Hzs.
iv. Composite system:– 1- Ph to 3 – Ph system or Kondo system and Single phase to DC system

Single-Phase AC System: In this system, ac voltages from 11 to 15 kV at 16.67 or 25 Hz are used. If, electric supply is taken from the high voltage transmission lines at 50 Hz, then in addition to step-down transformer, the substation is provided with a frequency converter. The frequency converter reduced the frequency to 16.67 or 25 Hz. The 15 kV at 16.67 or 25 Hz supply is fed to the electric loco-motor via a single over-head wire.

A step-down transformer carried by the locomotive reduces the 15-kV voltage to 300-400 V for feeding the ac series motors. Speed regulation of ac series motors is achieved by applying variable voltage from the tapped secondary of the above transformer. Low-frequency ac supply is used because following advantages:

i. Improvement in the commutation properties of ac motors, it increases their
ii. The efficiency and power factor of ac motor increases.
iii. At low frequency, line reactance is less so that line impedance drop and hence line voltage drop is reduced. Because of this reduced line drop, it is feasible to space the substations 50 to 80 km apart.
iv. At low frequency, the telephonic interference will reduces.

Three-phase AC System: It uses 3-phase induction motor (Slip ring) which work on a 3.3 kV, 16.67 Hz supply. Sub-stations receive power at a very high voltage from 3-phase transmission lines at frequency of 50 Hz. This high voltage is stepped down to 3.3 kV by transformers whereas frequency is reduced from 50 Hz to 16.67Hz by frequency converter.

Induction motors used in the system because simple and robust construction and gives trouble-free operation. However, this system is not popular because of its limitations as given below :

i. The overhead contact wire system becomes complicated at crossings and junctions.
ii. The constant-speed characteristics of induction motors are not suitable for traction work.
iii. The induction motors have speed/torque characteristics similar to dc shunt motors. Hence, they are not suitable for parallel operation.

Composite System: The composite systems are classified as

1) 1-phase to 3-phase system also called Kando system **2)** 1-phase to dc system.

Kando System: In this system, single-phase 16-kV, 50 Hz supply from the sub-station is picked up by the locomotive through the single overhead contact wire. It is then converted into 3-phase ac supply at the same frequency by means of phase converter equipment carried on the locomotives. This 3-phase supply is then fed to the 3-phase induction motors. By using silicon controlled rectifier as inverter, it is possible 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 without taking excessive current.

Single-phase AC to DC System: In this system, the 25-kV, 50-Hz, 1-phase ac supply is stepped down by the transformer which is installed in the locomotive. The low-voltage ac supply is then converted into dc supply by the rectifier which is placed in the locomotive. This dc supply is finally fed to dc series traction motor. The system of traction employing 25-kV, 50-Hz, 1-phase ac supply has been adopted for all future track electrification in India.

Types of Railway Services

There are three types of passenger services offered by the railways:

1. **City or Urban Service.** In this case, there are frequent stops, the distance between stops being nearly 1.5 km or less. Hence, high acceleration and retardation are essential to achieve moderately high schedule speed between the stations.
2. **Suburban Service.** In this case, the distance between stops averages from 3 to 5 km over a distance of 25 to 30 km from the city terminus. Here, also, high rates of acceleration and retardation are necessary.
3. **Main Line Service.** It involves operation over long routes where stops are infrequent. Here, operating speed is high and accelerating and braking periods are relatively unimportant.

