

# 45

## Railways

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## 45.1 Railway electrification

The benefits of using electrified lines for heavy traffic loadings are established and many countries now operate electric trains. About 180 000 route kilometres are electrified, with a variety of systems. The USSR contains about one-third of this total. Electric transmission is standard for high powered diesel locomotives.

### 45.1.1 Supply

Electrified-line systems fall into two broad divisions: (1) a.c. systems and (2) d.c. systems.

For city and suburban services, d.c. is most common; for main-line services there are many examples of both a.c. and d.c. systems. The use of a.c. has developed mainly in Europe and has become the standard for new schemes. In countries where the electrification of railways took place in the period 1920–1940, d.c. systems predominate and extensions maintain compatibility. For new high-power schemes, 25 or 50 kV a.c. is used for the distribution of power and sometimes as the voltage delivered to the locomotive. For lower power schemes such as new suburban lines, 25 kV a.c. is the usual voltage.

#### 45.1.1.1 A.c. systems

A.c. systems can be divided into (1) single-phase low-frequency (16 $\frac{2}{3}$  and 25 Hz) and (2) single-phase industrial frequency (50 or 60 Hz). Early three-phase systems have been replaced, although some special vehicles use three-phase collection.

*Single-phase low frequency* This system is widely used in Europe at 16 $\frac{2}{3}$  Hz and to a limited extent in the USA at 25 Hz. The low frequency was chosen to allow commutator motors to be used directly, with simple voltage control of power. Supply is taken from an overhead conductor at voltages up to 16 kV, with the rails used for return.

Figure 45.1 shows a typical power control circuit for a two-motor equipment. The supply is taken from the overhead line through a circuit-breaker to the primary of a step-down transformer, the secondary of which is tapped for low-voltage feed to the traction motors. Motor voltages of a few hundred volts are typical.

*Single-phase industrial frequency* The advantage here is the use of main national grid systems as the power source,

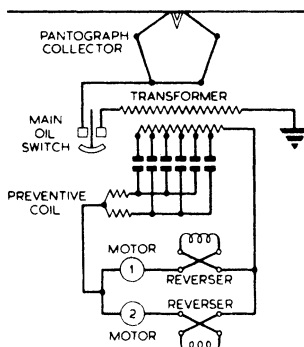


Figure 45.1 Main-circuit diagram for two-motor multiple-unit equipment with single-phase series motors

instead of special low-frequency generation or conversion stations. Pioneering work was done by the French in 1951, with several experimental locomotives subsequently being built. Although 50 Hz commutator motors were feasible, the use of d.c. motors from a rectified supply was preferred. Power control is either by control of the a.c. voltage prior to full-wave rectification, using a tap-changer, or control of the d.c. voltage by phase-angle control of a thyristor bridge. British Railways adopted the 25 kV, 50 Hz system in 1956; an early traction-control circuit in which a tap-changed voltage was used to buck or boost a fixed voltage in the feed to the rectifier is shown in Figure 45.2.

Industrial frequency is now used in many countries, with about 20 000 route kilometres in operation. Voltages of 50 kV are used, in some cases with locomotive equipment rated for this voltage, in other cases being used for feeding autotransformers to deliver 25 kV to the train. In the UK, 25 kV has been used for all schemes, but the Channel Tunnel route to London will use 50 kV with autotransformers. Figure 45.3 shows the principle of autotransformer feeding with these transformers connected between catenary, rail and the auxiliary feeder which is at  $-25$  kV. Current is forced to be equal in the two windings of these transformers and the 200 A train load is provided by addition of the components shown. The supply transformer is then feeding 100 A at 50 kV.

#### 45.1.1.2 D.c. systems

Systems operating at 600–1000 V are used extensively for urban and suburban electrification, usually with one live insulated rail and running rail return. Some four-rail systems exist, with positive and negative insulated electrical supply rails. Systems working at more than 1000 V use overhead catenary-supported conductors; typical voltages are 1500 and 3000 V. For heavily trafficked routes, 12 000 V has been considered.

