ELEC7404 Advanced Railway Engineering

1 Railway Operation

1.1 Railway System

Railway is to move people and/or goods in a train from one place to another, in a safe, timely and sustainable manner.

For different types of railway system, including

	High Speed Railway [HSR]	Suburban Rail	Metro	Light Rail	Tram	Automatic People Mover [APM]
Route length [km]	142 [HK to GZ]	41.1 [e.g. TCL/WRL]	16 [ISL]	36.2 [few km]	29 [HK]	2.5 [HK – AA]
Journey Time [min]	50	45	31			
Headway [min]	4 operating (3 design headway)	2.73 (27 trains/hr)	1.87	3	1 - 2	2.4
Speed [kph]	200 - 300	120 (average 50)	80 (average 33)	15 - 80	9 - 42	20 – 70 [62]
Stop	6	12	17	68	118	3
Train Length [m]	200 (8 cars)	292 (12 cars, converter to 9 cars)	184 (8 cars)	19.4 x 2 cars	9	9.85 x 4 cars
Capacity	160000 p/day, 580 p/train	3600 p/ train	2400 p/ train	393000 p/day, 248 p/ car	230000 p/ day, 140 p/traim	76 p/car
Design max loading [pphpd]	580 p/train x 60/3 train/h/d = 34800	3600 x 27 = 97200	2400 x 32 = 76800	496 p/LR x 60/3 = 9920	140 p/tram x 60/2 = 8400	304 p/tram x 60/2.4 = 7600
Fare	High	Significant	Cheap	Cheap	Cheap	Free
Comfortability	High (Limited Lateral Acc.)	Low (Limited Seating)	Low (Limited Seating)	Low (Mainly Standing Passenger)	Low (Mainly Standing Passenger)	
Safety Measures	Crashworthiness Design	Crashworthiness Design	High Risk with High Capacity			
Others	8 cars ~ 10MW 16 cars ~ 16 MW	High Passenger Capacity	Low Dwell Time (with more doors) High Acc. & Braking		550V, 2 x 25 kW DC	600V AC Supply, 110kW DC Shunt

For Magnetic Levitation (Maglev), it is propelled with linear magnets in 450kph with superconducting magnets as bogie placed underneath the train, and rubber wheels to rest and operate at low speed (< 150kph). Hyperloop with suspension and propulsion in vacuum tube can reach 700kph.

Tobu Kyuryo Line (LINIMO): 9 km long levitated by attractive force of conductive magnetics operated with linear induction motor (10 units, 39.8 kW per car) with VVVF control.

1.2 Railway Operation (Safety Vs Economy)

Operation Management of Railway System requires: Engineering, Marketing, Service/Product Development, Human Resources, Accounting & Finance, and Purchasing. Public expects railway in high level of safety (as compared to road traffic). Risk is dependent on speed and corresponding safety measures.

Operation Tasks

1. Train Plan (Train Schedule/Timetable): Specification, Weekly Plan, Timing, Publishing
2. Performance Management: Passenger Journey on time, Train Punctuality, Train Service Delivery, Reliability to ticketing gate and lift and escalator, Customer Service Pledge (inc. train reliability, ticket reliability, station temp and ventilation, station cleanliness, enquiry response time), Customer Satisfaction, Maintenance Management, Emergency Operation
3. Safety Management: Safety Performance (inc. serious rail accident such as collision, derailment, fatal and serious injury), Rule Books, Continuous Improvement (inc. better measurement, risk management and equipment such as CCTV), Safety Culture, Improved Signaling
4. Human Resources Management: Engineering Staff, Crew, Signaler, Supervisor Management (Organization, Recruitment and Promotion, Training and Development, Refresher, Competence Assessment), Staff Management, O&M Staff Roster

To conclude, Railway Operation is to 1) set the specification/ operation requirement, 2) design effective operation plan, 3) publish the plan, 4) resource the plan, 5) execute the plan safely and effectively, 6) monitor the effectiveness and 7) excel the plan (plan-do-check-act)

1.3 Line Capacity

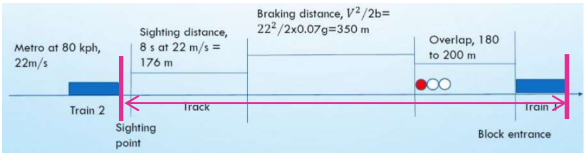
It is expressed in unit of **trains/hr/dir**. or **passengers/hr/d**. The factors are **number of tracks**, **signaling**, **aspects, sighting distance**, **junctions**, **train length**, **train performance** (acc/braking, auto/manual), **train capacity** (seats and standing space, 2 – 6 passengers/m^2), and **stopping time** at station.

Line Capacity Calculation:

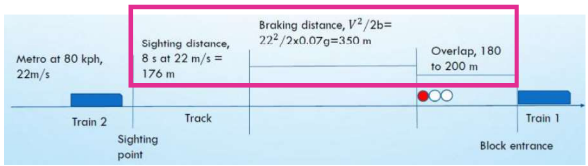
1. Determine section carrying peak number of passengers in passenger/hr/dir or train/h/dir
2. Calculate train capacity = (no. of seated passenger + no. of standing passenger) x no. of car
3. Standing Passenger = passengers / m^2 (4 – 6, or 8 in metro) x standing area
4. Calculate no. of trains required per hour to carry peak hour load.
5. Determine the peak load passenger carrying capacity (passenger / train x train / hr/ d)

1.4 Headway

Time elapsed between passing of front of one train and passing of front of the next is headway. It is the **minimum time** between trains the signal will permit such that the next train is not affected by train ahead. It depends on the train performance, signaling performance and dwell time.



As the driver needs sighting point, **sighting distance**, **braking distance** and **overlap** (safety margin), headway can be divided into **technical headway** (calculated with defined train braking profile and signaling system), and **operating headway** (defined by train timetable purpose and inc. time elapsed for junction, multiple line sections, station stops and reversal)



Dwell time is dependent on **door opening** (stopping accuracy, speed, release strategy e.g. pneumatic/electric), **boarding** (platform design with no. of entrance and exits), platform space (width, stand back), train designs (no. of door and its width), **door closing** (staff and passenger culture), **train application** (driver training, technology, acceleration and braking, response time), extra doors such as automatic platform gates.

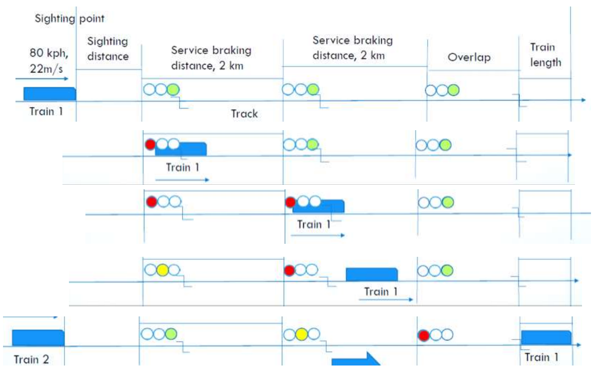
For a 4-aspect signaling system with technical headway of 90s and train speed 160kph, the operating headway will be > 180s to allow for **junctions**, **variable train speed**, **driving techniques**, **sighting problems** at specific location, **variation in block length** to accommodate station and other structure.

1.5 Signalling

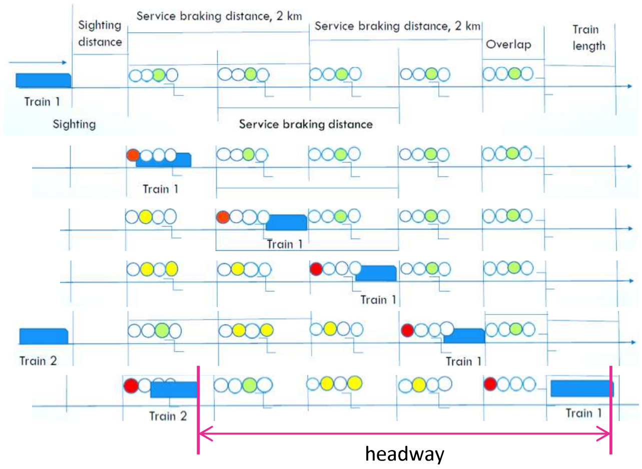
Training signal is to convey movement authority message to drivers on **next location** [m] and **speed** [kph], and junctions to avoid **conflicting moves**. It maintains safe operation, safeguard the movement to avoid conflicting moves and avoid movement in conflict with the infrastructure.

Technical Headway Distance = a x BD + SD + Overlap + Train length (where a = 2 for 3-aspect signalling, and a = 1.5 for 4-aspect signalling)

3-aspect signaling



4-aspect signaling



Example [Headway and Capacity]

A metro adopted a **3-aspect signaling system**.

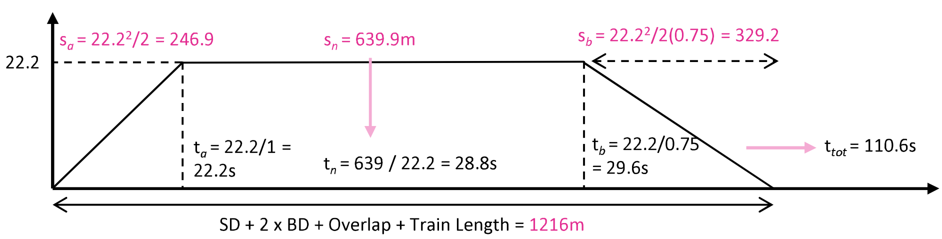
Given that
Length of Train = 180 m (manual driven)
Braking Rate b and acceleration a = 0.75 ms^{-2}, 1 ms^{-2}
Sighting Time = 8s
Max Line Speed = 80 kph (22.2 m/s)

(a) Calculate its minimum headway and technical capacity in trains/hr.
(b) Given also a station with 200m platform and 30s dwell time, calculate the min headway and operating throughput.

Solution

(a) Assume overlap = 200m.
Minimum Technical Headway = SD + 2 x BD + Overlap + Train Length
= 8 x 22.2 + 2 x 22.2^2 / 2 x 0.75 + 200 + 180 = 1216 m
Technical Time Headway = 1216 / 22.2 = 55.3 s
Service Headway Throughput = 3600s / 55.3s = 65.1 trains/hrs

(b) The new headway includes run-in time, run-out time and dwell time.
Run-in Time = 22.2 / 0.75 = 29.6s, Run-in Distance = v^2 / 2b = 22.2^2/ 2 x 0.75 = 329.2 m
Run-out Time = 22.2/ 1 = 22.2s, Run-out Distance = 22^2 / 2 x 1 = 246.9 m
Remaining Full Speed Distance = 1216 – 329.2 – 246.9 = 639.9 m, i.e. 639.9 / 22.2 = 28.8s at line speed.
New Headway Time = 28.8 + 29.6 + 22.2 + 30 = 110.6 s
New Theoretical Throughput = 3600 / 110.6 = 32.5 trains/hrs (32 tph)
Operating Throughput = 32.5 x 75% = 24.4 trains/hr (24 tph)

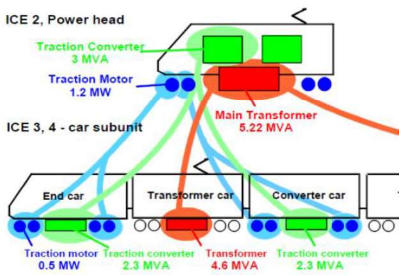


2 Railway System Design (I)

2.1 Train Type

with IGBTs

	Distributed Power	Conc. Power [Locomotive]	Loco Hauled
Propulsion	Small and More Motor	Large and Less Motor	Large and Less Motor
Performance	Higher Adhesion (Less Derailment)	Lower Adhesion	Lower Adhesion
Max. Axle Load	Lighter (17 ton/axle)	Heavier	Heavier
Passenger Cap.	More (more space for ppl)	2 cars less than distributed	1 cars less than distributed
Noise in Saloon	More (drive below ppl car)	Quiet	Quiet
Mains Cost	Low (smaller drives and traction control)	High	High
Flexibility in train set	Less	Less	High
Redundancy of main component	High	Low	Very Low



Electric Trains Vs Diesel Trains: better acceleration, no refueling (time saving & no pollution), higher reliability, low mains cost, regenerative braking helps save 10% - 20% energy cost, lighter in weight, better specific power (W/kg), quieter.

Other types includes **conventional trains** (2 bogies per car), **articulated trains** (bogies shared between 2 cars for better ride comfort), **tilting trains** (high speed at curves, shorter journey time), and **variable guage trains** (to avoid train change)

2.2 Car Body

	Mild Steel	Rust Proofed	Stainless	Aluminum
Mass	Heaviest	Heavy	Lower	Lightest
Deflection	Low	Low	Low	High
Corrosion R	Poor	Good	Best	Good
Fatigue Strength	Good	Good	Best	Worst
KE Absorption	Good	Better	Best	Least
Ease of Repair	Easy	Easy	Difficult	Difficult
Fire Resistance	Fair	Fair	Fair	Melt!

For HST to reduce traction power in long distance

Metro with Frequent service, best for fatigue load

Other Requirement

- **Structure Material**: Al for LRT and HSR Car Body, Stainless Steel for metro underframe
- **Design Life**: 25 – 40 years
- **Weight**: 310 ton (8-car, max) 17 ton/axle
- **Strength**: Proof, Fatigue, Collision and Energy Absorption
- **Purpose**: Support passenger load, protect against collision, facilitate loading/unloading

Strength Requirement for Car Body:

1. **Proof Load** (Car Body – Compressive and Tensile Load at Coupler, Compressive Load at windowsill and cant rail, braking load, passenger load, lifting and jacking load, twist load) Note: without permanent deformation
2. **Fatigue Load** (Vertical, Lateral and Longitudinal Loads under specific fatigue cycle)
3. **Collision and Energy Absorption** (Prevent Damage to train structure and coupler in event of collision with energy absorbed by coupler and anti-climber with plastic deformation, standard collision scenario: 8-car train in tare condition at speed up to 22.5kph collides with a similar train at parking brake applied.

[Note: Multi-stage Deformation Concept can be applied. Finite Element Method can evaluate the overall strength of car body.]

2.3 Bogie

Bogie frame holds wheels parallel, supports vehicle car body, runs stably on straight and curve track and carries braking, traction and suspension equipment.

Suspension is to isolate passengers from acceleration, absorb vibration and ensure ride comfort by reducing KE and prevent track/train damage.

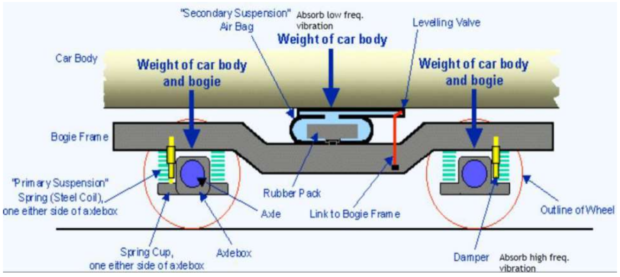
It is to maintain car sway (roll) within specific gauge and support car body firmly when running on straight and curved track without derailment risk by minimizing track force and track corrugation and wheel flange/rail wear.

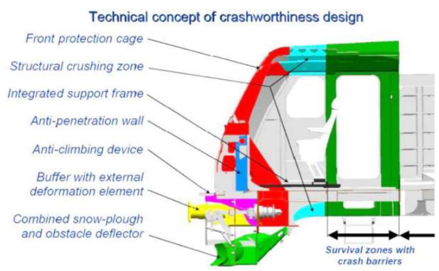
2.4 Wheel Set and Wheel Rail Contact

Wheel Load $F_w = M_c g/n_w = 40000 \times 9.81 / 8 = 49kN$

where M_c = mass of car, n_w = no of wheels, F_w = typical wheel load of a car

When the wheel and rail come into contact, the **contact stress** is higher than yield stress and materials deforms until 1300MPa. Stress distribution of Hertzian wheel-rail contact patch is ideally **parabolic** with **elastic deformation**. **Lateral displacement** of wheelset causes the wheels run in different radii and hence different speed.





Component	Description
Primary Suspension	includes a **coil spring** with a **viscous damper** (to dissipate energy), or a leave spring or friction damping. It attaches the weight of the bogies and equipment onto the axles and remove **high frequency vibration**
Secondary Suspension	is to remove **low frequency vibration** with **air-bags** for auto height and level adjustment, increase ride comfort and reduce noise. It can also be a coil spring
King Pin	transfer the traction and braking and guidance forces to the car body
Yaw Damper	prevents swaying side-to-side and reduce car body and bogie rotation (raises critical speed)
Hollow Axles	minimizes weight without losing stiffness and allow ultrasonic inspection

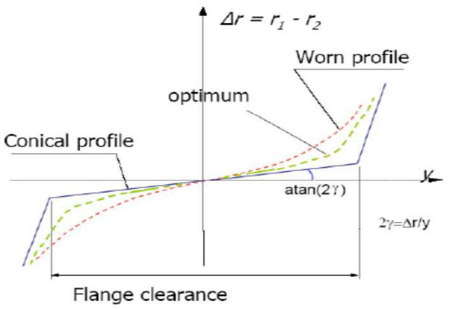
Rolling Radius Difference (RRD) is calculated as

$$\Delta r = r_1 - r_2 = (r + \gamma y) - (r - \gamma y) = 2\gamma y, \qquad 0.05 \le \gamma \le 0.2$$

Ratio of Rolling Radii of Left and Right wheel must equal to the radii of curvature of left and right rails, i.e.

$$\frac{r - \gamma y}{r + \gamma y} = \frac{R - l_0}{R + l_0} \qquad \text{Note: } 2l_0 = 1435 \text{ mm}$$

Wheel profile with **low conicity** is good for **running stability**. A conical profile can ensure good steering with high contact force. A worn profile has a less wear but it is unstable.



[Note: Trail should be designed to be dynamically stable under **all speed range** and **new and worn wheel profile**. Sufficiently high speed and high conicity can lead to continuous oscillation. Eventually the large lateral force can lead to derailment with kinematic oscillation.]