Typical Speed/Time Curve

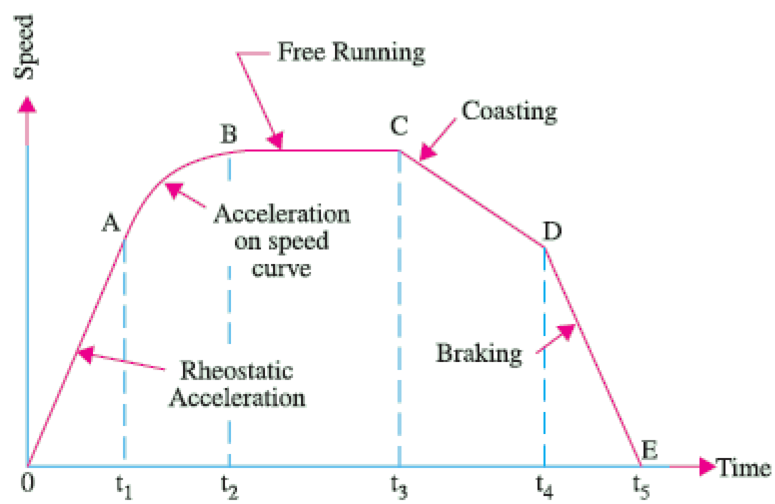
Typical speed/time curve for electric trains operating on passenger services is shown in below figure. It may be divided into the following **five** parts:

Constant Acceleration Period (0 to t_1)

It is also called notching-up or starting period because during this period, starting resistance of the motors is gradually cut out so that the motor current (and hence, tractive effort) is maintained nearly constant which produces constant acceleration.

Acceleration on Speed Curve (t_1 to t_2)

This acceleration commences at point t_1 and full supply voltage has been applied to the motors. During this period, the motor current and torque decrease as train speed increases. Hence, acceleration gradually ***decreases*** till torque developed by motors exactly balances that due to resistance to the train motion. The shape of the portion *AB* of the speed/time curve depends primarily on the torque/speed characteristics of the traction motors.



Free-running Period (t_2 to t_3)

The train continues to run at the speed reached at point t_2. It is represented by portion *BC* in figure and is a constant-speed period which occurs on level tracks.

Coasting (t_3 to t_4)

Power to the motors is cut off at point t_3 so that the train runs under its momentum, the speed gradually falling due to friction, windage etc. (portion *CD*). During this period, retardation remains practically constant. Coasting is desirable because it utilizes some of the kinetic energy of the train which would, otherwise, be wasted during braking. Hence, it helps to reduce the energy consumption of the train.

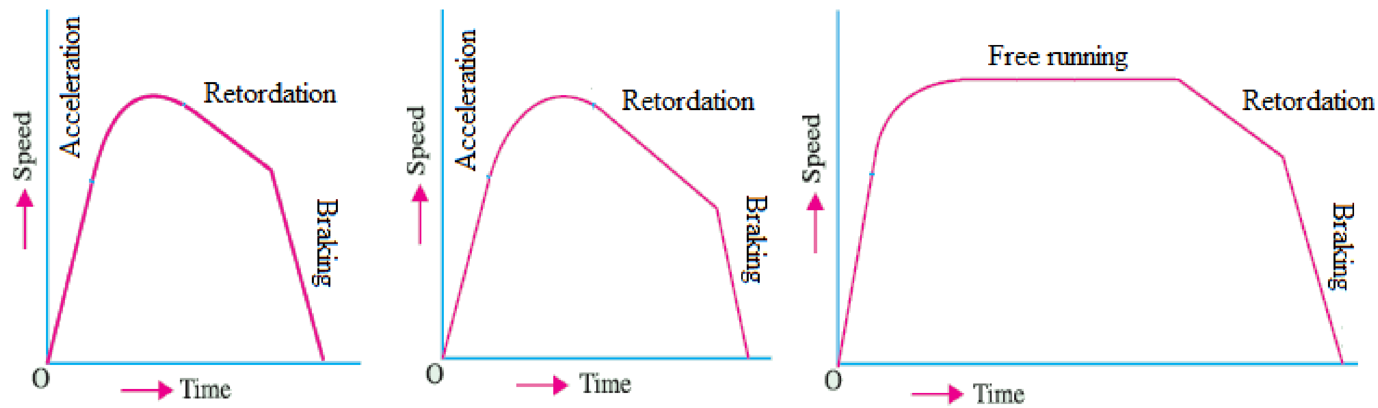
Braking (t_4 to t_5)

At point t_4, brakes are applied and the train is brought to rest at point t_5.