D.c. motors are customary, although the trend is now towards the use of three-phase induction motors, driven from semiconductor inverters. The use of d.c. will reduce problems of electromagnetic compatibility, since voltages are not induced in track-side conductors. High power is more difficult to provide in d.c. systems than in a.c. systems since the voltage rating of d.c. train equipment cannot approach the 50 kV of the a.c. train. Currents are therefore high, requiring the use of heavy overhead conductors and closely spaced substations. With d.c. lines there are also possible problems of corrosion due to leakage currents.

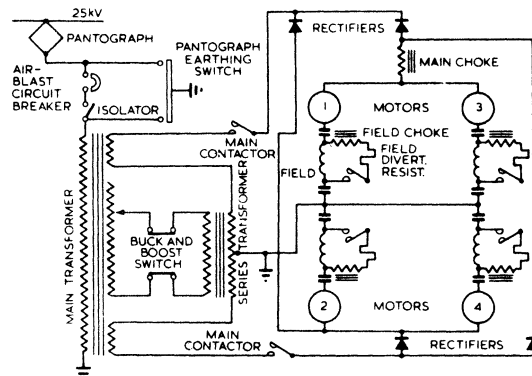


Figure 45.2 Main-circuit diagram for a 25 kV locomotive

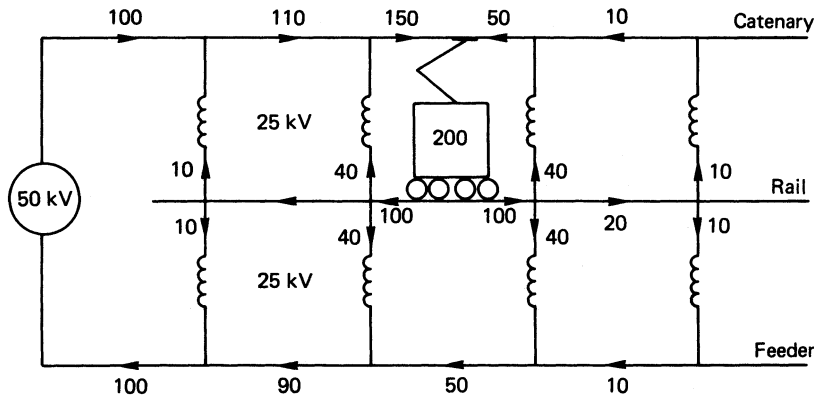


Figure 45.3 Current distribution in an autotransformer system for 200 A train load

### 45.1.2 Fixed equipment

Provision of the live conductor for carrying power to the trains is complex and expensive, probably costing as much as the trains which will be used.

#### 45.1.2.1 D.c. conductor rail

The d.c. conductor rail is typically a flat-bottomed cast iron (99.75% Fe) rail of 50–75 kg/m mounted on porcelain insulators at the side of, and spaced about 40 cm from, one of the running rails. The negative return is via the running rails unless (as on London Underground lines) circumstances require an insulated return rail, usually mounted on insulators between the two track rails. A 45 kg/m rail has a resistance of about  $20 \mu\Omega/\text{m}$ .

A composite conductor rail is available with an aluminium body and a stainless steel contact surface. This has the advantages of reduced electrical resistance (typically half) and mass, but at a higher cost. This may be recouped if the substations can be placed further apart for the same voltage drop. Such rail is used on the Botley to Fareham line of British Railways, on the Docklands Light Railway, London (under-side contact), and the Singapore Mass Transit.

#### 45.1.2.2 D.c. overhead conductor

A hard-drawn copper contact wire is supported above the track by a catenary and dropper wires, in such a way that the contact wire sags by a small amount in mid-span. This sag results in an approximately level path for the pantograph at speed. On heavily loaded 1500 V lines, a twin contact wire may be used.