Suggestion: Variable Yaw Damping, Wheel/Rail Profile Optimization, Suspension Modification

Flange Climb Limiting Factor:

High Y due to changing rail section, hunting on straight track

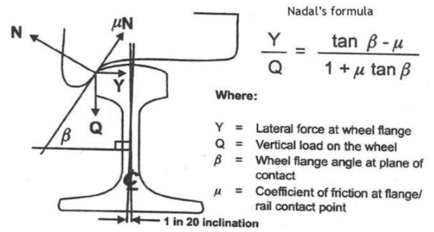
High β due to worn rail

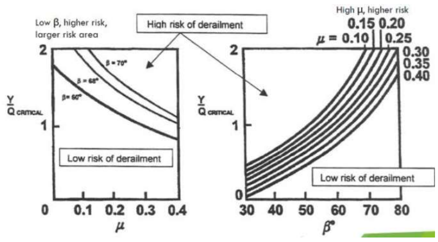
$$\frac{Y}{Q} = \frac{\tan\beta - \mu}{1 + \mu\tan\beta} > 1 \qquad \text{(Derailment)}$$

Low Q due to track twist, uneven loading, bogie failure

High μ due to ungreased rail

Condition	μ
Lubricated	0.1
Damp and Rusty	0.05-0.15
Wet and Clean	0.2
Dry and Rough	0.35-0.45





2.5 Coupler

- It connects cars (air and electric systems) together and **transfers traction loads** (push/pull, crashes)
- It provides **longitudinal suspension** and buffer to absorb compressive load.
- It can be manually or automatically coupled with permanent/ semi-permanent connection.
- Technician required to get between cars to manually lift the **shackle in position manually** and connect air and electric hoses.

2.6 Risk Matrix – Likelihood x Consequence

R1 (High Risk): Must be reduced

R2 (Size of Risk Vs Cost): Must be reduced if it is reasonably practicable to do so

R3 : Tolerable but should be further reduced if it is cost effective to do so

R4 (Low Risk): Acceptable

	Consequence				
Likelihood	1	2	3	4	5
5	M	H	H	H	H
4	M	M	H	H	H
3	L	M	M	H	H
2	L	L	M	M	H
1	L	L	L	M	M

Frequency Category	Risk Levels			
Frequent	Undesirable	Intolerable	Intolerable	Intolerable
Probable	Tolerable	Undesirable	Intolerable	Intolerable
Occasional	Tolerable	Undesirable	Undesirable	Intolerable
Remote	Negligible	Tolerable	Undesirable	Undesirable
Improbable	Negligible	Negligible	Tolerable	Tolerable
Incredible	Negligible	Negligible	Negligible	Negligible
	Insignificant	Marginal	Critical	Catastrophic
	Severity Levels of Hazard Consequence			

Risk Level	Actions to be applied against each level
Intolerable	Shall be eliminated
Undesirable	Shall only be accepted when risk reduction is impracticable and with the agreement of the Railway Authority
Tolerable	Acceptable with adequate control and with the agreement of the Railway Authority
Negligible	Acceptable with/without the agreement of the Railway Authority

Example 1 [Conicity]

A sub-urban rail route with a minimum radius of curvature of **800 m** with a speed limit of **150 kph**.
The track gauge is **1435 mm**, and the curved track is normally canted. The conicity is **1 in 20**.
Calculate the lateral shift of a wheel set on a minimum radius of curvature assuming perfect curving and a nominal wheel diameter of **860 mm**.

Solution

Given that

$$\frac{r - \gamma y}{r + \gamma y} = \frac{R - l_0}{R + l_0} \to \frac{430 - \frac{y}{20}}{430 + \frac{y}{20}} = \frac{800000 - \frac{1435}{2}}{800000 + \frac{1435}{2}} \to y = 7.75\text{mm}$$

Example 2 [Conicity]

a) A train, with wheel sets of **1000 mm diameter wheels**, has the wheels profiled to **1 : 20 conicity** and travels around a curve with the **lateral displacement measured at 6 mm**. Assuming perfect curving, calculate the radius of the curve (in m). The nominal track gauge is **1435 mm**.

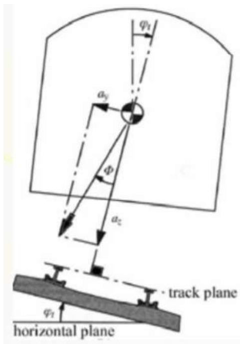
b) According to Railway Group Standard GC/RT5021, the max. permissible cant deficiency on plain line CWR is **110 mm** at the rail head. Establish the max. line speed through the curve with the radius calculate in (a) (in km/h), assuming the curve is canted at 150 mm.

c) A train travels through the curve in (a), at the max. line speed calculated in (b). Assuming that the train body rolls **1.5 degree**, calculate **the lateral acceleration** experienced by the passengers and comment on whether this is acceptable or desirable.

Solution

a) Given that

$$\frac{r - \gamma y}{r + \gamma y} = \frac{R - l_0}{R + l_0} \to \frac{500 - \frac{6}{20}}{500 + \frac{6}{20}} = \frac{R - \frac{1435}{2}}{R + \frac{1435}{2}} \to R = 1195 \text{ m}$$



b) Note that equilibrium cant is the cant resulting zero acceleration in y-direction, i.e.

$$\begin{cases} a_y = \frac{v^2}{R}\cos\varphi - g\sin\varphi = \frac{v^2}{R}\cos\varphi - g\frac{h_t}{2l} \\ a_z = \frac{v^2}{R}\sin\varphi + g\cos\varphi \end{cases} \xrightarrow[a_y=0]{} h_{eq} = \frac{2l}{g}\frac{v^2}{R}$$

Cant Deficiency is that the provided cant is less than the equilibrium cant such that additional cant, i.e. a fictitious elevation, is needed to achieve equilibrium cant.

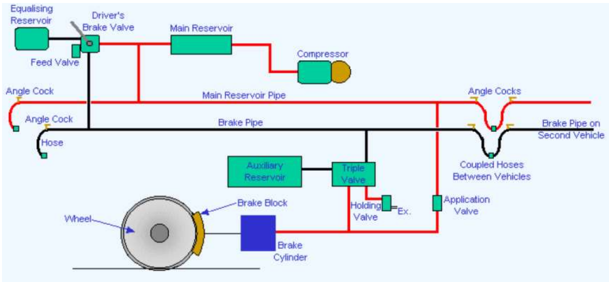
$$h_d = h_{eq} - h_t = \frac{2l}{g}\frac{v^2}{R} - h_t \to 110 = \frac{2\left(\frac{1435}{2}\right)}{9.81}\frac{v^2}{1195} - 150 \to v = 46.1 \text{ ms}^{-1} \text{ (165 kph)}$$

c) Lateral Acceleration =

$$a_y = \frac{v^2}{R}\cos\varphi - g\sin\varphi = \frac{(46.1)^2}{1195}\cos 1.5^o - 9.81\sin 1.5^o = 1.52 \text{ ms}^{-2}$$

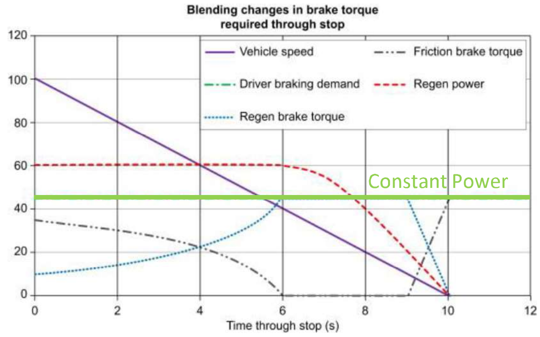
3 Railway System Design (II)

3.1 Braking System and Regenerative Braking



Types of Brakes:

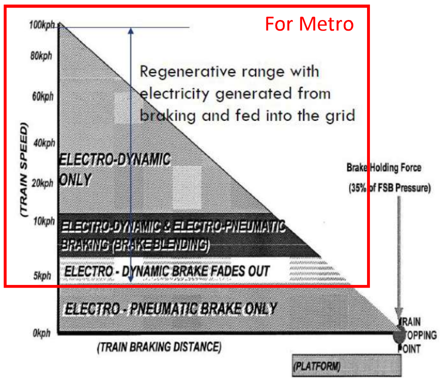
1. **Emergency brake**: Electro-pneumatic brake (EB) and/or pure pneumatic (air) braking
2. **Service brake**: Electro-dynamic brake (Regenerative Braking) + Electro-pneumatic brake (Frictional Braking by brake disks)
3. **Parking brake** (only apply at parking position): Mechanical brake/pneumatic brake only



Electro-Pneumatic Brake: It uses a number of train wires to control electrically operated brake valves in each car (i.e. no time lapse problem, or push-pull problem due to time lapse in different trains), It is connected to brake valve and controllers in driver console. It operates as service brake, whilst air brake remains as the emergency brake. It does not compromise the fail-safe features of air brake, i.e. under low air pressure, the brake block applies itself.

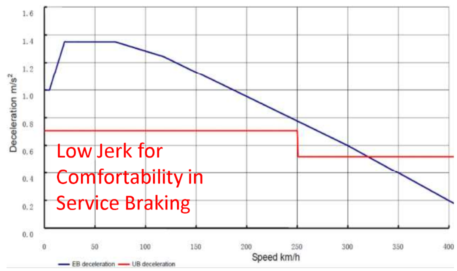
Regenerative Brake: It uses traction motors as generators to provide braking force. Power generated can be dissipated as heat with rheostats (rheostatic braking) or returned to the traction supply. Traction control system determines the braking forces required and decides if additional braking from air friction is needed. As regenerative braking effect drops off at low speed, friction braking takes over and stops the train.

Regen. Braking as Additional



Braking for High-Speed Train

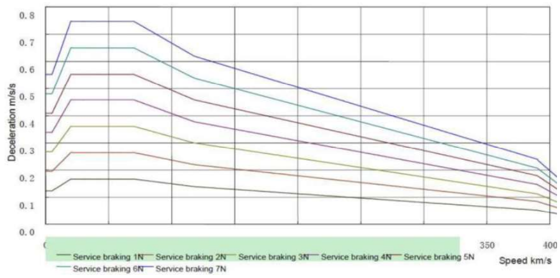
1. Emergency Braking: Safe Stopping Distance - 4 km at 300 kph. EPB as principle braking and air (pure pneumatic) as redundancy braking. Service Braking: by Regenerative and Rheostatic Braking (RB) with Electro-Pneumatic Braking (EPB), i.e. disks attached to axle for heat dissipation
2. Service Braking: Pneumatic Braking at each car, Regen. Braking at M car. Once when RB applied, RB takes priority to activate until addition friction braking is needed. (reduce wear of brake pads) Friction brake at low speed. [Note: Service Braking with 7 levels at driver controller (1 – 7N), 3 steps (1, 4, 7N triggered by ATP)
3. Automatic Control is required under blending mode (RB + EPB)
4. It is impossible to capture all braking energy through RB. Hence constant power braking by RB + EPB is needed. (with only RB can lead to long journey time and hence low throughput).
5. Parking Brake: Mechanical Brake for holding the train at 2% gradient at max. load condition and 3% at no-load condition. Parking brake is applied by the driver, and it is automatically applied at low air condition.



3.2 Design Features

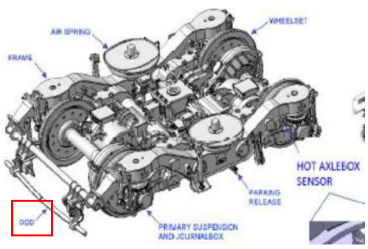
Urban Rail Line (URL):

- Car Loading (60kg/ passenger): Axle Integrity [450], KE Braking [375], Air Con / Parking Brake [300], Excavation [312]
- Train Performance: v_{MAX} = 80 kph, a_{MAX} = 1.1 – 1.2 ms^{-2}, ATO service brake = 0.8 ms^{-2}, Max Service Brake of M car= 1.35 ms^{-2}, Max Jerk = 0.8 ms^{-3}, Emergency Brake = 1.4 ms^{-2} (< 1.6s response time)
- Emergency Ventilation: > 1 hr with 2.5 m^3/s 100% fresh air per car, Emergency Saloon Lighting: > 1 hr after loss of OHL supply. Fire Load: 6.2 MW, spread of flame and smoke > 30 min.



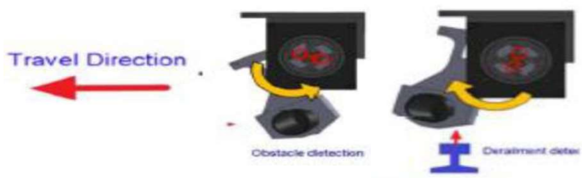
Shatin-to-Central Link (SCL) – 6M 3T

- Car Loading (65kg/passenger): > 323 person/car (6 person/m^2), Axle Load [18.3 ton], No Load train weight [4M: 307 ton, 5M: 320 ton], Excavation time [3042 person/train]
- Train Performance: v_{MAX} = 130 kph, a_{max} = 1 ms^{-2}, service brake = 1 ms^{-2}, jerk = 0.8 ms^{-3}, emergency brake = 1.35 ms^{-2} (< 1.8s response time).
- Emergency Ventilation: > 1 hr with 2.5 m^3/car, Emergency Lighting: > 1 hr after loss of OHL supply, Fire Compartment: > 30 min, Fire Load = 17 MW.
- Obstacle and Derailment Detection Device (ODD): Applied to detect obstacles > 6 mm and derailment. [Detrainment Door at each cab end and Detrainment Ladder at each PT car. Both can trigger TMS alarm].



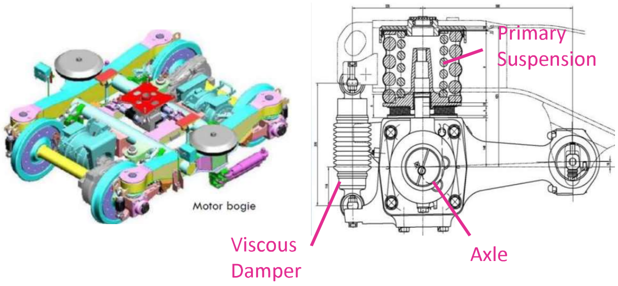
High Speed Rail Requirement:

- Service Journey [300 – 1500 km]
- System Features: Dedicated Line, Strong Track, 25kV Traction Supply, Fencing
- Rolling Stock – Electric Traction Drive, high MW, Effective Braking, Return Current Collection



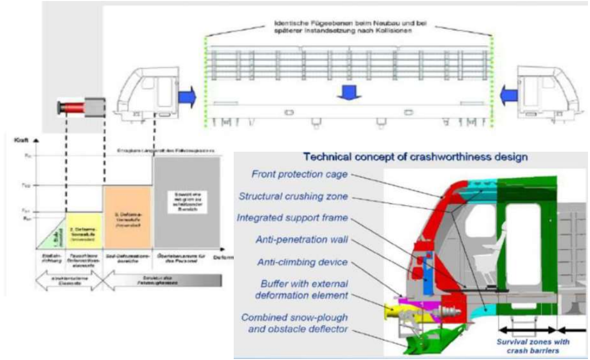
High Speed Rail [CRH380A in HK]

- 9 nos. 8 car train, 6M(16 motor bogie) 2T (4 trailer bogie), v_{MAX} = 350kph, capacity = 580, 25 years service life
- Car Body Structure: Welded anti-corrosion Al alloy structure, Head car length = 26.2 (Crashworthiness Design), Width = 3.38 m (Aerodynamics Concern), Height = 3.7m (tunnel height with pantograph), with air-tight treatment.
- Wheelset: Hollow Axle, Primary Spiral Steel Spring with Axle Box and Bearing, Secondary Suspension – Air spring with pressure differential valve.
- Bogie Monitoring Units – Speed Sensor, Stability Sensor, Air Spring Pressure Sensor, Axle Box Bearing Temp Sensor, Gearbox Temp Sensor



3.3 Crashworthiness and Derailment

- HSR running at 300kph can have **KE = 1388 MJ**. A car structure is designed for end load failure of 1960kN and crumples over ~ 1m to absorb ~ **2MJ / car** end.
- Train derails and collides with lineside structures or other trains. It aims to reduce passenger injuries due to collision with luggage, seats or other passengers. Anti-climbers locks together in train clash without overriding.
- Collision Energy Management: Crumple Zones and Collision Energy Distribution Crush Tubes are designed to collapse progressively, energy absorbed is calculated under impact force vs collapse distance graphs.
- [Shatin-to-Centre Line]: 6 < V < 10 kph: no damage to car except cover, sacrificial energy absorbers activated; 10 < V < 30 kph: damages confined to 1m of car ends.



- EN15227: a) Compression – Survival Spaces limited to <50mm for any 5m length, and cab survival space adjacent to driver seat maintain length and width of 0.75m, b) Deceleration – < 5g (gravitational), c) Overriding – with an initial vertical offset of 40mm, wheel life-off distance up to 100mm.
- **Design Approach**: Stage 1) 1D model to energy absorption, 2) 3D Nonlinear analysis for collapse zone, 3) Crashworthiness test to validate, 4) 3D Nonlinear FEM of train, 5) 1D model for collapse zone and coupler characteristics, 6) 1:1 model experiment, 7) 3D FEM under collision for compression, overriding, survival space and deceleration limit.
- **Cause of Derailment**:
    - P Way Defect: Gauge Spread, Broken Rail, Track Twist, Flange Climb, Thermal Track Buckle, Derailment on Switch and Crossing
    - Vehicle Defect: Broken Axle, Loosen Wheel, Locked Wheel, Broken Suspension, Failed Axle Bearing, Component Detached.
    - Operation: Collision with Trains or Buffer Stop, Mismanagement of Points, Excess Speed.

4 Railway System Maintenance

4.1 Maintenance Strategies and Asset Management

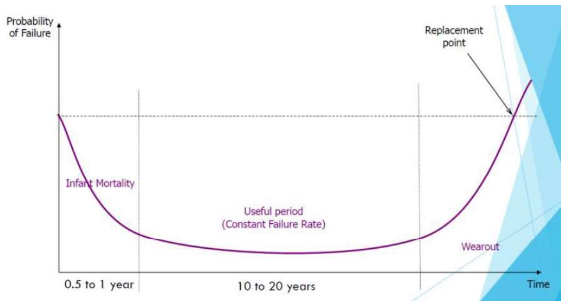
Railway System Maintenance is to **maximize asset values** and **optimize service costs**.