Speed/Time Curves for Different Services

Fig (a) represents the city or urban service speed time curve. Here the values of acceleration and retardation are high. Due to short distances between stops, there is no possibility of free-running period but there is a short coasting period.

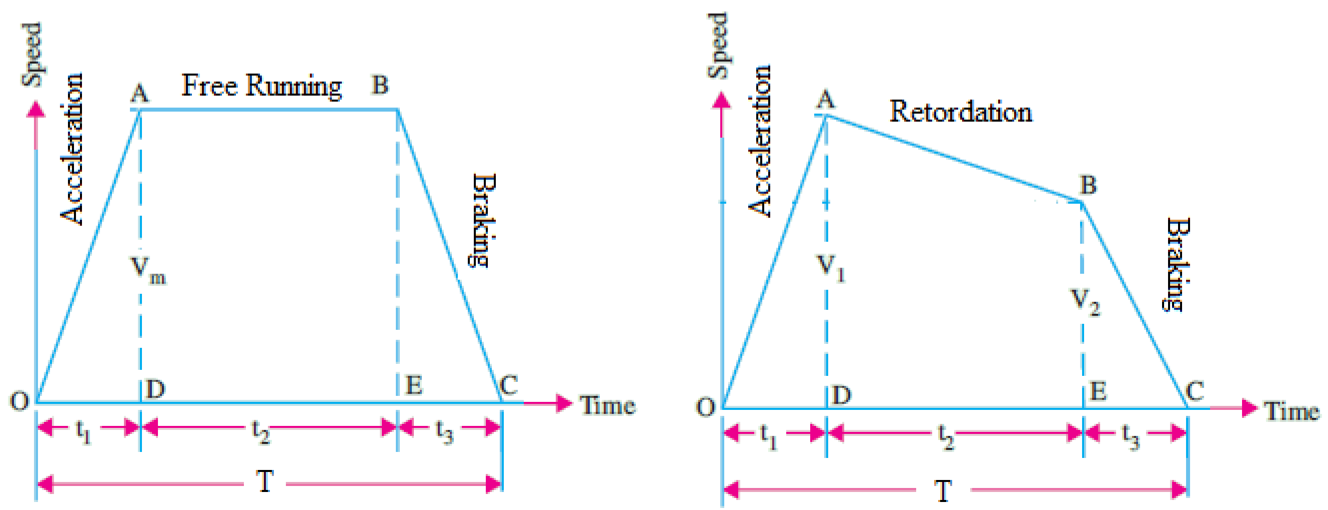
In suburban services [Fig. (*b*)], again there is no free-running period but there is comparatively ***longer*** coasting period because of longer distances between stops. In this case also, the values of acceleration and retardation are relatively high.



For main-line service, as shown in Fig.(c), there are long periods of free-running at high speeds. The accelerating and retardation periods are relatively unimportant.

Simplified Speed/Time Curve

For the purpose of comparative performance for a given service, the actual speed/time curve is replaced by a simplified speed/time curve which does not involve the knowledge of motor characteristics. Such a curve has simple geometric shape so that simple mathematics can be used to find the relation between acceleration, retardation, average speed and distance etc. The simplified speed/time curve is of two shapes:



(i) Trapezodal Speed time curve (ii) Quadrilateral Speed time curve

(i) Trapezoidal speed time curve: Here the running and coasting periods of the actual speed/time curve have been replaced by a constant speed period. It is found that trapezoidal speed time curve represents main-line service on level track.

(ii) Quadrilateral speed time curve: This speed time curve represents Urban or sub-urban service.