To maintain the wire tension in varying weather conditions, the catenary and contact wires are anchored via insulators to a structure at the mid-point of the wire length and are then stretched by weights at each outer end. The longitudinal force in catenary and contact wire is about 10 kN. The lateral position of the contact wire alternates from side to side of the track centre line, traversing the active width of the pantograph collector strip during running to equalise the wear of the contact materials.

#### 45.1.2.3 Feeder stations (d.c.)

Multipulse rectification is used with star/delta transformer connections and the basic ripple frequency on the d.c. output

is 6 or 12 times the a.c. frequency. Mercury arc rectifiers are still in service, but new stations use silicon rectifiers. The d.c. rail (or overhead conductor) is connected as a continuous circuit, energised at each feeder station.

#### 45.1.2.4 A.c. overhead conductor

This is similar to the d.c. system. For high-speed operation, a compound arrangement is used with an intermediate catenary. In another design, a partial second catenary some metres long is placed at the support, to reduce the change of mechanical impedance at the contact point. The tension may have to be increased for high-speed use and the Deutsches Bundesbahn use 15 kN for their 250 km/h design (70 mm<sup>2</sup> catenary and 120 mm<sup>2</sup> contact wires).

The Mark III design used by British Railways has a catenary of five strands of aluminium each 3.95 mm diameter with two equal strands of steel to give strength. This has an equivalent copper area of 42 mm<sup>2</sup>. A copper contact wire of 107 mm<sup>2</sup> is provided. Where overhead conductors are provided to give a preferential path for return current, these have 10 strands of aluminium, each 4.22 mm in diameter.

A consideration is the avoidance of conductor clashing in the event of short circuit. This places a minimum value on the vertical separation between the catenary and contact wires.

Where vertical space is at a premium such as in tunnels, a solid bar can be used instead of a contact wire. Such an arrangement can be used at speeds up to 140 km/h.

#### 45.1.2.5 Feeder stations (a.c.)

The 16 $\frac{2}{3}$  and 25 Hz systems use frequency converter stations at the points of connection to the national electrical network. Static frequency converters using thyristors are now in service at ratings of several megavolt-amperes, displacing the earlier synchronous converters.

Each feeder station at 25 kV supplies about 50 km of route and, to distribute the single-phase load on the main electrical network, different phases are used at succeeding feeder stations. The mid-point between feeders consists of an insulating neutral section through which the trains coast at zero power.

A wide spacing between feeder stations is a particular advantage in countries which do not have an extensive

industrial frequency network. In extreme cases, the electrical supply for the railway has to be taken along the railway route as a three-phase high-voltage system, sometimes using structures common with those which support the overhead contact wire. One alternative feeding method is to use a 25 kV supply from overhead wire to rail, feeding this through autotransformers fed from a 50 kV longitudinal feeder.

The traction current passing through the locomotive transformer returns to the feeder station via the rails. If no special arrangements are made, the current will enter the earth as well as the rails. This current distribution can induce voltages in parallel electrical conductors such as communication cables. These voltages can reach dangerous values and it is customary to provide a return conductor in parallel with the rails to reduce induction. A further improvement is obtained if current transformers are connected in the energised and in the return conductors, forcing the current into the latter and removing the current from the track rails and earth.

The feeder station includes protection switchgear to remove the supply in the event of a short circuit. Vacuum circuit-breakers are used, giving a small switch which can be mounted on a steel mast as part of the overhead construction. Motorised or hand-operated isolators are provided to ensure safety during maintenance work.

### 45.1.3 Power collection

#### 45.1.3.1 D.c. shoe

The collector shoes are of cast iron, and adequate contact between shoe and rail is effected by the mass of the shoe (10–25 kg). For high-speed running a spring-loaded shoe may be used with a contact force of about 300 N.