Railway System in Hong Kong adopts the **latest asset management** and railway assets **maintenance techniques**. Its evolution is with

- **Enhance understanding** of the railway **assets** and rolling stocks **maintenance requirements**
- **Big data systems** help collect maintenance, operation performance, failures data and asset life.
- Increasing needs of **availability** of Railway assets and minimized **downtime**.
- **Modular maintenance skills** are adopted to reduce downtime.
- Maintenance Strategies: **Condition-Based Monitoring** (CBM) is employed to extend maintenance period.
- **Safety Critical Items** (SCI) system has been used to focus critical items

Maintenance Strategies

1. Preventive Maintenance (PM)
    - **Time Based**: maintenance after a *predetermined km run* (e.g. traction motors, brakes) or *time elapsed* (eg. relays, electronic cards)
    - Intervals are determined by **experience** and past maintenance **statistics**
2. Corrective Maintenance (CM)
    - **Event Based**: Activities taken to **repair and restore** defective system back to normal status.
    - Suitable for low value **non-safety critical items** in which safety is not comprised
3. Condition-Based Maintenance (CBM)
    - **Sensors** to monitor the status of the system, determine **healthiness**
    - **Automation** determines the current **conditions** of component, and orders **replacement** for deteriorated items
    - Maximize use of components, e.g. train on-board management system, SCADA, and reduce maintenance and overhaul costs
4. Reliability Centered Maintenance (RCM)
    - **Statistical based** maintenance program, i.e. likelihood of failure
    - Common methods – RAM (Reliability availability maintainability), MTTF (Mean time between failure), MTTR (Mean time to repair), FMEA (Failure modes and effects analysis), FTA (Fault tree analysis), ETA (Event tree analysis), FMECA (Failure mode, effect and criticality analysis)



For **Preventive Maintenance**, it is divided into light preventive maintenance, train heavy maintenance and equipment overhaul.

Light Preventive Maintenance works to maintain day-to-day service conditions of the trains. It includes **inspection and adjustment** (e.g. lubrication oil level), **functional test** (e.g. batteries charging and discharging test), **routine cleansing** (e.g. annual cleaning of air-con), **calibration** (e.g. car leveling), **non-destructive test** (e.g. axle NDT), **re-conditioning** (e.g. commutator), **hard time replacement** subject to wear and tear (e.g. brake pad).

Train Heavy Maintenance is carried out in regular basis and divided into level 1 to 4 with balanced or cumulative examination to maintain a train over a specific cycle. It includes **equipment replacement**, **thorough inspection**, **deep cleansing**, **commissioning tests** and replacement or refill consumable parts of equipment such as rubber sealing or bearing.

Equipment Overhaul (Level 5) is to replace major components of bogies, engines, compressors, HVAC, couplers, doors and brakes. Equipment dismantled from trains is transported back to workshop to perform inspection, cleaning and replacement of components inside equipment. Functional tests is to confirm normal function before retrofitting to the train.

Corrective Maintenance requires high fault location techniques. It includes **in-situ repair** and **replacement** to rectify the fault. Functional test and performed in test track or running line after repair to ensure the fault is cleared. The faulty train is recovered as soon to reduce downtime.

Condition Based Maintenance is to maintain normal function of equipment at the right time determined by **health conditions** with real time data. It is to **prioritize and optimize** maintenance resources.

Safety Critical Item (SCI) is the items with integrity critical to safe operation of railway. Its failure can lead to accident involving **loss of life** or injury. Safety critical system includes traction system, coupler, bogie, wheel, axle, emergency brake system, car body structure, passenger door system, ATP, interlocking system. SCIs are maintained in accordance with established PM/CM maintenance procedures (with periodic audits, safety checks in record).

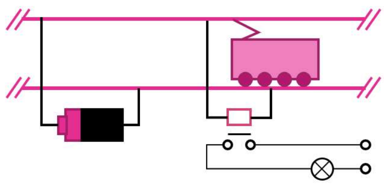
Check Type	Mileage / Maintenance Interval
I	6.75 kkm
BE	13.5 kkm (Supersede I-check)
Light Overhaul (L1 & L2)	660 kkm ± 66 kkm (3 years) Overhaul pattern: L1 – I – L2 - G
Intermediate Overhaul (I)	
General Overhaul (G)	
Interim Overhaul (T Check)	For safety and service critical systems: brake, bogie, wheel-set, door, coupler, traction control and main transformer

4.2 Track Position System

It can be divided into **track circuit** and **axle counter**.

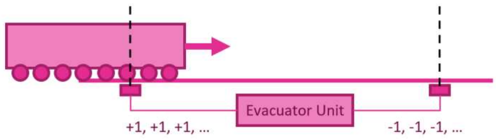
Track Circuit detects with sectionalized track, power sources and detection relay. It is a **fail-safe design** with red light ON with battery failure, **broken rail**, dropped obstacles, indicating presence of train. It is applicable to circuit with length 20 m to 5 km. It provides an accurate location of train front and the length of train.

DC Track Circuit



Axle Counter provides an alternative means for train detection when track circuit cannot be used, such as a long section of rail line. It includes at least 2 counter head (inductive) and an evaluation units to form a section. Counter heads are in pairs so that the **direction of travel** is detected. The 1st wheelset detected sets the status “occupied” and the whole train must leave the section before it is declared as “cleared”.

Axle Counter



4.3 Train Navigation Unit

It includes:

1. Odometry: Wheel driven tachogenerator (output with voltage proportional with velocity) and gear teeth counter. NOT good precision due to **wheel slip**.
2. Doppler Radar (Advanced Odometry): It transmits **ultra short waves signal** towards the track (devices, doppler transducer/receiver at underframe) and collect reflected signals from the track to calculate the speed of train by comparing the phase angle of signal. Yet, the surface must be retro-reflective (not with water and ice). It is suggested to use two beams with one forward and one backward with high intensity to calculate the mean.
3. Balises: It is divided into Active Balises, powered by signalling system, and Passive Balises, powered by the train. It is with precise location and can transmit several types of information inc. actual position and position-to-position. An odometry system may be needed to know the trains location between Balises. Reader antenna is on board.
4. GPS: A GPS receiver is installed on-board. Yet, reliability, availability and accuracy can be a problem.

4.4 Aerodynamics of Railway System

Aerodynamics resistance of air flow includes pressure drag from nose, tail, pantographs, inter-car gaps, underframes and skin friction drags from shear forces along the surfaces parallel to air flow. It can be estimated with Davis Equation, $F_d = A + BV + CV^2$, where A = rolling resistance, B = bearing friction and C = aerodynamics drag. Cross wind effect can lead to train sway and overturning. Train passing pressure with lateral air displacement can lead to rapid change in static pressure propagating laterally as a fatigue load. Slipstream effect can produce strong longitudinal airflow due to viscous shearing of train through air. Good aerodynamic design (e.g. with long nose) can reduce **train resistance** and hence **energy consumption**. It is also important to reduce **pressure variation** for passengers’ comfort with doors with inflatable seals, automatic closure of air-con vents, airtight compartment, large cross-section tunnel, and excess air-pressure inside train. When speed increase, pantograph and contact wire contact deteriorates results in sparks or excessive contact force. **Spark**, i.e. current collection, and **contact force** at OHL are measured to ensure within limits.

4.5 Next Generation Design

With increasing cost, particularly life cycle cost vs installation cost, safety requirement and comfortability, the next generation trains are designed with

1. Performance: enlarged **operation speed**, increased **capacity**, improved **comfort** (noise, vibration and environment), reduced **wear and tear**
2. **Safety design** of vehicle body and bogies, reduced **energy consumption** (by 50% compared to ICE 3 trains and 25% to ICE 2) with reduced drag, light-weight construction and energy management.
3. **Wind tunnel model** is employed to study cross wind stability, drag optimization, aerodynamic induced noise and tunnel passing aerodynamics.
4. Material: **Hybrid Al sandwich with folded core** structure provides low weight and high stiffness for floor and side panels, while **carbon fibre reinforced polymer** (CFRP) provides light weight and high strength for roof and intermediate floor structure.
5. Wheel rail computer simulation for **dynamic loads**, wheel/rail forces, **longitudinal wear**, **rail contact fatigue**.
6. Mechatronic system for active steering and running gear control to enhance **running stability**, wear and noise reduction
7. Traffic oriented microscopic simulator (TOMICS) was developed for individual passenger movements, entry and exit flow or between train and platform with different arrangement of seats, doors, toilet and stairs.

4.6 Safety Enhancement

It is to avoid train failure, e.g. collision, derailment or fire with proper handling of incident, train operation and goods handling. The methodology changes from compliance-based, risk-based, integrated management system and safety governance structure with human factor management. Safety Management System (implement, control and monitor) allows managers and supervisors to incorporate safety onto all tasks with objectives set out in the safety tasks and managing them through SM process to standard set out in safety modules.

5 Traction Drives and Control

5.1 Traction Motor

For Traction Applications, DC Series Wound Motor, DC Separately Excited Motor and AC Induction Motor are widely employed.

DC Series Motor

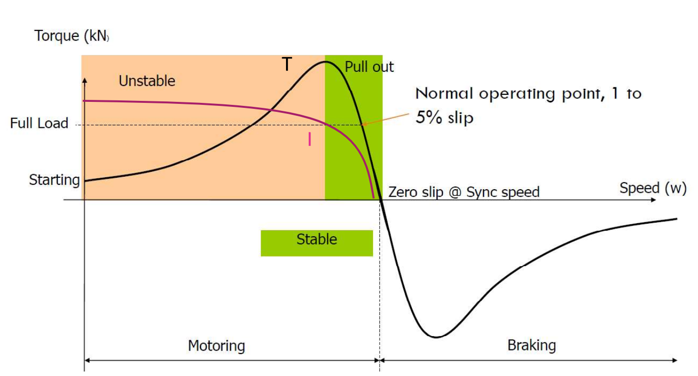
It has a simpler, small and robust design, with low voltage difference between coils giving **low insulation to copper ratio**. Its inherent characteristics **prevent overload** as speed increases and torque decreases. It has a **large starting torque** for heavy load, but it cannot provide regenerative braking. Field coil is formed from bare copper bar and cover with insulation tape, brazed together with insulation added, overheated and epoxy dipped. Second layer of insulation (750V: 2 layers, 1500V: 3 layers, 3000V: 5 layers) is then applied. Armature rotor is assembled with multiple thin laminations held together on a shaft with 300 – 700 stamped steel sheet insulated for reduction of **eddy current loss** and bolted together. The major problem is that it requires **continuous maintenance** with worn out carbon brush and dust from brushes can **short-circuit** the commutator.

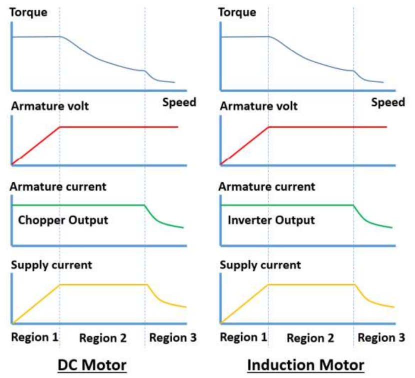
DC Separately Excited Motor

It provides independent control of speed and torque and regenerative braking. Yet, it requires two controllers.

3 Phase AC Induction Motor

For AC motor, windings are fixed to the stator to create rotating magnetic fields. With **balanced three phases**, magnetic field is constant. The magnetic field induces a voltage into rotor bars with shorted rings. For EMU applications, rotor configurations are **squirrel cages**, induction rotor with current induced within the rotor due to stator current, **electromagnetic wound rotor**, which is energized with DC to create constant magnetic field, and **permanent magnet**, with magnetic field created by permanent magnets within rotor. For induction motor, armature current is induced by stator field and slip between stator field and armature rotation speed. It requires a variable voltage variable frequency drive (VVVF) to operate at variable speed. 3 phase PWM IGBT inverter is preferred.





AC Synchronous Motor

Armature coil powered with DC through **slip ring** rotates at the same speed with field. It provides **constant speed** independent of load and **better power factor** than asynchronous machines. It has the best **power-to-weight ratio**, but it is no longer used for railway application with its **maintenance requirement**.

Permanent Magnet (PM) Motor

It is highly **efficient** with **high power-to-weight ratio**. The supply can be DC, asynchronous or synchronous. It is expensive with **rare earth magnets**. It is popular for latest traction application.

5.2 Traction Control

To control a traction motor, resistance control, chopper control and PWM control with IGBTs are often used.

Power Electronics for Traction Control

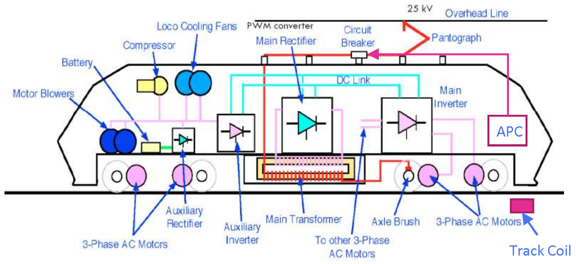
1. Diode: Conducts in one direction with **forward voltage** V_F = 0.7V. Four diodes formed a **bridge rectifier** to convert AC to DC.
2. Thyristor: Conducts current to flow in one direction ONLY when **gate** is energized. It provides controllability to rectifier.
3. Gate Turn-Off (GTO) Thyristor: It conducts as thyristor (a high-power device) with **gate** switching ON and OFF in < 2 kHz.
4. IGBTs: It is a MOSFET driven BJT, which is switched at high frequency (10 – 50 kHz). The high switching frequency **smoothens train acceleration** and **reduces traction noise**. It is available with **high power** (< 1MW in ON-OFF mode) and **high current** (> 1kA) and it can block high voltage. It is **voltage driven** (low loss). IGBTs are used for **VVVF inverter** to control IM. With high current at high switching frequency, it provides more compact traction control with **lower cooling requirement**.

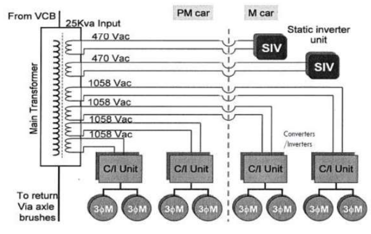
Control Methodology

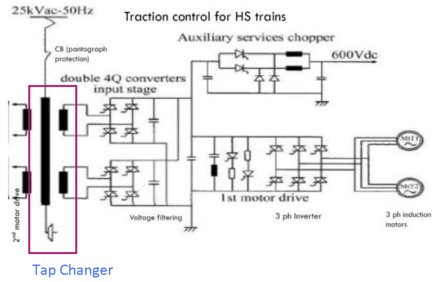
1. Resistance Control: **Resistors** in series with DC motor can limit current and hence the torque and speed. Separately excited motor requires motors with resistors for both and armature. It is **bulky** and **waste of energy**. **No fine control** is allowed, and **maintenance** is needed.
2. Chopper Control: It can be built with thyristor, GTO or IGBTs. It regulates current applied to motor. DC current is produced with ripples causing **EMI**. When duty cycle (D) is increased, average voltage is increased $V_O = DV_{IN}$.
3. PWM Control: Pulses of varying time with inductive output allows generation of sine wave of **variable frequency**. IGBTs are best suited to PWM with high frequency switching. Input PWM can be used for **unity power factor**. PWM converter with intermediate DC links and AC drives largely avoids power factor and **harmonics issues**. Older GTO or thyristor locos can have current harmonics issues which requires **line-side tuned filter**. PWM converter can also be employed to control **DC link voltage** by varying **phase angle** between OHL supply and PWM input voltage. As motor speed increases, Constant Torque Region ($V \propto f$) operation is shifted to Constant Power Region (V constant, torque decreases) operation after max. output voltage is reached. PWM inverter provides **bi-directional operation** (i.e. with regenerative mode), as an advancement over GTO inverter with high switching frequency and voltage (6.5kV).

[Note: **LC input filter** at supply is required to smoothen input voltage and current, prevent harmonics entering DC supply and avoid interference to line side signal and related equipment with broadband noise]

AC Supply for AC Motor



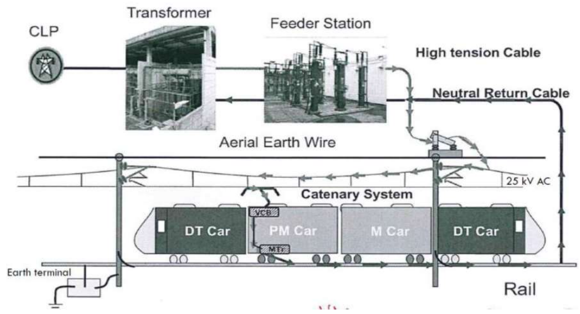




5.3 Traction Supply

- Design and Risk Management for Traction: **Availability** of independent power infeed and emergency supply (without harmonics, power factor and interference issues).
- DC traction supply is NOT provided for main line and HS rail as DC supply suffers large **voltage drop** with high current in OHL. High-capacity high speed **CBs with interrupt time** < 40ms (< 10ms on train) are needed. This is only available in AC technology (with zero-crossing). **Stray Current** causes electrolytic corrosion of pipes.
- S/S rectifier with capacity 2.4 MW provides 600V DC traction voltage with rated DC traction current 4kA and short circuit protection at 40kA within 0.25s. Infeed 22kV/415V transformer rated 2.5MVA is also provided.
- High AC voltage is easily provided with transformer (with OLTC) and it can provide smallest current to **minimize I^2R loss**.
- Yet, **high voltage** AC traction supply is NOT suitable for metros/ urban railway due to safety reasons, as it is hard to provide **adequate insulation clearance** at specific location like metro tunnels (additional space and tunneling cost), **public safety** and **low voltage drop** through OHL (1 mH/km).
- In modern design, DC is preferred for **short headway** and **high frequency service**, while AC is for **long distance** and **heavy suburban** railway system. For HS rail, each train requires 8 – 20MW and headway of 3 min, a 25kV 50Hz traction supply is needed.