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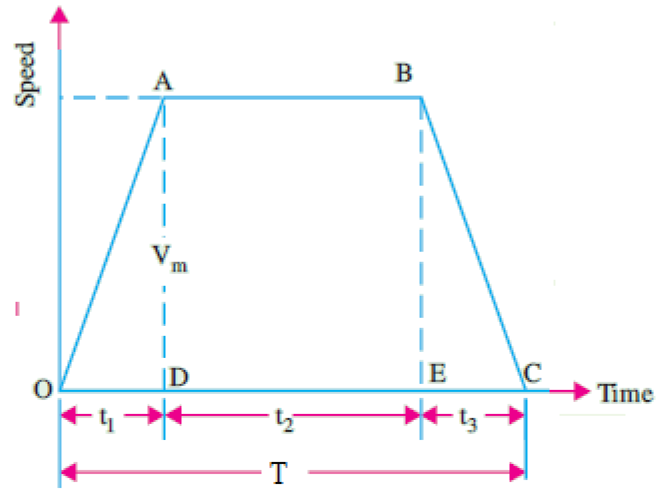


Let D = distance between stops ;
α = Acceleration during starting period ;
β = Retardation during braking
V_a = Average speed ; V_m = Maximum (or crest) speed
T = Actual time of run or Total time for the run
t_1 = Time of acceleration ;
t_2 = Time of free running = T − (t_1 + t_3) ;
t_3 = Time of braking

From the figure

α = Acceleration during starting period = $\frac{V_m}{t_1} \rightarrow t_1 = \frac{V_m}{\alpha}$

β = Retardation during braking = $\frac{V_m}{t_3} \rightarrow t_3 = \frac{V_m}{\beta}$

Distance covered D = area OABC = area OAD + area ABED + area BCE

$$= \frac{1}{2} V_m t_1 + V_m t_2 + \frac{1}{2} V_m t_3$$

$$= \frac{1}{2} V_m t_1 + V_m [\mathrm{T} - (t_1 + t_3)] + \frac{1}{2} V_m t_3$$

$$= V_m \left[\frac{t_1}{2} + \mathrm{T} - t_1 - t_3 + \frac{t_3}{2}\right] = V_m \left[\mathrm{T} - \frac{1}{2}(t_1 + t_3)\right]$$

$$= V_m \left[\mathrm{T} - \frac{V_m}{2}\left(\frac{1}{\alpha} + \frac{1}{\beta}\right)\right] \quad \text{Let, } K = \frac{1}{2}\left(\frac{1}{\alpha} + \frac{1}{\beta}\right)$$

$$\therefore D = V_m(\mathrm{T} - KV_m) \longrightarrow KV_m^2 - V_m \mathrm{T} + D = 0$$

$$\therefore \text{Maximum Speed, } V_m = \frac{\mathrm{T} \pm \sqrt{\mathrm{T}^2 - 4KD}}{2K}$$

Rejecting the positive sign which gives impracticable value, we get

$$\therefore \text{Maximum Speed, } V_m = \frac{\mathrm{T} - \sqrt{\mathrm{T}^2 - 4KD}}{2K}$$

Quadrilateral speed time curve: This speed time curve represents Urban or sub-urban service.

Let D = distance between stops ; α = Acceleration during starting period ; β = Retardation during braking
V_a = Average speed ; V_m = Maximum (or crest) speed; T = Actual time of run or Total time for the run
t_1 = Time of acceleration ; t_2 = Time of free running = T − (t_1 + t_3) ; t_3 = Time of braking

From the figure α = Acceleration during starting period = $\frac{V_1}{t_1} \rightarrow t_1 = \frac{V_1}{\alpha}$

β_c = Retardation during braking = $\frac{V_1 - V_2}{t_2} \rightarrow t_2 = \frac{V_1 - V_2}{\beta_c}$

β = Retardation during braking = $\frac{V_2}{t_3} \rightarrow t_3 = \frac{V_2}{\beta}$