The use of an upwards-facing contact surface on the rail permits the use of a simple gravity shoe but the surface is vulnerable to contamination and ice formation. Alternative systems use side contact or bottom contact, with spring-loaded shoes.

#### 45.1.3.2 Current collectors (overhead)

A mechanism is required to maintain a current collector in contact with the overhead system. This, normally a pantograph, can be of several forms: a typical version comprises a folded arm which is raised by an air cylinder, carrying a contact head on separate springs. The collector material which slides along the overhead conductor can be of various materials, but metallised carbon is used in the UK. The pantograph frame ensures that the head moves on an approximately vertical path and maintains a constant contact force of about 90 N between head and conductor.

### 45.1.4 Power control

#### 45.1.4.1 A.c. supply to train

*Transformer design features for traction* The prime objectives in transformer design are low mass and high reliability. A modern 1.5 MVA naturally cooled transformer weighs about 3100 kg. A 7.7 MVA unit weighs about 8200 kg.

*Tap-changer* Older designs used mechanical switches to change the taps on a transformer, this stepped voltage being fed to rectifiers and then to the d.c. motors. On

16 $\frac{2}{3}$  Hz the traction motors are capable of working with the a.c. voltage source.

*Thyristor phase angle* Recent designs use thyristors to regulate the voltage. *Figure 45.4* shows the basic elements of the armature power control circuit of a phase-angle-controlled locomotive. The output winding of the transformer is divided into a number of parts (usually two but more can be used), which feed asymmetrically controlled thyristor/diode bridges. Each bridge is sequentially advanced to full conduction as increased power is required.

Thyristor current normally extinguishes by natural commutation as the voltage reverses. *Figure 45.5(a)* shows the voltage and current waveforms for partial conduction of a single bridge; *Figure 45.5(b)* shows full conduction. The latter shape is that which applies for tap-changer/diode circuits.

The power factor can be improved if the current is forcibly reduced to zero during the half-cycle, a system known as sector control. The drawback is an increase in harmonic content. *Figure 45.6(a)* shows part power and *Figure 45.6(b)* full power for a single sector-controlled bridge.

An improved harmonic performance is available if the firing angles of both bridges are controlled simultaneously, with different angles for each bridge. This can reduce the selected harmonic content of the primary current.

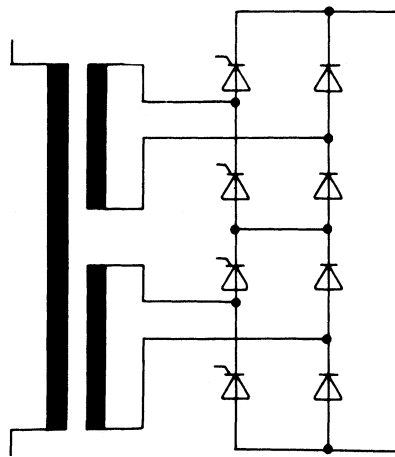


Figure 45.4 Two sequential half-controlled bridges

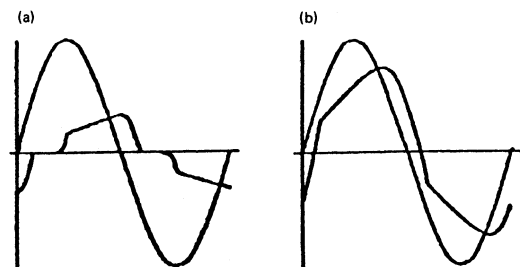
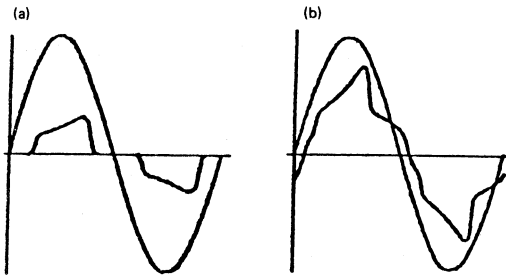