AC Transmission In-feeds (at 132 kV level, 50 Hz)			
AC Traction Supply Infrastructure Transformer		DC Traction Supply Infrastructure Transformer	
		Transformer	
		Rectifier	
Onboard AC (25 kV)		Onboard DC (1500 V DC)	
Transformer	Transformer	Chopper	Chopper (IGBTs with some GTO applications)
PWM	Phase Angle Controlled Rectifier	Inverter (variable frequency AC, 0.5 to 120 Hz, IGBTs for most drives)	
Inverter		AC Drive	DC Drive
AC Drive	DC Drive		



Traction Supply - Distributed Power per line:

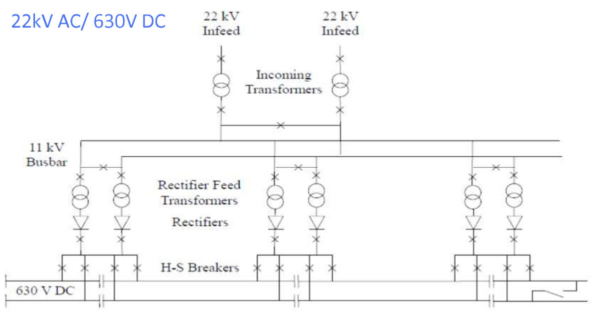
	Distance b/w S/S	Cu Section of OHL [mm^2]	Power through OHL [MW]
1.5kV DC	10 – 20 km	400	2.7
25kV AC	40 – 60 km	150	16
2x25kV AC	50 – 90 km	200 (Fdr wire: 150)	45

- 25kV AC (50/60Hz) OHL is international standard for main line.
- AC supply reliability is enhanced with **dual infeed and transformer**.
- Phase imbalance is reduced with rotated in-feed around 3 phase at successive S/S, arrange loading balance for other phases and install compensator
- Leakage current: It requires good insulated rails.

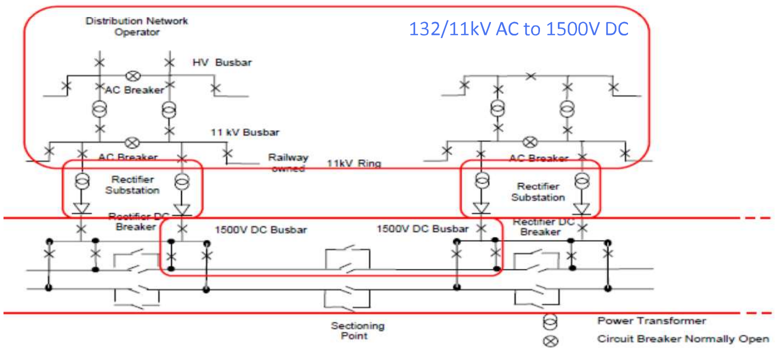
Comparison between Supply:

	AC	AC with Auto-Tx	DC
Principle	Lower V through 1ϕ Tx, 15/25 kV output	Lower V through 1ϕ Tx, 30/50 kV output. Power transfer in fdr wire at 30/50kV, OHL at 15/25 kV through Auto-Tx	Lower V through 3ϕ Tx Rectifier
Advantage	40 – 60km b/w S/S	70 – 100km b/w S/S Strong EMI reduction	No unbalance on supply grid
Disadvantage	25kV supply grid phase unbalance, PF, harmonics from traction unit	Complex design with extra cost on fdr wire and Auto-Tx	High V drop along the line. Short distance b/w S/S, ~ 10km at 1.5kV and ~20km at 3kV, harmonics at rectifier.

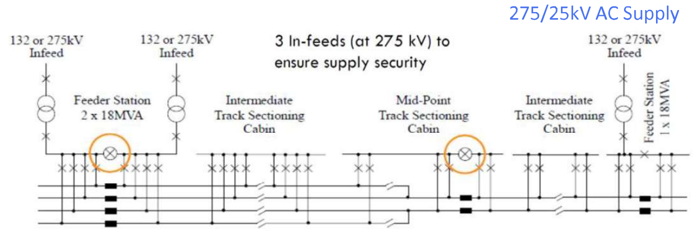
22kV AC/ 630V DC



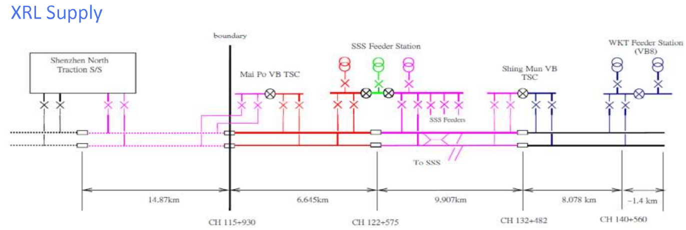
132/11kV AC to 1500V DC



275/25kV AC Supply

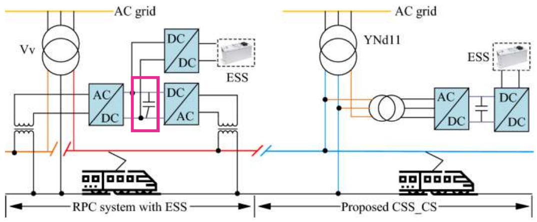


XRL Supply



6 Traction Control

6.1 Traction Energy Storage



Traction Energy Storage aims to **charge up** under low demand or braking and **release** during high load period or under acceleration. It is important to have a storage (e.g. flywheels, supercapacitor, batteries …) to have **high power density** and **light weight**. **Li-ion** and **Li-polymer** batteries has a power density of 0.36 MJ/kg and 0.56 MJ/kg.

e.g. Hitachi – Class 43 Train: 4 x 300kW AC Induction Motor
Li-ion Batteries: 48 Batteries, 48kWh, 960kg weight, $1MW_{MAX}$ for 170s

Latest Development Batteries are Li-air, Li-S, Nano-Carbon, Solid State and Dual Carbon.

6.2 Traction Equation

Acceleration of a train can be determined by a *force balance* equation relating traction force and different resistances.

$$T - F_D - F_g - C_D = M_{eff} \times a$$

given that

$T = \mu_r M_p g$; $F_D = A + BV + CV^2$ (Davis Equation) ; $F_g = Mg\ 1/X$; $C_D = MK/R$; M_{eff} = tare mass $(1 + \lambda)$ + payload

where

- T = Traction Force, $\mu_r = 0.3$ for loco, M_p = mass on powered wheels.
- F_D = Friction Drag, A = rolling resistance = 3 – 5kN, B = bearing friction = 20N/ton at warm move, C = aerodynamics drag.
- F_g = Gradient Force, 1/X = gradient.
- C_D = Curve Drag, M = train mass, K = 23000 m²/s², R = curve radius = r / 5729.58
- M_{eff} = Effective Mass, λ = 5 – 15%, rotary allowance (more for aluminum car body, less for steel car body with less motored axles)

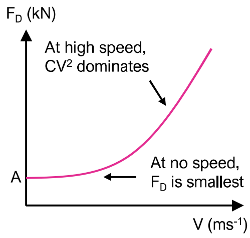


FIGURE 1-1
Variation of Friction Drag with Velocity

Example 1

A light rail train is travelling up a gradient of 1 in 50 at a line speed of 43.2 kph (12 m/s). The mass of the vehicles including passengers is 60 tonnes. Ignore friction drag and other losses, calculate the traction effort and instantaneous power supplied by traction motors.

Solution

$$T - F_D - F_g - C_D = M_{eff} \times a, \qquad a = 0 \;\rightarrow\; T = F_g = Mg\frac{1}{X} = (60 \times 10^3\ \mathrm{kg}) \times (9.81\ \mathrm{ms^{-2}}) \times \frac{1}{50} = \mathbf{11.772\ kN}$$
$$P = T \cdot v = (11.772\ \mathrm{kN}) \times (12\ \mathrm{ms^{-1}}) = \mathbf{141.3\ kW}$$

Example 2

A train has 9 coaches (35 tonnes each) and is powered by 2 locomotives (70 tonnes each). What is the maximum acceleration the train can achieve?

Solution

$$T - F_D - F_g - C_D = M_{eff} \times a \;\rightarrow\; T = \mu_r M_p g = M(1+\lambda)a \;\rightarrow a = \frac{\mu_r M_p g}{M(1+\lambda)} = \frac{(0.3)(70 \times 2\ \mathrm{kg})(9.81\ \mathrm{ms^{-2}})}{(2 \times 70 + 9 \times 35)(1.1)} = \mathbf{0.82\ ms^{-2}}$$

Example 3

A freight train has 6 powered axles with a maximum power 3.4 MW and a mass of 96 tonnes. It hauls a wagons with total mass of 950 tonnes up a slope of 1/37. The train is travelling at its balancing speed and the locomotive is using its maximum power. Calculate the balancing speed and the tractive effort produced by the locomotive. Assume a negligible running resistance.

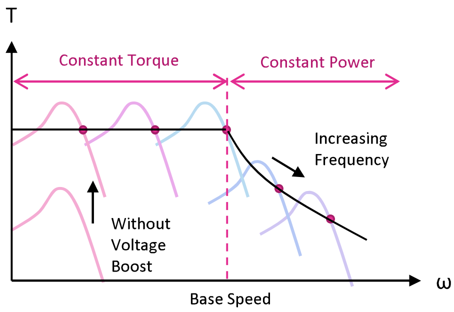
Solution

$$T - F_D - F_g - C_D = M_{eff} \times a \rightarrow T = \mu_r M_p g = Mg\frac{1}{X} \rightarrow \mu_r = \frac{Mg\frac{1}{X}}{M_p g} = \frac{\left((96+950) \times 10^3\mathrm{kg}\right)(9.81\mathrm{ms^{-2}})\left(\frac{1}{37}\right)}{96 \times 10^3\ (9.81\mathrm{ms^{-2}})} = \mathbf{0.294}$$

$$P = Tv \;\rightarrow v = \frac{P}{T} = \frac{3.4 \times 10^6\mathrm{MW}}{\left((96+950) \times 10^3\mathrm{kg}\right)(9.81\mathrm{ms^{-2}})\left(\frac{1}{37}\right)} = \mathbf{12\ ms^{-1}}$$

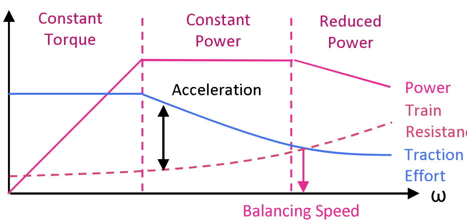
Coefficient of Adhesion μ_r must be above 0.3 to prevent wheel slide.

6.3 Traction Effort Curves – Torque Speed Characteristics

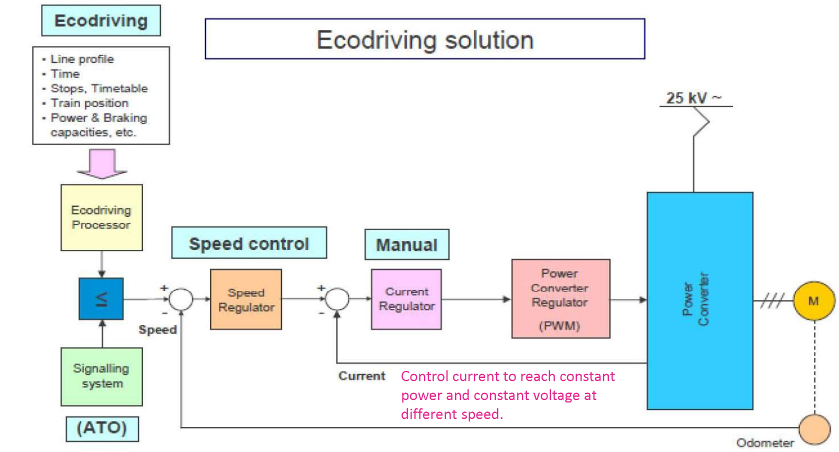


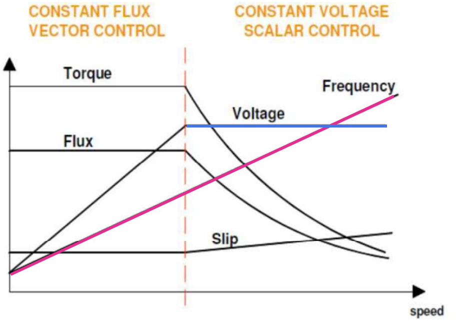
- Traction effort is limited by **number of powered wheels** and **max torque of traction motors**.
- **Distributed traction** gives better traction effort performance and regenerative power.
- Once constant power region is reached, the traction effort falls off with 1/speed. It provides better traction at low power.
- Hertzian **wheel-rail contact** patch is about 1 cm² and it transmits > 5.5 kN of **tractive forces**. For a 6-axle loco. (132 tonnes), 12 cm² wheel rail contacts transmit 7 MW **installed power** by the loco.
- **Balancing Speed** has a balance between traction effort and train resistance, and it is the max. speed it can reach.

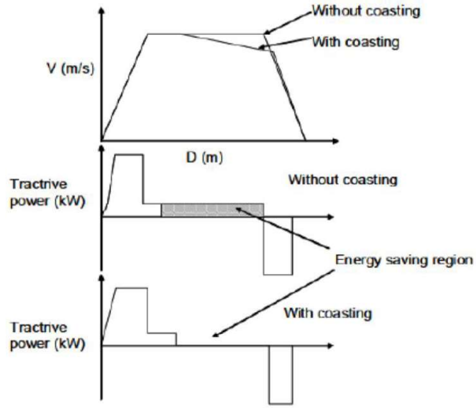
6.4 Earthing System



- It provides a **fault current path** to the earth and keep the connected part closed to **earth potential** (i.e. limit touch voltage). **Single point bonding** is often used.
- **Independent earthing system** (inc. earth rod and earth mat) for signalling and power is needed.
- Ground current can induce dangerous voltage in trackside conductor causing a fault, lead to interference in telecom circuit and increase self-inductance in overhead line with voltage drop.



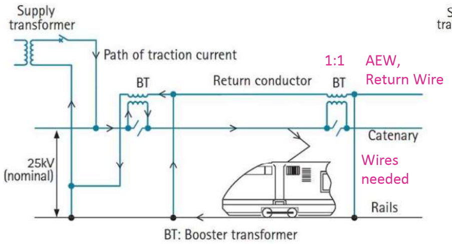


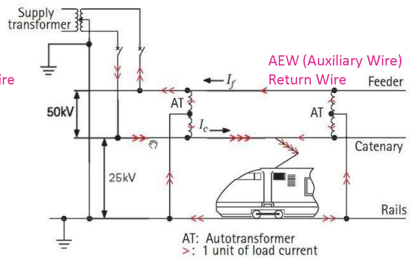


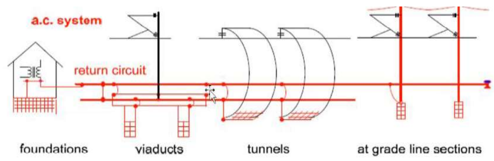
6.5 Stray Current for AC and DC System and Stray Current Collection

Booster Transformer (BT, NOT used anymore), and **Auto-transformer** (AT) are solution to **collect stray current**. The problem is the touch voltage on rail for AT. **Traction return cable** should be run along as closed as possible with feeder cable to minimize the EMC.

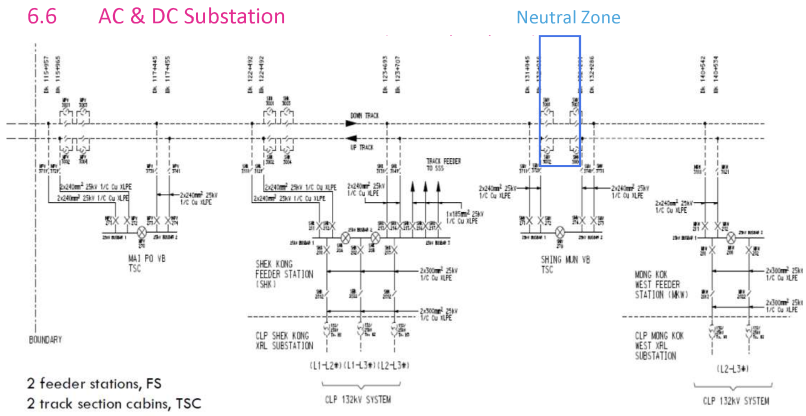
For DC traction, the infrastructure is **floating** with high impedance to earth. Stray current from DC supply system can cause **stray current corrosion** for buried pipelines. **Rail-to-earth resistivity**, insulation, **equipotential bonding** and **cathodic protection** can divert, limit and control stray current. [Note: 10Ωkm single track means a 1km track with shunt resistance of 10 Ω]



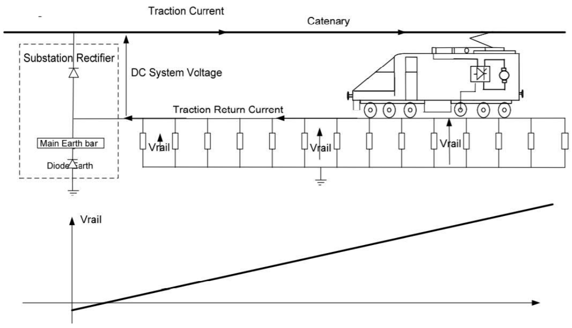




6.6 AC & DC Substation



2 feeder stations, FS
2 track section cabins, TSC

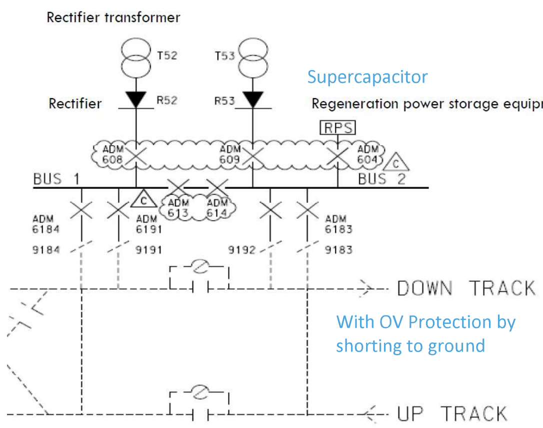


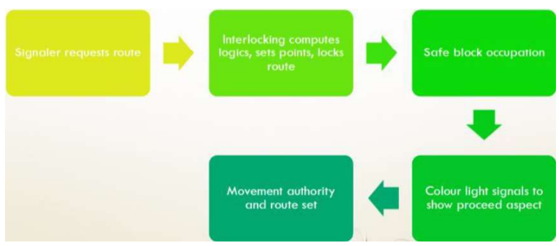
6.7 Route Setting, Movement Authority (MA) and Possession

Route Setting is to prepare the route for train movement with **interlocking**, which prevents conflicting trains movement, trains collision and train protection. Interlocking provides lock, block, interlock (at junction and level crossing), issue authority, supervise (enforce the train to stay within its MA) and unlock (release the route).

Movement authority (MA) is given with interlocking for trains to proceed with light signals and in-cab display. The entrance signal must not give authority to proceed until the route is cleared to maintain **block separation**. Route is set and locked if there is no conflicting route, point is in position and locked, related track circuit unoccupied and related emergency stop device is not activated. MA is limited by distance, or **time and distance**.