Distance covered D = area OABC

= area OAD + area ABED + area BCE

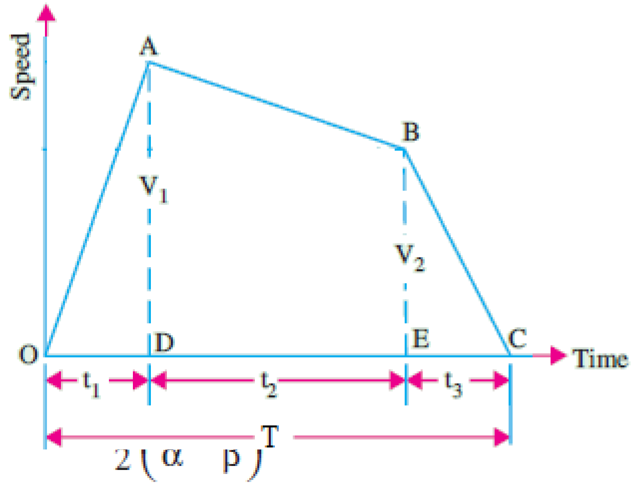
$$= \frac{1}{2}V_1 t_1 + t_2\left(\frac{V_1 + V_2}{2}\right) + \frac{1}{2}V_2 t_3$$

$$= \frac{1}{2}V_1(t_1 + t_2) + \frac{1}{2}V_2(t_2 + t_3)$$

$$= \frac{1}{2}V_1(T - t_3) + \frac{1}{2}V_2(T - t_1)$$

$$= \frac{1}{2}T(V_1 + V_2) - \frac{V_1 t_1}{2} - \frac{V_1 t_3}{2}$$

$$= \frac{1}{2}T(V_1 + V_2) - \frac{1}{2}V_1 V_2\left(\frac{1}{\alpha} + \frac{1}{\beta}\right)$$



Distance covered, D = $\frac{1}{2}T(V_1 + V_2) - KV_1V_2$

β_c = Retardation during braking = $\frac{V_1 - V_2}{t_2}$

$$\therefore \; V_2 = V_1 - \beta_c t_2 = V_1 - \beta_c(T - t_1 - t_3)$$

$$= V_1 - \beta_c\left(T - \frac{V_1}{\alpha} - \frac{V_2}{\beta}\right) = V_1 \beta_c\left(T - \frac{V_1}{\alpha}\right) + \beta_c \frac{V_2}{\beta}$$

$$V_2\left(1 - \frac{\beta_c}{\beta}\right) = V_1 - \beta_c\left(T - \frac{V_1}{\alpha}\right)$$

$$\therefore \; V_2 = \frac{V_1 - \beta_c(T - V_1/\alpha)}{(1 - \beta_c/\beta)}$$

Tractive Effort: It is the force developed by the traction motor at the wheel rims to move the train. It is represented y F_t. The tractive force developed by the traction motor has

- To overcome the liner acceleration of the train
- To overcome the train resistance
- To overcome the gravitational force.

Tractive effort during acceleration:

Let W = Mass of the train in ton

α = Acceleration in *kmphps*

According to newton's 2nd law of motion,

Tractive effort during acceleration F_a = Mass *x* acceleration

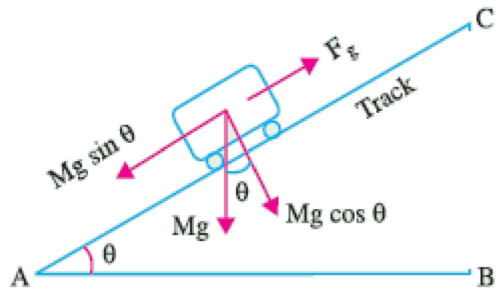
$$= 1000W \, x \, \alpha \frac{5}{18} = 277.8 \, W \, \alpha$$

Tractive effort to overcome the train resistance:

The tractive effort is needed to balance the resistance to the train motion. The train resistance is due to friction at the track, friction at various rolling parts and air resistance.

Let r is train resistance, tractive effort to overcome the train resistance F_t = W r

Tractive effort to overcome the gravitational force: When the train is moving on the up gradient as shown in figure, the train mass W is resolved into WCosθ and WSinθ. The WSinθ component opposes the motion of the train. To overcome this opposition, an additional tractive force is required and is given by $F_g = 1000W \times 9.81 W Sin\theta$



In railway practice, gradient is expressed as the rise (in metres) a track distance of 100 m and is called percentage gradient i.e

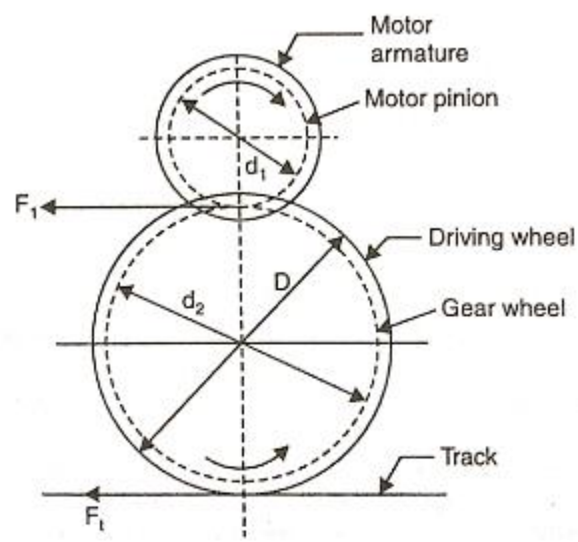
$\%G = 100 Sin\theta \rightarrow Sin\theta = G/100$

$\therefore F_g = 1000W \times 9.81 (G/100) = 98.1WG$

$$\text{Total tractive effort } F_t = F_a + F_r \pm F_g = 277.8\, W\, \alpha + W\, r \pm 98.1WG$$

The positive sign for F_g is taken when motion is along an ascending gradient (up gradient) and negative sign when motion is along a descending gradient (down gradient).

Mechanism of Train Movement: The essentials of driving mechanism in an electric vehicle are illustrated in below Figure. The armature of the driving motor has a pinion which meshes with the gear wheel keyed to the axle of the driving wheel. In this way, motor torque is transferred to the wheel through the gear.



Let, T = torque exerted by the motor;

F_1 = tractive effort at the pinion

F_t = tractive effort at the wheel;

γ = gear ratio = d_2/d_1 ;

D = diameter of the driving wheel

d_1, d_2 = diameters of the pinion and gear wheel;

η = efficiency of power transmission from the motor to driving axle

Now,

Torque developed by the motor $T = F_1 \times d_1/2$

Tractive effort at the pinion $F_1 = 2T/d_1$

Tractive effort transferred to the driving wheel $F_t = \eta F_1 \frac{d_2}{D} = \eta \frac{2T}{d_1}\frac{d_2}{D}$

$$= 2\eta \frac{d_2}{d_1}\frac{T}{D} = 2\eta\gamma\frac{T}{D}$$

Power Output from the driving wheel:

Let F_t = Tractive effort, V = Speed of the train, P = Power output

Power output = Tractive effort (F_t)* Train speed (V) = $F_t V$ in watts if V in m/sec

$= \frac{F_t V}{3600}$ KW if V in Km/Hr

Power input to motor = Power output/η $= \frac{F_t V}{\eta * 3600}$ KW

Adhesive Weight:

The adhesive weight of a train is ***equal to the total weight to be carried on the driving wheels***. It is less than the dead weight by about 20 to 40%.

Coefficient of Adhesion:

It is defined as the ratio of tractive effort required to slip the driving wheels to the adhesive weight. It is represented by μ.

$$\text{Coefficient of Adhesion } \mu = \frac{\text{Tractive effort required to slip the driving wheels } (F_t)}{\text{Adhesive weight } (W_a)}$$

Tractive effort required to slip the driving wheels = μ . Adhesive weight = μ (gW_L)

$= \mu\,(9.81*1000*W_L)$

$= 9810\,\mu\,W_L$

The value of Coefficient of Adhesion μ may varies based on the following factors

i. Train speed – Higher the train speed, lower the Coefficient of Adhesion
ii. Rail or track condition – If Rail or track is wet or greasy, the coefficient of adhesion is 0.15 to 0.2. For dry or clean track, the coefficient of adhesion is 0.25 to 0.33.