Possession, as defined by rule books, as the **designated section of track** where an EIC takes **control** from the traffic controller. Unauthorized train movement into the section is prevented. **Minor possession**, which has no change to timetable, requires a possession plan for regular maintenance (booked > 6 weeks in advance). **Major possession** affects normal timetable operation, and it should be booked > 13 weeks in advance. **Emergency possession** is arranged by the controller to ensure the section is protected from unauthorized trains / staff and the rail shall not be energized with signalling system stop and divert trains or with physical barriers or switching off traction current. EIC and possession master must be appointed.





7 Traction Control – Signalling Systems

7.1 Capacity Equations

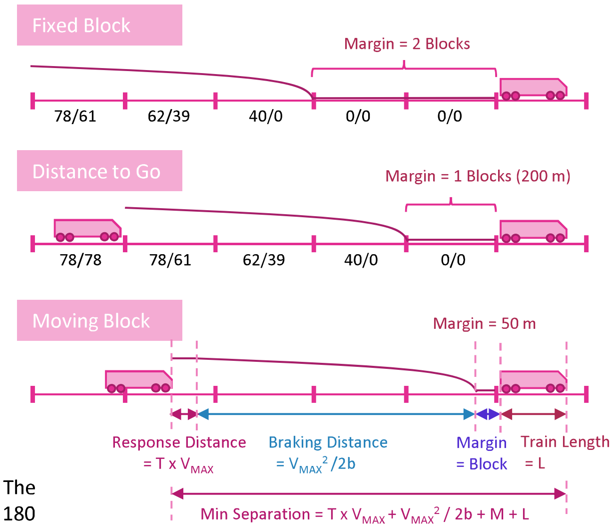
1. $C_l = C_t$ x Tmax (line capacity = train capacity x max. throughput)
2. Ts = 3600 / Hmax (Service headway = 3600 s / time headway [s])
3. Hmin = Hs + δH (Min Headway = Service Headway + Headway Margin)
4. $S > V^2 / 2b$ (Min Headway > Braking Distance)
5. Hmin = (S + L)/v (Min Headway = (Separation + Train Length) / Velocity)
6. Tmax = 3600 / Hmin = 3600 / (v/2b + L/v)

where
C_l = Line Capacity, [passenger per direction per hour],
C_t = Train Capacity, [passenger per train]
Ts = Maximum Throughput, [trains per hour]
Ts = Service Headway Throughput
Hmax = Maximum Time Headway [s]
Hmin = Minimum Headway [s]
δH = Headway Margin [s]
S = Separation [m]
L = Train Length [m]

7.2 Block Systems

Different block signalling system provides different separation between 2 trains due to the discrepancy in safety margin. Yet, to provide a larger throughput, moving block system, which operates trains with minimal distance with feeler of a train touching the tail of leading train, i.e. look ahead distance. It is noted that moving block system requires **continuous 2-way communication** between train and track with sufficient bandwidth and safe integrity to transmit information on **accurate train position and speed measurement** through track circuit, axle counter, Balises, odometry, doppler radar, GPS for position detection.

Block System	Safety Margin
Fixed Block	2 Blocks
Distance to Go	1 Blocks (= 200 m)
Moving Block	50 m



Example

A metro uses an equi-block railway control system with 2 intermediate speeds. The line speed limit is 90 kph. The trains can achieve a braking rate of 1.2 m/s² and are 180 m long.

(a) Estimate the minimum headways provided by these systems when the trains are simply following each other on a plain rail. Explain what assumptions you have made in your calculation and justify the formulae used.

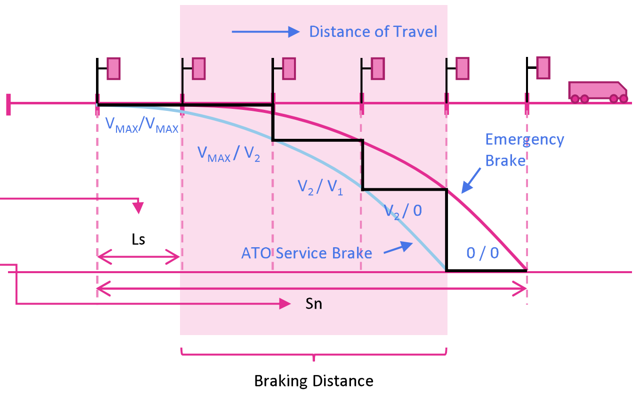
(b) Calculate the capacity gain by the metro with
(i) a distance-to-go signaling,
(ii) a moving block signaling.

Solution

Fixed Equiblock:
Divide braking distance from line speed into blocks in equal length. Given 2 intermediate speeds {V_2, V_1} with speed code {V_{MAX} / V_2, V_2/ V_1, V_1/ 0} in 3 blocks (n – 1 = 3). n = 4, where n is number of aspects.

Block Length: $$L_S = \frac{1}{n-1}\frac{V_{MAX}^2}{2b}$$

Separation: $$S_n = \frac{n+1}{n-1}\frac{V_{MAX}^2}{2b}$$



(a) Under ATP, the trains should be allowed to run at full speed at full length of V_{MAX} / V_{MAX} block and stop at V_1 / 0. Brake takes n – 1 blocks.
V_{MAX} = 90 km/h / 3.6 = 25 m/s
Braking Distance = V_{MAX}^2/ 2b = (25 m/s)² / 2 (1.2 ms⁻²) = 260.4 m
Block Length = Ls = (V_{MAX}^2/ 2b)/ (n-1) = 260.4 m / 3 = 86.8 m
Separation = Sn = (n+1) Ls = 5 x 86.8 m = 434 m
= 1 block + Safety Margin Added
Distance Headway = Sn + L = 434 + 180 = 614 m
Hn = (Sn + L) / V_{MAX} = (434 + 180 m)/ 25 ms^{-1} = 24.56 s

(b) (i) For **Distance-to-Go**, minimum separation between trains is the braking distance + 1 block length
Distance Headway = 260.4 + 86.8 + 180 = 527.2 m
Time Headway = 527.2 / 25 = 21.1s
Capacity Gained = 1 – 527.2 / 614 = 14.1%
(ii) For **Moving Block**, minimum separation between trains is the braking distance + safety margin (= 50m)
Distance Headway = 260.4 + 50 + 180 = 490.4 m
Time Headway = 490.4 / 25 = 19.6 s
Capacity Gained = 1 – 490.4 / 614 = 20.1%

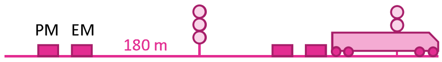
7.3 Automatic Warning System (AWS) and Train Protection and Warning System (TPWS)

As train signaling system should provide **planned movement** to prevent train collision. If track protection is not possible, train must be run at reduced speed (40 kph for HS line and 22kph for metro). It also **prevent train derailment** in incorrect setpoint and **provide movement authority** to proceed if not conflicted with route set. It also provides indication to enable safe **maximum speed** relative to track geometry, distance-to-signal and distance-to-obstruction and **detect and protect against failure** of or damage of structures and track and railway formation, warning and protection system is provided.

Automatic Warning System (AWS)

- Provide indications to signal (green/ caution/ red aspect) and intervenes with emergency braking if the driver fails to acknowledge caution warning provided for 2 – 3 seconds. AWS is a warning system, NOT a protection system. The driver acknowledgment overrides warning and brake application.

- Electromagnet is energized with green signal and driver receives an audible confirmation; Electromagnet is de-energized with caution or danger signal and driver receives a warning tone. If warning is NOT acknowledged, the AWS will initiate a full braking application (NOT emergency braking).
- Problem: No speed control. NOT stop at high speed and lead to SPAD.



Train Protection and Warning System (TPWS)

- It is fitted at all stop signals protection **junctions** or other points of conflict. It applies **emergency braking** when a train passes a red signal or approaching a red signal at overspeed.
- It provides 2 pairs of inductive loops (**speed limiting** and **stop location**)

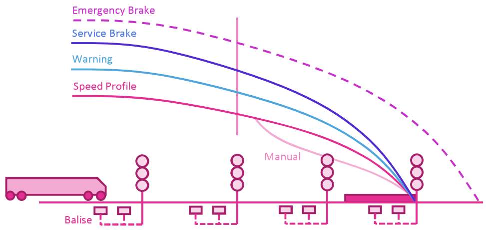
7.4 Automatic Train Protection (ATP) and Automatic Train Operation (ATO)

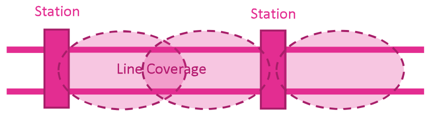
Automatic Train Protection (ATP)

- ATP enforces limit of **movement authority** and **safe speed**. When a train approaches a caution signal, it receives the **train location** and **distance-to-go message** from the track mounted **balise**. The onboard ATP check its speed and calculate the braking profile to stop the train.

Automatic Train Operation (ATO)

- Drivers tend to slow down the train earlier, but ATO knows exactly when and where to brake by using **movement authority** or **speed code** to calculate the operating speed profile. ATO shares ATP data on **movement authority**, **gradient profile** and **permitted speed profile**, while obtaining data itself on **coasting point** (v = constant), **stopping point**, **speed regulation command** and **departure time**. ATO improves headway by **maximizing safe speed** regardless of timetable.
- ATO exists in 3 form: GoA 2 – driver accompanied, GoA 3 – driverless, but staff on board, GoA 4 – full driverless.

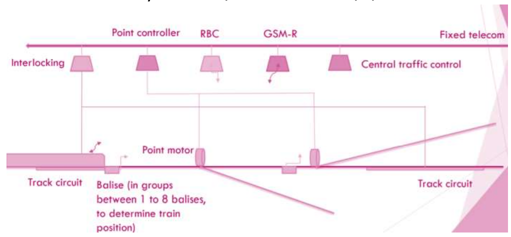




7.5 Global System for Mobile Communication – Railway (GSM-R)

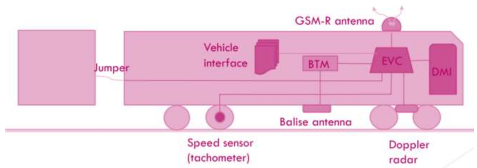
- GSM-R submit text message for ETCS by providing both **data and voice communication**. It provides a high capacity standardize system.
- Data: 900MHz (875 – 880 or 921 – 925 MHz), continuous link, line coverage, 19 frequency in 900MHz, max speed in network up to 500 kph
- Given that GSM-R under 270.8 kbit/s data rate and 200 kHz bandwidth (0.01W). It has a bandwidth efficiency = 270.8/200 = 1.35 bit/s/Hz.
- Digital System: AI → (Amplifier) → (Filter) → (Sampler) → (A/D Encoder) → DO (011001)

7.6 European Train Control System (ETCS) and European Rail Traffic Management System (ERTCS)



ETCS Trackside Subsystem:

- Balise – Provide fixed messages (telegram, e.g. location) to EVC. Organized in group.
- Radio Block Centre (RBC) – Provide movement authority (MA) to allow safe movement.
- Lineside Electronics Unit (LEU) – Electronic devices generating telegram sent by Balise
- Euroloop – provide signaling information in advance (as regards to next main signal)



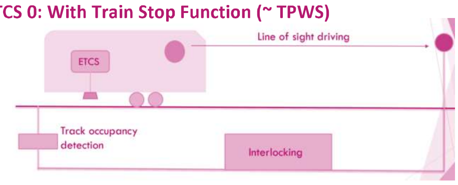
ETCS Onboard Subsystem

- European Vital Computer (EVC) – Computer based system supervises **movement of train** (based on RBC information)
- Driver Machines Interface (DMI) – Provide Information about **Movement Authority**, **Max Speed**, **Line Chainage**, **Driver Data Entry**
- Odometry (speed sensor) – Measure Wheel rotation to calculate speed
- Balise Transmission Model (BTM) – Analyse train position and message to Balises
- Doppler Radar – Secondary Speed Measurement System

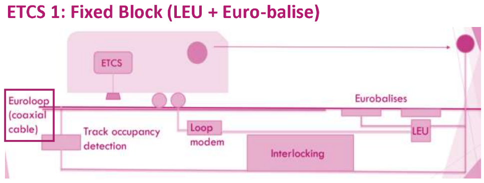
ERTMS

- A standardize **command**, **control** and **signaling system** utilizing standardized interface between lineside infrastructure and on-board system and between system and driver.
- **ETCS 1**: (Fixed Block Lineside Signalling) – Signaler *sets* route, signal aspect shows proceed, onboard EVC reads MA (distance to end of authority, speed profile, gradient, etc) from Balise group
- **ETCS 2**: (Fixed Block Lineside / Cab Signalling) – Signal requests route**, interlocking setpoint**, lock route, tell RBC to set signal to proceed (interlock = observe status of track, monitor route set, set new route, release route, monitor trackside equipment, prevent collision, prevent derailment), RBC check train position and associate location, MA tells distance from Balise group to end of MA, track geometry and speed profile, **compute braking curve**.
- **ETCS 3**: (Moving Block) – Eliminates trackside equipment and track circuit, **train integrity monitoring onboard**, onboard unit report safe train length to RBC, determines location of train and **extends MA** of following train up to reported safe rear end (air bubble concept)

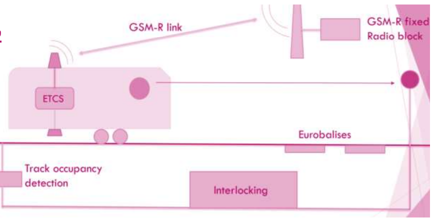
ETCS 0: With Train Stop Function (~ TPWS)



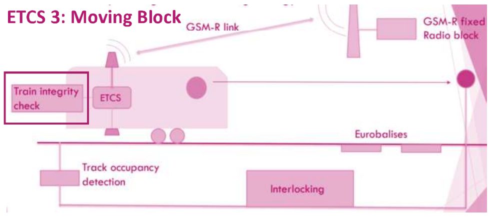
ETCS 1: Fixed Block (LEU + Euro-balise)

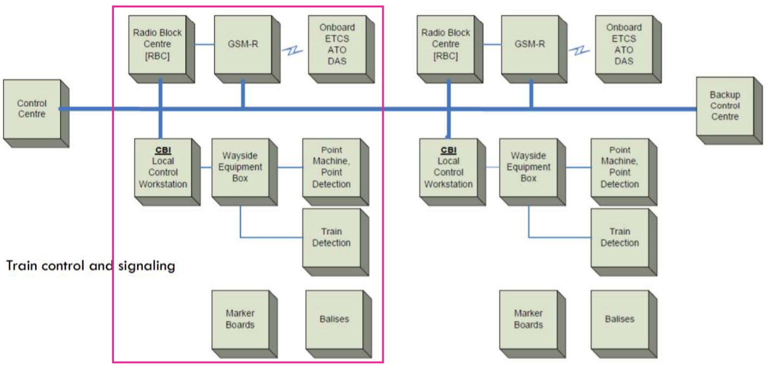


ETCS 2



ETCS 3: Moving Block

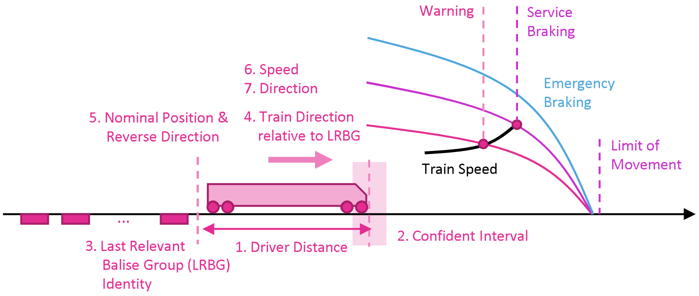




8 Signalling Systems & Automation

8.1 Driver Machine Interface (DMI)

The main tasks of DMI are speed control, planning and monitoring with driver's input.

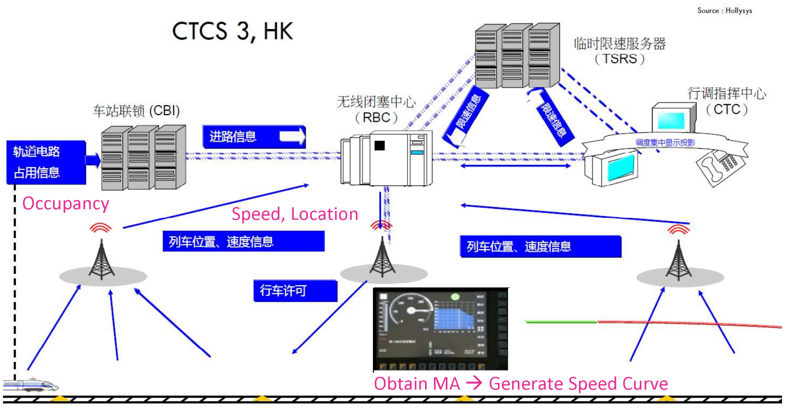


8.2 ETCS Vs CTCS

ETCS Operation Mode

Movement	Operation Mode	Description
Train Movement	Full Supervision	MA received, **Route Protected** and NOT Occupied
	Limited Supervision	ETCS Supervises in the background
	On Sight	MA received, Route protected but may be occupied. (Driver **stops short of any obstruction**. Drivers can enter an occupied track with ETCS supervision)
	Staff Responsible	System unable to give MA. **Driver and signaler** responsible to perform any train movement with **unknown route**.
	Override	**Allows the train to pass its end of authority**
	Standby	Operation mode at start up, standstill supervision enabled, train cannot be driven in this mode
Shunting	Shunting	to propel trains and undertake **shunting movements**
	Reversing	for **reversing away** from a **dangerous location**
Special Train Movement	System Failure	onboard system failed
	Non-Leading	ETCS onboard equipment (**slave engine**), NOT electrically coupled to the leading engine. It has its own driver.
	Sleeping	
Disturbed Situation	Trip	Trip mode is entered as a result of passing the end of authority (when no override is active)
	Post trip	mode entered once the driver has acknowledged the trip mode

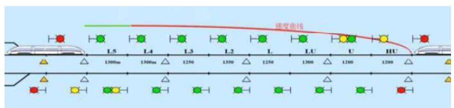
	Description
CTCS Level 0	• It consists of track circuits, universal cab signaling (trackside signals are main signals) • Train with Speed **< 120kph**
CTCS Level 1	• It consists of track circuits, **Balises** (or transponders) and **ATP system**. • Block signal could be removed, and train operation is **based on on-board system and ATP**. • Control Mode for ATP can be **distance-to-go** or speed step (**fixed block**) • Speed between 120 kph to 160 kph
CTCS Level 2	• It consists of digital track circuit, Balises and ATP system. • Control Mode is **distance-to-go**. (Fixed block mode is still applied) • Applicable for trains with speed > 160 kph.
CTCS Level 3	• It consists of track circuit, Balises and **ATP system with GSM-R**. • The function of track circuit is ONLY for **train occupation** and **train integrity checking**. (NOT for operational use.) • Fixed block system still applies. Speed > 200 kph
CTCS Level 4	• **Moving block system** can be realized by Level 4. • Information transmits between trains and wayside devices is made by **GSM-R**. GPS or Balises are used for train position. • Train integrity check is by **on-board system**. • **Track circuits** are only used at station. • **Trackside system** is reduced to a minimum to reduce maintenance cost.