Example . *A goods train weighing 500 tonne is to be hauled by a locomotive up an ascending gradient of 2% with an acceleration of 1 km/h/s. If coefficient of adhesion is 0.25, train resistance 40 N/t and effect of rotational inertia 10%, find the weight of locomotive and number of axles if load is not to increase beyond 21 tonne/axle.*

Solution. It should be clearly understood that a train weighing 500 tonne

$$\text{Tractive effort required } F_t = 277.8\,a\,(500+W_L) + (500+W_L)r + 98(500+W_L)\,G$$

$$= (500+W_L)(277.8\times 1\times 1.1 + 98\times 2 + 40) =$$

$$= (500+W_L)\,541.6 \quad \text{------ (1)}$$

If W_L is the mass of the locomotive, then

$$F_t = 9810\,\mu\,W_L = 9810*0.25*W_L \quad \text{------ (2)}$$

From equations (1) and (2)

$$(500+W_L)\,541.6 = 9810*0.25*W_L$$

Weight of the locomotive $W_L = 142T$

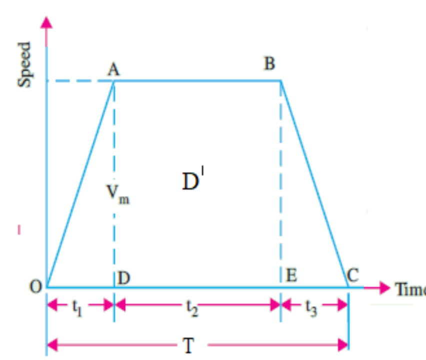
Hence, weight of the locomotive is 142 tonne. Since, weight per axle is not to exceed 21 tonne, the number of axles required is = 142/21 = 7.

Specific Energy Consumption (E_{spc}):

It is defined as the energy consumed (*Wh*) per tonne mass of train per *Km* length of the run. i.e

$$\text{Specific Energy Consumption } (E_{spc}) = \frac{\text{Total energy consumed (Wh)}}{\text{Train Mass (Tonne)} * \text{Run length (Km)}}$$

$$= \frac{\text{Specific energy output}}{\eta_{motor} * \eta_{gear}}$$



To find the specific energy output, first calculate the total energy output of the driving wheel and then divide it by train mass (tonne) and route length (Km). The output of the driving axles is used for accelerating the train, overcoming the gradient and overcoming the train resistance.

Consider the trapezoidal speed time curve as shown in figure.

Let D' = total distance over which the power remains 'ON' i.e from start to the end of the free running period in trapezoidal curve or from start to end of accelerating period in quadrilateral curve.

Energy required for train acceleration (E_a)

from trapezoidal diagram $E_a = F_a \times \text{distance } OAD = 277.8\,\alpha\, W_e \times \frac{1}{2} V_m . t_1$

$$= 277.8\,\alpha\, W_e \times \frac{1}{2} V_m \times \frac{V_m}{\alpha}$$

$$= 277.8\,\alpha\, W_e \times \left[\frac{1}{2} . \frac{V_m \times 1000}{3600} \times \frac{V_m}{\alpha}\right]$$

It will be seen that since V_m is in km/h, it has been converted into m/s by multiplying it with the conversion factor of (1000/3600). In the case of (V_m / t), conversion factors for V_m and a being the same, they cancel out. Since 1 Wh = 3600 J.

$$\therefore \quad E_a = 277.8\,\alpha . W_e \left[\frac{1}{2} . \frac{V_m \times 1000}{3600} \times \frac{V_m}{\alpha}\right] \text{Wh}$$

$$= 0.01072\, W_e\, V_m^2 \ \text{Wh}$$

Energy required for over coming gradient (E_g)

Let 'D'' is the *total distance over which power remains* ON. Its maximum value equals the distance represented by the area *OABE* in Fig. *i.e.* from the start to the end of free-running period in the case of trapezoidal curve

$E_g = 98\,WG.\,(1000\,D')$ joules $= 98{,}000\,WGD'$ joules It has been assumed that D' is in km.

When expressed in Wh, it becomes

$$E_g = 98{,}000\,WGD' \frac{1}{3600} \text{ Wh} = 27.25\,WGD' \text{ Wh}$$

Energy required for overcoming resistance (E_r)

$$E_r = F_r \times D' = W . r \times (1000\,D') \text{ joules} \qquad \text{— } D' \text{ in km}$$

$$= \frac{1000\,Wr\,D'}{3600} \text{ Wh} = 0.2778\,Mr\,D' \text{ Wh} \qquad \text{— } D' \text{ in km}$$

$\therefore$ total energy output of the driving axles $E = E_a + E_g + E_r$

$$= (0.01072\, V_m^2\, W_e \pm 27.25\, WGD' + 0.2778\, Wr\, D' \text{ Wh}$$

Specific energy output $E_{spo} = \dfrac{E}{W \times D}$ — D is the *total* run length

$$= \left(0.01072 \frac{V_m^2}{D} . \frac{W_e}{W} + 27.25\, G \frac{D'}{D} + 0.2778\, r \frac{D'}{D}\right) \text{Wh/t-km}$$

It may be noted that *if there is no gradient*, then

$$E_{spo} = \left(0.01072 \frac{V_m^2}{D} . \frac{M_e}{M} + 0.2778\, r \frac{D'}{D}\right) \text{Wh/t-km}$$

Problem: *The average distance between stops on a level section of a railway is 1.25 km. Motor-coach train weighing 200 tonne has a schedule speed of 30 km/h, the duration of stops being 30 seconds. The acceleration is 1.9 km/h/s and the braking retardation is 3.2 km/h/s. Train resistance to traction is 45 N/t. Allowance for rotational inertia is 10%. Calculate the specific energy output in Wh/t-km. Assume a trapezoidal speed/time curve.*

Solution.

Accelaration $\alpha = 1.9 \times 5/18 = 9.5/18 \text{ m/s}^2$: Retordation $\beta = 3.2 \times 5/18 = 8/9 \text{ m/s}^2$

we know $K = \frac{1}{2}\left(\frac{1}{\alpha} + \frac{1}{\beta}\right) = 1.5$; Distance $D = 1.25 \text{ km} = 1250 \text{ m}$

Schedule time $= 1.25 \times 3600/30 = 150$ s. Running time $= 150 - 30 = 120$ s

We have $KV_m^2 - V_m T + D = 0$

$$V_m = \frac{t - \sqrt{t^2 - 4KD}}{2K} = \frac{120 - \sqrt{120^2 - 4 \times 1.5 \times 1250}}{2 \times 1.5} = 10.4 \text{ m/s} = \mathbf{37.4 \text{ km/h}}$$

Braking distance $D_3 = \frac{1}{2} V_m t_3 = \frac{1}{2} \frac{V_m^2}{\beta} = 10.42/2 \times (8/9) = 0.06 \text{ km}$

$$\therefore D' = D - \text{braking distance} = 1.25 - 0.06 = 1.19 \text{ km}$$

$$\text{Specific energy output} = 0.01072 \frac{V_m^2}{D} \cdot \frac{M_e}{M} + 0.2778\, r \frac{D'}{D}$$

$$= 0.01072 \times \frac{37.4^2}{1.25} \times 1.1 + 0.2778 \times 50 \times \frac{1.19}{1.25} \text{ Wh/t-km}$$

$$= 16.5 + 13.2 = \mathbf{29.7 \text{ Wh/t-km}}$$

General Features of Traction Motor:

Electric Features:

- High starting torque
- Series Speed - Torque characteristic
- Simple speed control
- Possibility of dynamic/ regenerative braking
- Good commutation under rapid fluctuations of supply voltage.

Mechanical Features:

- Robustness and ability to withstand continuous vibrations.
- Minimum weight and overall dimensions
- Protection against dirt and dust

No type of motor completely fulfils all these requirements. Motors, which have been found satisfactory, are D.C. series for D.C. systems and A.C. series for A.C. systems. While using A.C. three phase motors are used. With the advent of Power Electronics it is very easy to convert single phase A.C. supply drawn from pantograph to three phase A.C.