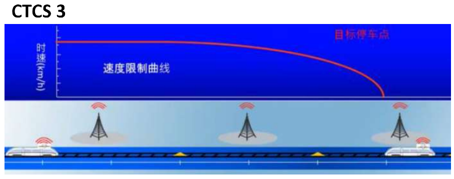
Trackside Subsystem

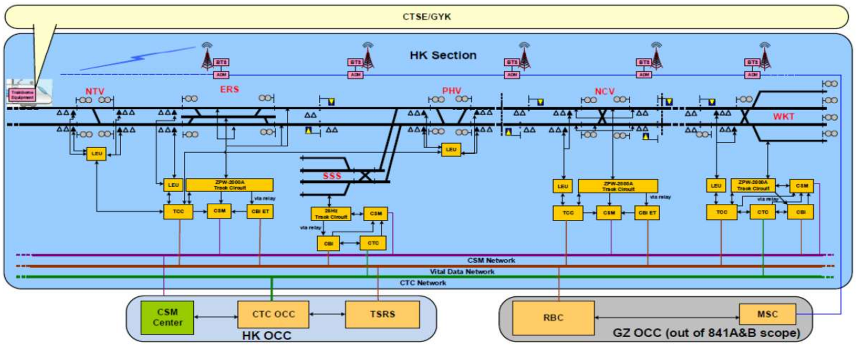
- **Radio Block Centre** (RBC): 2 ways continuous communication by **GSM-R** for train control. Information transferred includes **target distance**, **track speed**, **profile**, **TSR**, **protection zone**, and information from onboard to RBC includes **train parameters**, **train location**, registration details, train status, etc.
- **Computer Based Interlocking** (CBI): CTC sends **route requests command** to CBI for execution based on **trackside status** (occupancy from TCC and turnout point status). CBI **ensures no conflict route setting** and allow train to proceed.
- **Train Control Centre** (TCC): **For CTC2** Trackside train control (signalling code). Connected to ZPW2000 for **location detection** and **MA transfer**.
- Balise and **Local Electronics Unit** (LEU): For **CTCS3**, Balise provides **location identification**, **level switching** (CTCS2 to CTCS3), **RBC Control Boundary Handling**, **OHL neutral zone control**. For **CTCS 2**, it gives **line speed**, **track profile**, **temp speed restriction** (TSR).
- **Central Signaling Monitoring** (CSM): Monitor signaling equipment **status and alarm**, status of infeed power grid and earth leakage.

CTCS 2



CTCS 3





CBI : Computer Based Interlocking
CSM : Centralized Signalling Monitoring System
CTC : Centralized Traffic Control
CTSE : CTCS-3 Trainborne Signalling Equipment
ERS: Emergency Rescue Siding
GYK: 轨道车运行控制设备
LEU : Lineside Electronic Unit
MSC: Mobile Switch Centre
NCV: Nam Cheong Ventilation Building
NTV: Ngau Tam Mei Ventilation Building
OCC: Operations Control Centre
PHV: Pat Heung Ventilation Building
RBC : Radio Block Centre
SSS: Shek Kong Stabling Siding
TCC : Train Control Centre
TSRS : Temporary Speed Restriction Server
WKT: West Kowloon Terminus

- **CTCS 3** involves CBI, RBC, GSM-R, Balise and ZPW 2000 Track circuit; **CTCS 2** involves track circuit, Balises, TCC (Train control centre), LEU.
- **Active Balises** is used for TSR for block operating direction; **Passive Balise** is to transmit track information (max speed, position, gradient).

On-Board Signaling Subsystem

- On board receives wayside info. from RBC and TCC to generate **train speed profile** and transmits vehicle related info to trackside equipment.
- Onboard subsystem provides **system control function** such as **self-diagnosis**, **DMI management**, **speed curve generation**, **braking curve generation**, **OHL neutral zone management**.

Operation Mode

- Full Supervision (FS): MA received, **Route Protected**, **Max. Line Speed** supervised by CTCS 3 (= ETCS FS mode)
- Partial Supervision (PS): Reduced level of supervision with CTCS 2 with **max. line speed.**
- On Site (OS): Unable to give MA, driver and signaler responsible for any train movement, max. speed 40 kph (= ETCS SR mode)
- Call On (CO): MA received, route protected but may be occupied, max. speed 40 kph (driver to stop short of any obstruction) (= ETCS OS mode)

Comparison	CTCS 2	ETCS 1	CTCS 3	ETCS 2
Characteristics	Cont' ATP	Inter. ATP	Cont' ATP	Cont' ATP
Max Speed	250 kph	250 kph	350 kph	350 kph
Communications	TC (MA) Balise (data)	Balise (MA + data)	GSM-R	GSM-R
Major Equipment	TC, Balise, LEU, TCC	TC, Balise, LEU	RBC, TC, Balise	RBC, TC, Balise
Temp Speed Restriction	By TSRS	NA	By TSRS	NA
Redundancy	CTCS 0	NA	CTCS 2	NA

8.3 Grade of Automation (GoA) & Fully Automated Operation (FAO)

Grade of Automation (GoA)

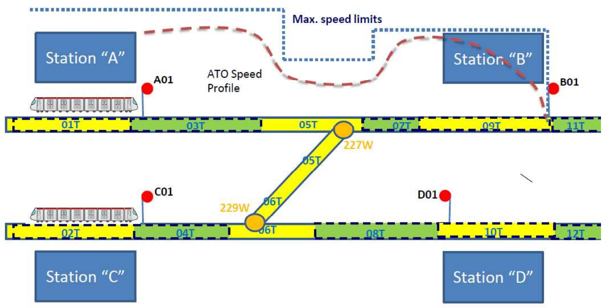
- GoA0 –On-sight driving without ATP where the **driver takes full responsibility**
- GoA1 – **Manual protected operation** (with ATP), which is usually applied as a fall back mode of operation
- GoA2 –Semi-automatic operation with the **support of ATO setting** the train operation, and **ATP ensuring safe separation distance** between 2 trains
- GoA3 –**ATO + ATP**. **No driver** in the cabin, but an **attendant** capable of handling irregular situations and guiding passengers in case of emergency
- GoA4 –UTO, **unattended train operation**, where the system operates the train with no on-board operational staff

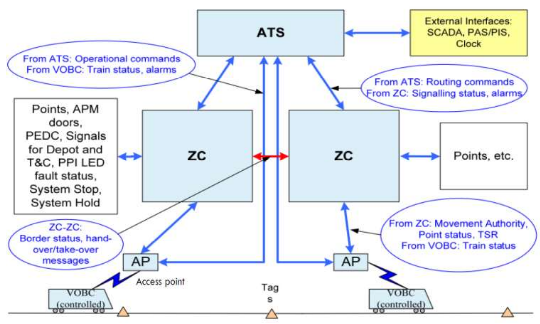
Fully Automated Operation

For FAO (driverless), train is automatically driven by **ATC** with **full ATP** under **safe route management**, **safe speed management**, **safe train separation**, **safe departure conditions** at stations. Train doors and platform doors are automatically opened and closed by ATC.

8.4 Communication based Train Control (CBTC) for Metro

- CBTC is an automated train control system for safe operation using data communication techniques with signaling system in 3 levels of automation: **ATP, ATO and ATS.**
- **Wireless Communications** between trains and stations are fully redundant with robust **radio network**.
- **Moving Block** is often used.
- Interlock Logic (A01 to B01):
  - TC 03T, 05T, 07T, 09T, 11T – "Cleared"
  - Points 227W and 229W – "Normal"
  - Signal A01 – "Cleared"
- ATP: limits movement with **MA** and **speed limit**, provides **overspeed protection**, ensure door open at **zero speed**, **correct side and position**.
- ATO: Auto-driving, **Energy Optimization**, running service with coasting.
- Metros: High capacity, high density, short station-to-station distance, short dwell time, high acceleration and braking, low op speed, large requirement on **service frequency** (than timetable)
- MA is transmitted by Balises, loop at track, track-circuit-based data transmission, leaky cable-based radio or WiFi.



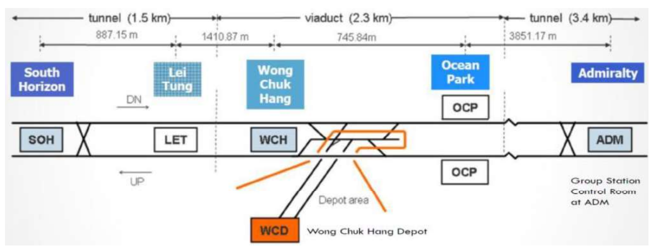


8.5 Safety Integrity Level (SIL)

- SIL correlates to the **probability of dangerous failure per hour**.
- Train detection (e.g. track circuit, axle counter, balise), interlocking, TCC, ATP = SIL 4; ATO, ATS = SIL 2

South Island Line (East)

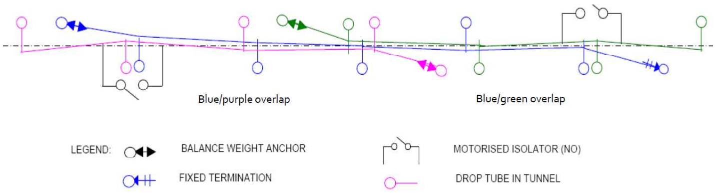
- SIL(E) employs **FAO functions** inc. remote control, online timetable modification and regulation, service running and work zone management.
- **ATP**: safety envelope based on train localization, speed and train attributes. **ATC**: Automatic Train Control by zone controllers (ZC)
- **Train Detection**: by radio-based continuous bi-direction comm.
- Signaling System includes **Eurobalise** for train localization, odometer calibration and precise stopping, **Axle Counter** for train detection and occupancy, **Antenna** to communicate with train borne DCS for train and trackside information (DCS Antenna x 2 per cab, red/ blue network).



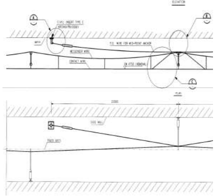
9 Railway Infrastructure

9.1 Overhead Lines and Conductors

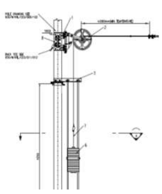
Phase Break – 6 Span and 2 Overlap Arrangement



Mid-Point Anchor

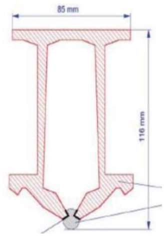


Balance Weight



Isolator

ORCR: Al profile with Cu alloy with **current rating** I_{MAX} = 3000A and R= 0.0135Ω/km and L = 10m or 12m.
Note: **Anti-corrosion grease** prevents ion exchange.



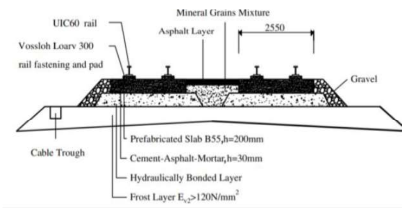
Advantage of using Overhead Rigid Conductor Rail System (ORCR):

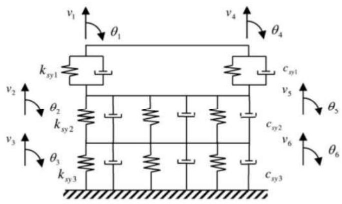
- Shorter Recovery Time in case of OHL breakage incident (3 – 5 hours shorten to within 1 hour)
- Longer Life – Contact Wire can be 50% worn out
- Less Maintenance – Less components, Replace shorter length than Catenary Wire
- No Tensioning Equipment needed

9.2 Ballast Track and Slab Track

Ballast Track

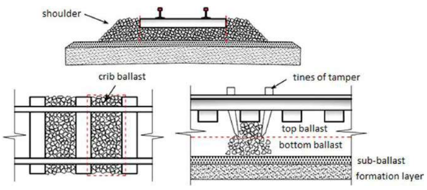
- Only used in **Open Tracks** in HK.
- It requires equi-axed angular sharp granite with high **frictional resistance**, **abrasion resistance** and **non-conducting**.
- Advantage: **water drainage**, easy **track re-positioning**, cheap in installation (but expensive in maintenance), high friction resistance and **damping**.





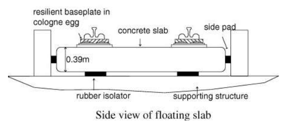
Slab Track

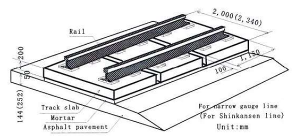
- Ballast is replaced with a **concrete slab layer**.
- It is commonly used as it provides easy **track access** in tunnels and bridges, a **rigid track bed** with better train performance and increased speed and axle loads, **reduced rail wear** and rail head problems. It is also with **low replacement cost** with less maintenance.



Type of Slab Track

- **Floating Slab Track** – Slab on resilient bearing ("pad") and foundation to improve resilience and reduce noise and vibration.
- **Direct on Baseplate** – Rail is clipped onto pad and baseplate with fasteners. The baseplate is laid on baseplate pad and concrete slab. It is hard to construct for accuracy tolerance.
- **Embedded Sleeper Slab Track** – Sleepers are embedded into concrete slap to retain track gauge. It spreads loads to ballast and concrete. Bi-Block Sleeper in Low Vibration Track (LVT) are provided in **LRT** and **trams** for rail fastening with rubber boot to provide excellent lateral stability and better resilience.
- **Embedded Rail Slab Track** – Rails embedded directly into concrete is used for tramway and LRT. It provides no resilience and maintenance adjustment.



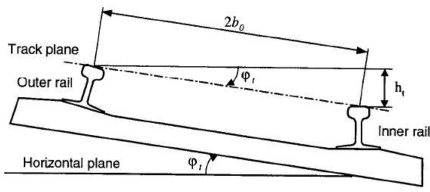


Seamless Track for XRL/Metros, HK

- It is seamless with **Continuously Welded Track** (CWR). Rails in 400m length are welded in workshop by **Thermit weld** with **stress free temperature** of 27°C

Track Cant

- To tackle for **comfort** and **speed** due to centrifugal force under turning, and to prevent **derailment**, the outer rail is normally raised at a higher level and the train is slightly tilted to make a turn. (reduce track forces and wear)
- Cant Deficiency occurs when train speed > balancing speed. A lateral acceleration is provided for **ride comfort**.
- Lateral Acceleration can be written as



$$a_y = \frac{v^2}{R}\cos\varphi_t - g\sin\varphi_t = \frac{v^2}{R}\cos\varphi_t - g\frac{h_t}{2b_0}$$

$$a_z = \frac{v^2}{R}\sin\varphi_t + g\cos\varphi_t$$

Example A sub-urban rail route with a minimum radius of curvature of 800 m with a speed limit of 150 kph. The track gauge is 1435 mm, and the curved track is normally canted to limit the lateral acceleration to 0.75 m/s². The cant is normally 125 mm, but during a maintenance check , a track cant was reduced to 75 mm on the minimum radius curve.

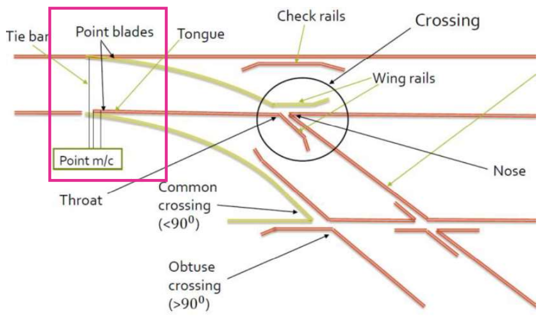
a) Calculate the lateral acceleration if a train goes around the curve at line speed
b) A speed restriction will be imposed on the curved track, what is the speed required that will keep the lateral acceleration acceptable?

Solution Given speed 150kph (= 41.67 m/s) and $\sin\varphi_t$ = 75/ 1435 = 0.0523, $a_y = \frac{v^2}{R}\cos\varphi_t - g\sin\varphi_t = \frac{41.67^2}{800}\cos 2.995^o - 9.81\,(0.0523) = \mathbf{1.64\ ms^{-2}}$

Given speed limit due to lateral acceleration restriction 0.75 ms⁻², $0.75 = \frac{v^2}{800}\cos 2.995^o - 9.81\,(0.0523) \rightarrow v = \mathbf{31.9\ ms^{-1}}$ (= 114.9 kph)

Rail **Chemical Composition** and **Mechanical Properties** are tested:

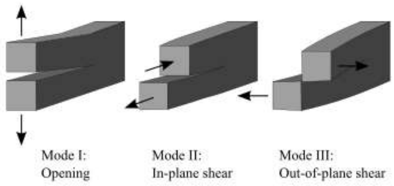
- Chemical Composition Analysis
- Hardness, Tensile Strength, Elongation, Slow Bending
- Non-Destructive Test
- Dimension Check

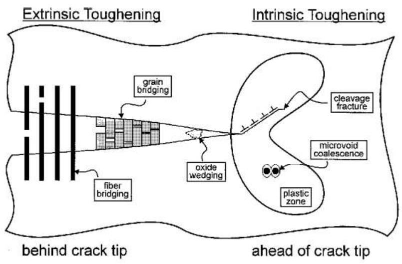


9.3 Turnover and Crossover

- Majority of crossings installed today are casted as a single piece, from **Austenitic Manganese steel** (AMS), initially very ductile, running surface hardens quickly
- Guard rails and check rails installed at the back face of the wheel provides guidance without bearing vertical load (to prevent derailment/flange climb). **Electro-mechanical point machines** use electric motor, gearbox and rods to move and check the points (Switches).
- **Vanguard** is provided for high resilience for low-speed section (e.g. low speed shunting)
- Tests for **Al Thermit Weld** (ATW) and **Flash Butt Weld** (FBW): Fatigue Test, Magnetic Particle Test, Hardness, Metallurgical, Slow Bending, Ultrasonic, Alignment Check, Visual Inspection

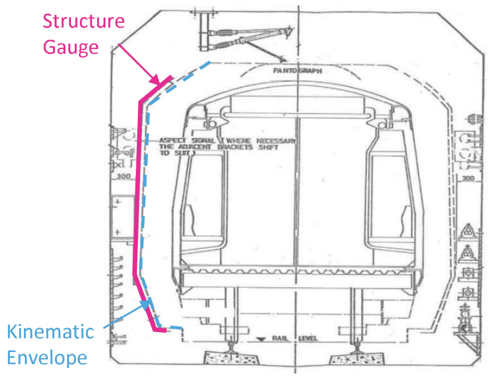
9.4 Crack Initiation and Propagation





- Crack can initiate at **grain boundary**, within grains by **slip plane motion**, by **impurities/** inclusions in metals, or through **thermal gradient**. There are 2 types of cracks, totally **internal cracks** and **surface breaking cracks**.
- There are three modes of **crack propagation**: opening, sliding and tearing.
- **Crack Tips** acts as a stress raiser. The amount of concentration depends on length of crack and width in direction of stress.
- **Surface breaking cracks** are more harmful. Internal cracks share stress concentration at two ends.
- **Cracks perpendicular** to the load are more harmful. Parallel cracks do not affect the strength of the metal if they are narrow.
- **Narrow cracks** are worse. A wide crack does not induce great change in stress direction. It can be stabilized by **drilling out** the crack ends.
- **Load cycle** increases crack length (crack growth rate).
- **Metal Fatigue** is metal failure due to **repeated load cycles. Fatigue Life** is a measure on how many cycles a component can withstand before failure. **Ratchetting** is low cycle fatigue with high stress with high crack propagation rate; **Shakedown** is high cycle fatigue with low stress and low crack propagation rate.
- A long and deep crack penetrating plastic layers is often driven by **bending stress** and **residual tensile stress**. At critical crack length, rail will fail by fast fatigue.

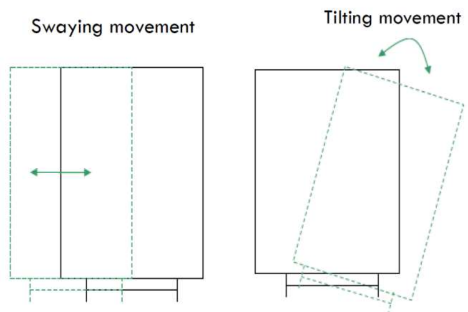
9.5 Structural Gauge and Kinematic Envelope



Structure Gauge

A line around the track within which no structure nor trackside equipment should be placed.

- Structure gauge is a set of measurements referenced to the rails which defines the minimum cross-section to be **left clear** of any structure.
- **Structure gauge assessment** is needed to ensure the railway vehicle can run safely along the track without coming unacceptably close to line side structures or equipment, or to vehicles running on the adjacent tracks.
- The amount of space required for the safe passage of a railway vehicle is significantly greater than its static body profile because of :
    - Track input excites the vehicle as it moves on its suspension
    - On curved track, its geometry position leads to **curve overthrows**
    - Track movement over the maintenance cycles, vehicle component deterioration, **wheel and rail wear**, etc
    - **External forces** such as wind loading in open sections



Kinematic Envelope (KE)

Kinematic envelope is the **envelope of body dynamic movement** resulted from

- Tilting and sway movement
- Wind load
- Track related tolerance

Conditions for kinematic envelope :

- Train speed
- Wheel wear and suspension creep
- Combined effect of vehicle curving and lateral accelerations due to track irregularities
- Max. installed cant, e.g. 150 mm
- Air suspension –inflated or deflated
- Car loading
- Max. built tolerances
- Force due to side wind, e.g. wind speed 130 km/h
- Suspension parameters at worst case
- Track tolerances/parameters

For SIL (E), there are 4 KEs respectively for mainline, depot, U/G station and O/G station.

SG and KE measurement

Laser devices are pulled along in a trolley with accuracy at +/-3 mm (accurate) at 30 kph.

10 Railway Line and Station Design

10.1 Line Selection

Railway is to transport a large flow between cities and towns. Line alignment selection at lowest viable cost, not necessary to be financial cost.

Government assesses railway route on 11 main criteria:

1. **Economy** – Promote economic growth
2. **Connectivity** – connect remote and disadvantaged communities
3. **Integration** –integrate by making journey planning and ticketing easier and ensure smooth connection between different forms of transport
4. **Environment** – Protect the environment and improve health by investing in efficient and sustainable transport to minimize the emissions and consumption of resources/energy, noise and vibration and pollution
5. **Geography** – Process of route selection should consider horizontal alignment, vertical alignment and geographical features such as valleys, river and streams, lake and sea front. Gradient is restricted to 1: 45.
6. **Geology** – Ground condition such as layers of rock, gravel, sand, clay and water affects tunnelling construction including depth, direction and method. It also affect surface track in terms of stability and durability.
7. **Existing infrastructures** – Roads, buildings and their foundations (tunneling need to clear of the foundations and not to affect the structure)
8. **Railway System** – maximum and minimum bending radius, jerk rate and gradient, ride comfort
9. **Political considerations** – economic and environmental values should be well balanced.
10. **Land considerations** – land ownership, land contamination (de-water) and archaeological remains
11. **Safety** – improve safety of journeys by enhancing personal safety of passengers, staff, drivers and pedestrians

10.2 Station Design

Stations provide a **safe and comfortable access and egress to the rail network** by –

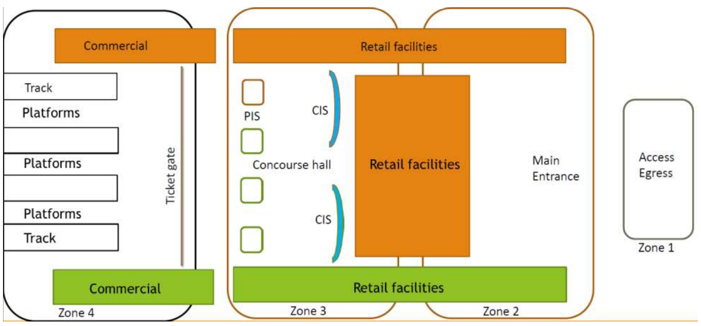
- Concentrate and **distributing** passengers
- **Control access** of passengers and 3rd parties
- Facilitate **connectivity** with other modes of transport
- Give a comfortable **waiting environment**

Stakeholders such as passengers, employees, network infrastructure managers, operating companies, retailers, owners, district councils, transportation department, other public transports should be considered.

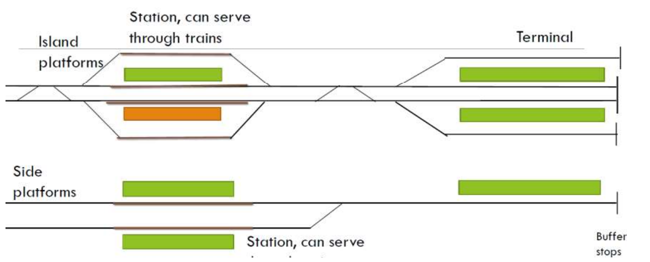
10.3 Station and Terminus Layout in High-Speed Station

- Stations usually link to **land-use planning and spatial development** (ideally in city centre or urban area)
- For connectivity, peripheral, **road-based access for park-and-ride station** (car parking provided). Combination of both city centre and peripheral is the best.
- Access by other **public transport and private transport modes**.

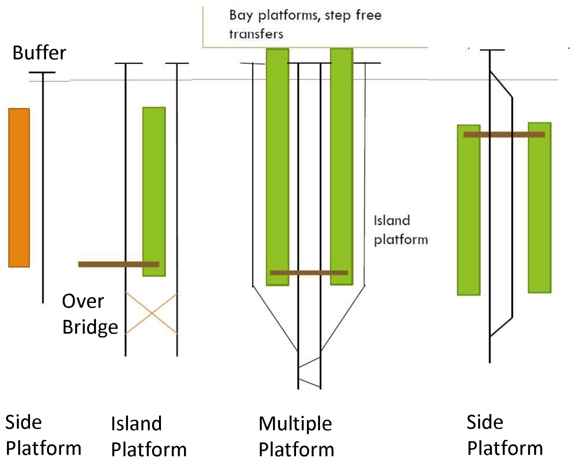
Each gate = 25 p/min



Terminal Design



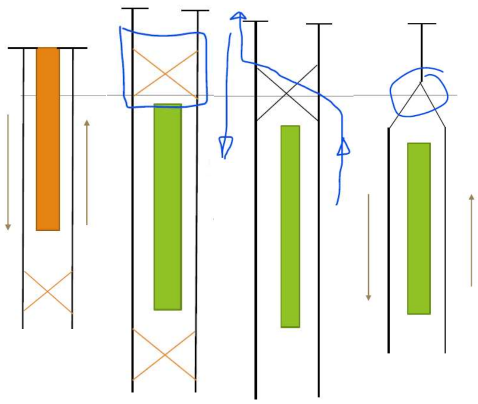
High Speed Terminus Layout



Layout

- No. of platforms dictated by **train services** and **train types**
- Platform requirement also affected by **timetable**, **EMU or loco-hauled** operation
- Long platforms require additional underpasses/links

High Speed Terminus – Two Track Layout



1. Double Reversing Track **before** platform
2. Double Reversing Track **before and beyond** platform
3. Double Reversing Track **beyond** platform
4. Single Reversing Track

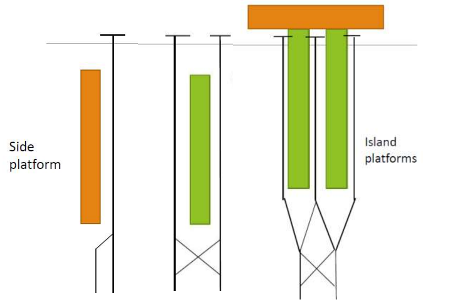
Platform and track requirements affected by

- Overtaking and through tracks for non-stopping trains
- Passing of trains (in opposite direction) and recovery time
- Connections between services (mainline and branch)
- Servicing requirements and overnight stabling
- Non-passenger services (freight, inspection/working)

	Double reversing tracks **before** platform	Double reversing tracks **around** terminal platform	Double reversing tracks **beyond** terminal platform	**Single** reversing track beyond terminal platform
Advantages	Incoming trains can arrive at either platforms **Low construction cost**	**Highly flexibility for operation** in either direction **Full speed ATP overrun, Space for stable trains**	All trains arrive at 1 platform **Reversing trains clear of station** **Space for full ATP overrun** Simple passenger interface **Can accommodate 1 defective train**	Simple trackwork, 2 platform faces one each for arrival and departure Low construction costs Simple passenger interface
Disadvantage	**Inflexible in train movement**, reversing trains have to pass platform to reverse **No spare space for trains**, Medium recovery opportunity after disruption	Expensive trackwork, high maintenance **Additional space, expensive in land intake/tunneling** Complex information system for passenger management	Inflexible platform use, no spare **space to hold multiple trains** Medium recovery opportunity after disruption Moderate expensive in construction **Additional train required for short headway**	**Inflexible in operation**, no spare space for trains Poor recovery opportunity after disruption, Additional train required for short headway service

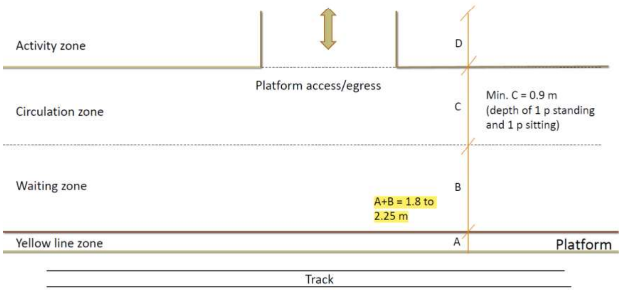
Metro Station design

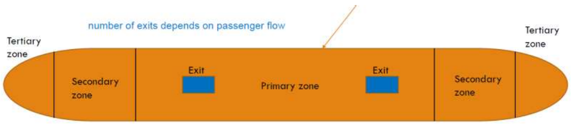
- Good and **short access on foot**, stations usually close to highly populated urban areas. Distance between stations, 1 to 2 km for metro stations, urban tram 0.5 to 1 km
- **Escalators and lifts** are installed to get vertical access
- Integration with **other public transport** modes



10.4 Platform Design

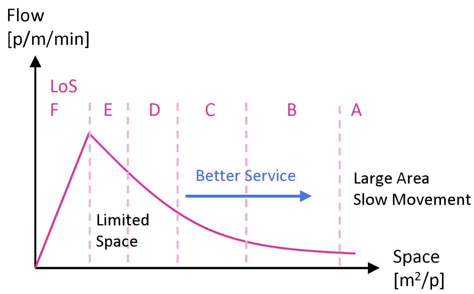
- Platform must be wide enough to cope with passengers (alight/boarding/waiting) – typical 3 to 4.5 m (6 to 9 m for island platform)
- Avoid obstructing passenger flow
- Direct routes for time-sensitive passengers is vital
- Yellow Zone - Danger zone, crowd pushing/squeezing, suicidal jumps → avoid crowd pushing and accidental fall/ suicidal jump
- Sufficient waiting space to accommodate at least train largest capacity (300 x 8 = 2400 p/train – sufficient circulation space)
- Accessibility for persons with disabilities and persons with reduced mobility (PRM) – min width: 1.6m outside of danger zone

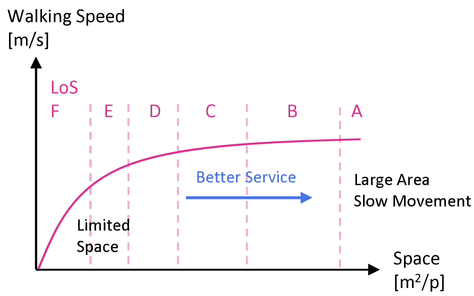




10.5 Passenger Flow

- Avoid congestion
- Can cope with peak demands and train service disruption
- Capacity for evacuation
- Design for logical flow of tasks, avoid conflicting flow
- Separate free and paid areas
- Allow extra space where queues are needed.
- Vertical and Horizontal Movement - Lifts and escalators segregate in-bound and out-bound passenger flows (one way flow). In HK, passengers flows in and out of each platform will be **computer simulated** in whole **transportation network** (staircase, escalator and lifts, entrance and exits, corridors) to ensure smooth passenger flow during **peak hours** and **emergency evacuation**.
- Limits on Escalator Capacity – 50 - 100 passengers/min. (without luggage) depending on the speed of the escalators (for safety, around 0.5 to 0.8 m/s)
- **Maximum load** exists with – train delays, cancelled trains or possibly 2 trains simultaneously.
- **Horizontal flow along the platform**, passengers increase in no. in the direction **towards the exits**. Exit capacity is essential in the design.

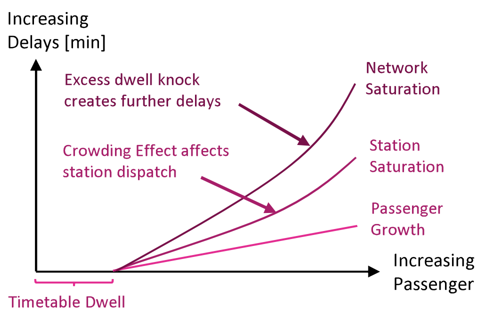




Example 1

Existing tunnel width is 4 m. The max. no. of passengers entering and exiting are 271 and 71 p/min. Gate capacity is 25 p/min. Calculate :

1. LoS.
   With tunnel width 4 m: LoS = 271 / 4 = 67.75 (LoS E)
2. Required tunnel width
   Assume LoS C with 33 – 49 p/m/min horizontal movement with average 41 p/m/min.
   Required tunnel width = 271 / 41 = 6.6 m
3. Number of ticketing gates required and the overall width.
   Exit Gate = 271 / 25 = 10.8 (11 gates); Enter Gate = 71 / 25 = 2.8 (3 gates)
   With every 10 gates, 1 wide gate is needed → total = 11 + 3 + 2 (wide gate) = 16 gates.
   Overall width = 14 x 0.8 + 2 x 1.0 + 0.2 = 13.4 m



10.6 Tunneling

- Methods: Drill and Blast (small hole drilled and packed with explosive), Road Header (drill and spray with concrete), Tunnel Boring Machine (TBM, drill and install lining with balancing pressure)
- Concern: Ground water pressure (200 bars or more), granular materials around solid rock, proximity to surrounding foundations, cost and time constraints.

TRACTION EFFORT

Acceleration of a train can be determined by a *force balance* equation relating traction force and different resistances.

$$T - F_D - F_g - C_D = M_{eff} \times a \qquad (1.1)$$

given that

$T = \mu_r M_p g$; $F_D = A + BV + CV^2$ (Davis Equation) ;

$F_g = Mg\ 1/X$; $C_D = MK/R$; M_{eff} = tare mass $(1 + \lambda)$ + payload

where

T = Traction Force, $\mu_r = 0.3$ for loco, M_p = mass on powered wheels.

F_D = Friction Drag, A = rolling resistance = 3 – 5kN, B = bearing friction = 20N/ton at warm move and C = aerodynamics drag.

F_g = Gradient Force, 1/X = gradient.

C_D = Curve Drag, M = train mass, K = 23000 m^2/s^2, R = curve radius = r / 5729.58

M_{eff} = Effective Mass, λ = 5 – 15%, rotary allowance (more for aluminum car body, less for steel car body with less motored axles)

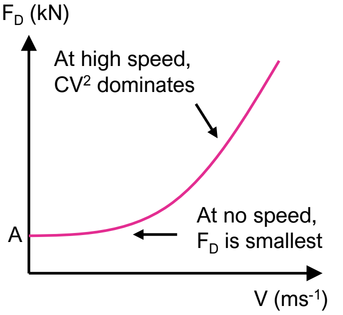


FIGURE 1-1
Variation of Friction Drag with Velocity

QUESTION 1 ACCELERATION AND BRAKING ENERGY

The early ICE trains adopt concentrated power technology. A concentrated power ICE train is driven by 2 locomotives, one at each end of the train consists. Each locomotive weighs 75 tonne. The train has 9 coaches, and each weighs 40 tonne. (a) Calculate the acceleration that this ICE train can achieve. State your assumptions when you do the calculation.

The CRH380 high-speed trains are proposed to be used in a high-speed line connecting two northern cities in Mainland China. The CRH380 train has a maximum design speed of 380 km/h, and an operating speed of 300 km/h with brakes at 0.9 m/s^2. The train set weighs 380 tonne, and the traction power supply is operationally rated for 10 MW. (b) Calculate the power to be dissipated by the braking system at the maximum operating braking rate. Describe a braking system that can sustain this braking performance.

SOLUTION

(*a*) To obtain the largest acceleration, it is assumed that no gradient, no curve, no payload, negligible friction drag and a steel body for rotary allowance.

From the traction effort equation (1.1),

$$T = M_{eff} \times a \ \rightarrow \ \mu_r pMg = M(1+\lambda)a$$

$$(0.3)(150 \times 10^3\ \text{kg})(9.81\ \text{ms}^{-2}) = (510\ \text{kg})(1 + 5\%)a \ \rightarrow a = \mathbf{0.824\ ms^{-2}}$$

(*b*) Given that with initial (operating) speed 300 km/h (= 83.33 m/s) and braking rate 0.9 m/s^2. It is noted that the equivalent torque leading to the braking rate can be represented as

$$T_{eq} = mb = (380 \times 10^3\ \text{kg})(0.9\ \text{ms}^{-1}) = 342\text{kN}$$

Power dissipated can be represented as

$$P = T_{eq}v = (342\text{kN})\left(\frac{300}{3.6}\text{ms}^{-1}\right) = \mathbf{28.5MW}$$

Note: If the initial speed is the design speed (380 km/h, =105.56 m/s), the *designed maximum* dissipated power can be calculated as **35.9 MW**.

It is noted that the traction power supply is designed to operate at 10 MW. Purely by regenerative braking cannot absorb all dissipated power at both speed. Hence, a combination of *electro-pneumatic brake* and *electro-dynamic brake* (i.e. regenerative braking) is employed to sustain the braking performance at initial stage.

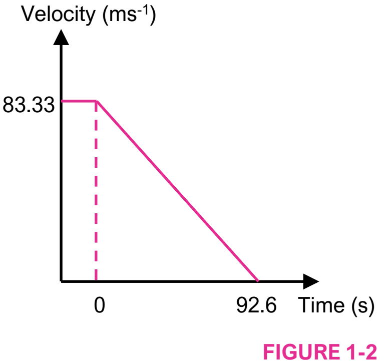


FIGURE 1-2
Velocity Profile for Question 1(b)

QUESTION 2 STOPPING DISTANCE

Rail contamination with leaves hardened on rail head commonly causes a wheel-rail sliding problem. A near-miss incident occurred as a suburban commuter train slid 3000 m beyond the open section station due to railhead contamination (i.e. leaves on the rail line). The commuter train was travelling at 108 km/h when the train driver applied the brakes. Assume the brake application response time as 2 seconds.

(a) Calculate the distance required ahead of the station for the train driver to start to apply the brakes so that the commuter train can stop right at the station. Assume the braking rate of 0.7 m/s^2.

(b) Calculate the average rate of deceleration achieved by the train during the incident, and what was the actual coefficient of friction between the wheel and rail?

(c) There was a level crossing 2000 m beyond the station, and slid across the level crossing is a SPAD incident. Assume the train is equipped with an automatic sanding system, which helps increase the braking rate by 0.25 m/s^2. Calculate the stopping distance of the train and state whether or not, it will slide through the level crossing with a SPAD

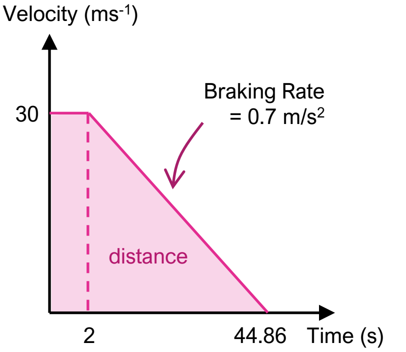


FIGURE 2-1
Velocity Profile for Question 2(a)

SOLUTION

(a) Given that an initial speed 108 km/h (= 30 m/s) and braking rate 0.7 m/s^2. Time for braking is calculated as

$$t = \frac{v - u}{b} = \frac{30\ \text{m/s}}{0.7\ \text{m/s}^2} = 42.86\ \text{s}$$

Distance travelled during braking can be found by

$$s = \text{area under curve} = (30\ \text{m/s}) \times 2\text{s} + \frac{1}{2}(30\ \text{m/s})(42.86\ \text{s}) = \mathbf{702.9\ m}$$

(b) With the sliding distance represented as

$$s = \frac{1}{2} \times (30\ \text{ms}^{-1}) \times t_F = 3703\ \text{m} \quad \rightarrow \quad t_F = 246.9\ \text{s}$$

The average deceleration during the incident is

$$\bar{b} = \frac{v_0}{t_F} = \frac{30\ \text{m/s}}{246.9\ \text{s}} = \mathbf{0.122\ m/s^2}$$

Actual coefficient of friction (μ) can be found with

$$F = \mu m g = m\bar{b} \quad \rightarrow \mu = \frac{\bar{b}}{g} = \frac{0.122\ \text{m/s}^2}{9.81\ \text{m/s}^2} = \mathbf{0.0124}$$

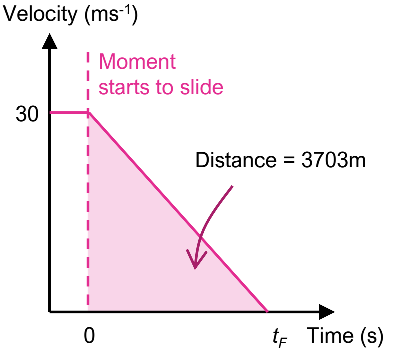


FIGURE 2-2
Velocity Profile for Question 2(b)

(c) With 2 seconds reaction time, initial speed 108 km/h (=30 m/s) designed braking distance ahead the station is as calculated in Question 2(a), i.e. 702.9 m, and sliding deceleration due to wheel-rail friction in case of Question 2(b), i.e. 0.122 m/s^2,

The actual braking rate including friction from sanding system is

$$b_{tot} = 0.122 + 0.25 = 0.372\ \text{m/s}^2$$

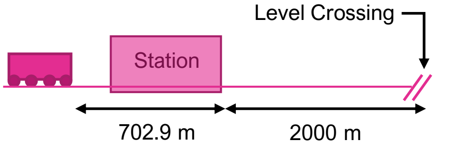
The braking time is calculated as

$$t_F = \frac{30\ \text{m/s}}{0.372\ \text{m/s}^2} + 2 = 82.6\ \text{s}$$

The distance travelled with the braking rate is

$$s = 30 \times 2 + \frac{1}{2}(82.6 - 2)(30) = \mathbf{1270m} < 2000\ \text{m}$$

It is noted that the stopping distance with only the sanding system is still smaller than 2000 m (*1860 m with only deceleration of 0.25 m/s^2*). It means that even if the train in full speed starts braking at the station, it can still brake before reaching the level crossing.



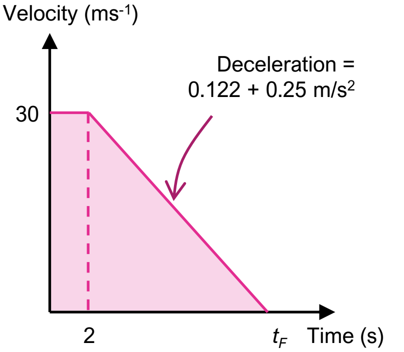


FIGURE 2-3
Velocity Profile for Question 2(c)

EQUIL-BLOCK HEADWAY

Divide braking distance from line speed into blocks in equal length. Given 2 intermediate speeds $\{V_2, V_1\}$ with speed code $\{V_{MAX} / V_2, V_2/ V_1, V_1/ 0\}$ in 3 blocks $(n - 1 = 3)$. n = 4, where n is number of aspects.

Block Length:

$$L_S = \frac{1}{n-1}\frac{V_{MAX}^2}{2b}$$

Separation:

$$S_n = \frac{n+1}{n-1}\frac{V_{MAX}^2}{2b}$$

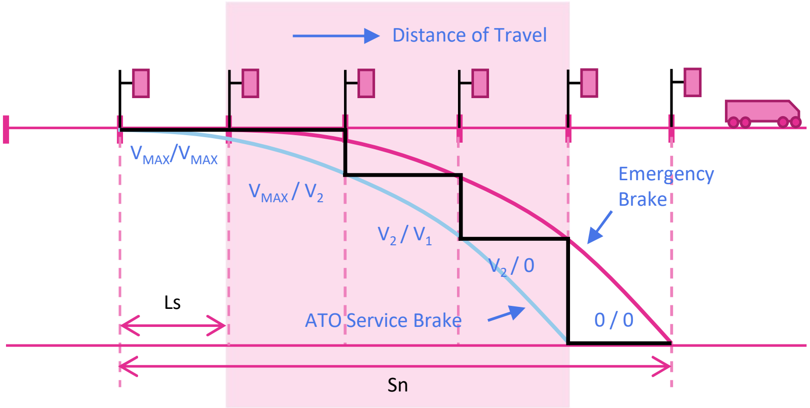


FIGURE 1
Velocity Profile for Equi-block Operation

QUESTION 1 HEADWAY

An urban metro uses an equi-block signaling system with Automatic Train Protection, ATP. There are 2 intermediate speeds. The trains are 200 m long at a line speed of 80 kph, and can achieve a braking rate of 1.1 m/s^2.

(a) Calculate the intermediate speeds and block section length for a plain track.

(b) Calculate the technical headway of this urban metro when the trains are following each other, in terms of time and distance. State your assumptions.

(c) This urban metro has now been upgraded to a moving block system. Calculate the new technical headway in terms of time and distance.

SOLUTION

(a) Divide braking distance from line speed into blocks in equal length. Given 2 intermediate speeds $\{V_2, V_1\}$ with speed code $\{V_{MAX} / V_2, V_2/ V_1, V_1/ 0\}$ in 3 blocks $(n – 1 = 3)$. n = 4, where n is number of aspects.

Given the maximum speed = 80 km/h (= 22.22 m/s)

Braking Distance:

$$s_b = \frac{v_{MAX}^2}{2b} = \frac{\left(22.22\ \mathrm{ms}^{-1}\right)^2}{2(1.1\ \mathrm{ms}^{-2})} = 224.47\ \mathrm{m}$$

Block Length:

$$L_s = \frac{1}{n-1}s_b = \frac{1}{n-1}\frac{v_{MAX}^2}{2b} = \frac{224.47\ \mathrm{m}}{3} = \mathbf{74.82\ m}$$

Intermediate Speed:

$$v_2 = \sqrt{2bs + v_{MAX}^2} = \sqrt{2(-1.1)(74.82) + 22.22^2} = \mathbf{18.14\ ms^{-1}}$$

$$v_1 = \sqrt{2bs + v_2^2} = \sqrt{2(-1.1)(74.82) + 18.14^2} = \mathbf{12.83\ ms^{-1}}$$

The intermediate speed are **65.3 kph** and **46.2 kph**.

(b) For an equi-block 4-aspect signaling system with n = 4,

Separation:

$$S_n = (n+1)L_s = 5(74.82\ \mathrm{m}) = \mathbf{374.11\ m}$$

Headway:

$$\text{Distance Headway} = S_n + L = 374.11 + 200 = \mathbf{574.11\ m}$$

$$\text{Time Headway} = \frac{S_n + L}{v_{MAX}} = \frac{374.11 + 200\ \mathrm{m}}{22.22\ \mathrm{ms}^{-1}} = \mathbf{25.84\ s}$$

(c) For Moving Block System,

$$\text{Distance Headway} = s_b + M + L = 224.47 + 50 + 200 = \mathbf{474.47\ m}$$

$$\text{Time Headway} = \frac{s_b + M + L}{v_{MAX}} = \frac{474.47\ \text{m}}{22.22\ \text{ms}^{-1}} = \mathbf{21.35\ s}$$

Note: Capacity gained 17.4% by using Moving Block System.

REDTENBACHER FORMULA

Construct two rays from the origin of curve O. OBD passes through contact point of inner wheel and rail B, and that of outer wheel and rail D. The second ray lies along the central axle axis to center of inner wheel A and center of outer wheel C. Consider ΔOAB and ΔOCD,

$$\frac{r_{inner}}{R - l} = \frac{r_{outer}}{R + l}$$

Rewrite the radius r_{inner} and r_{outer} in terms of conicity of wheelset γ,

$$\begin{cases} r_{inner} = r - \gamma y \\ r_{outer} = r + \gamma y \end{cases} \rightarrow \frac{r - \gamma y}{r + \gamma y} = \frac{R - l}{R + l}$$

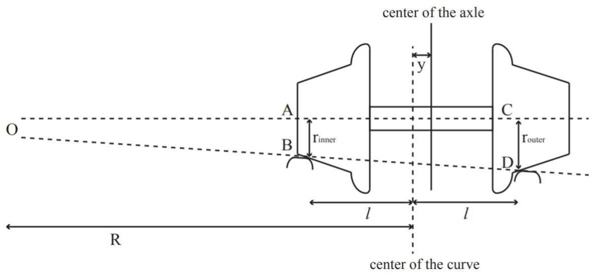


FIGURE 2
Traction Geometry for Redenbacher Formular Derivation

TRACK PLANE ACCELERATION

In case of quasistatic curving (i.e. curving at constant speed, radius and cant on perfect track geometry) the vehicle is exposed to two accelerations: horizontal centrifugal acceleration and gravitational acceleration. The resultant acceleration vector can be split up into two components: a_y, parallel to the track plane and a_z is perpendicular to the track plane.

The acceleration a_y is called track plane acceleration, or simply, lateral acceleration. The equations can be written as follows.

$$a_y = \frac{v^2}{R}\cos\varphi_t - g\sin\varphi_t = \frac{v^2}{R}\cos\varphi_t - g\frac{h_t}{2b_0}$$

$$a_z = \frac{v^2}{R}\sin\varphi_t + g\cos\varphi_t$$

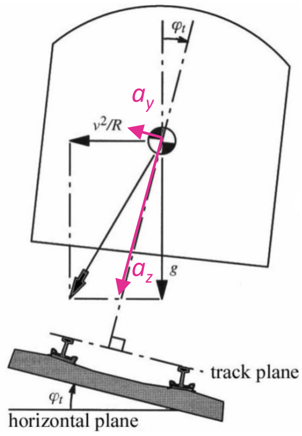


FIGURE 3
Track Plane Acceleration

QUESTION 2 **LATERAL ACCELERATION AND CANT DEFICIENCY**

A modern suburban commuter line has a maximum line speed limit of 144 km/h. due to land constraint. There exists curved track sections with a minimum radius curve of 615 m. The rail track is normally canted to limit the lateral acceleration to around 0.75 m/s^2. In the case of minimum radius curves, the cant is normally 150 mm. The track gauge is 1435 mm, and the conicity can be taken as 1 in 20.

Following a scheduled maintenance activity, it was discovered that the track cant was somehow reduced to 75 mm on one of the minimum radius curves, and there is no time to rectify the problem before the line re-opens.

(a) Calculate the lateral acceleration if a train goes around this bend at the line speed.

(b) A speed restriction will need to be imposed on the section of track. What is the speed restriction required that will keep the lateral acceleration at an acceptable level?

(c) Calculate the lateral shift of a wheelset on a minimum radius curve, assuming perfect curving and assuming a nominal wheel diameter of 860 mm. Comment on your result.

(d) Describe the concept of kinematic oscillation of a wheelset.

SOLUTION

(a) Consider the track gauge with reduced cant (= 75 mm) scenario and track gauge = 1435 mm. With maximum line speed limit = 144 km/h (= 40 m/s),

$$\sin\varphi_t = \frac{75}{1435} \rightarrow \varphi_t = 3^o$$

$$a_y = \frac{v^2}{R}\cos\varphi_t - g\sin\varphi_t = \frac{40^2}{615}\cos 3^o - 9.81\sin 3^o = \mathbf{2.08\ ms^{-2}}$$

(b) Speed is limited by the lateral acceleration requirement (b_{max} = 0.75 ms^{-2}).

$$a_y = \frac{v^2}{R}\cos\varphi_t - g\sin\varphi_t \rightarrow 0.75 = \frac{v^2}{615}\cos 3^o - 9.81\sin 3^o$$

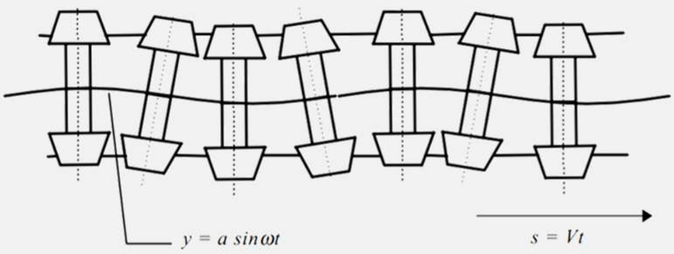
Solving, the speed restriction is at v **= 27.89 m/s** (= 100 kph)

(c) Given that

$$\frac{r-\gamma y}{r+\gamma y} = \frac{R-l}{R+l} \rightarrow \frac{430-\frac{\gamma}{20}}{430+\frac{\gamma}{20}} = \frac{615000-\frac{1435}{2}}{615000+\frac{1435}{2}}$$

The lateral shift γ is **10.03 mm**.

(d) A wheelset is rolling along the track and is displaced slightly to one side, the wheel on one side is running on a larger radius and the wheel on the other side is running on a smaller radius. Because the wheels are mounted on a common axle one wheel will move forward faster than the other because its instantaneous rolling radius is larger. Hence, if pure rolling is maintained, the wheelset moves back into the centre of the track − a steering action is provided by the coning. However, the wheelset overshoots the center of the track, and the result is the kinematic oscillation.



$$\frac{1}{R} = -\frac{d^2y}{ds^2} = \frac{\omega^2 y}{V^2} = \frac{\omega^2 r_0 l}{V^2 R\lambda}$$

FIGURE 4
Derivation on Klingel's Formula