Figure 45.5 Voltage and current waveforms of a phase-angle-controlled bridge: (a) partial power; (b) full power



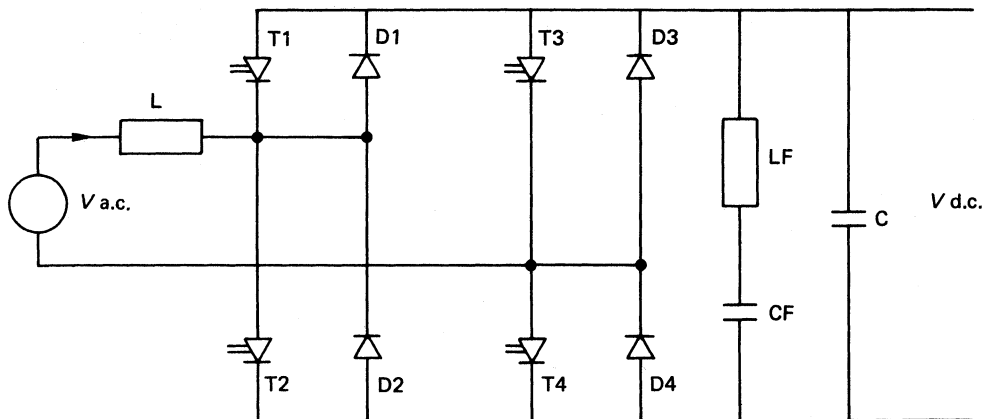
**Figure 45.6** Voltage and current waveforms of a sector-controlled thyristor bridge: (a) partial power; (b) full power

The use of several secondary windings with sequential control can improve the harmonic content and power factor, but at the expense of weight and cost.

The fields of the traction motors are supplied from a separate thyristor bridge, with arrangements to link the armature and field-control circuits to maintain a satisfactory operating balance between currents in the motor.

*Gate turn off* The advent of the power gate turn off (g.t.o.) thyristor has changed power circuits in a dramatic way. As well as assisting the design of inverters it has allowed the use of power conditioning of the single-phase input in novel ways. Individual g.t.o.s of 4000 V and 2500 V are available, allowing single device per arm circuits to be built for traction ratings.

*Four-quadrant chopper* This circuit, shown in *Figure 45.7*, converts single-phase a.c. into d.c. (or vice versa) with a high power factor and low harmonic content. The essential process is the creation of energy in the inductor L and transfer of this energy to the link capacitor C. The g.t.o. thyristors T1 to T4 are switched to provide three voltages across the inductor; either ( $V$  a.c.) or ( $V$  a.c. +  $V$  d.c.) or ( $V$  a.c. -  $V$  d.c.). For positive a.c. current, the ( $V$  a.c.) condition is provided via (T2 + D4) or (T3 + D1), ( $V$  a.c. +  $V$  d.c.) via (T1 + T3), and ( $V$  a.c. -  $V$  d.c.) via (D1 + D4).



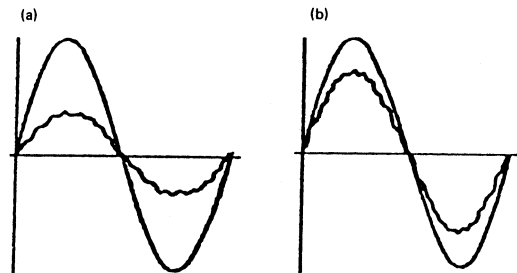
**Figure 45.7** Four-quadrant chopper circuit

Other circuit paths are switched to cope with negative a.c. current. The four-quadrant chopper circuit can operate in all four quadrants of the voltage/current vector diagram and permits inversion from d.c. to a.c. In traction use the circuit is usually controlled to give a constant d.c. link voltage. Switching operations take place at 300–500 Hz and pairs of four-quadrant circuits can be interleaved to give a.c.-side harmonics at 600 or 1000 Hz. On/off control can be regulated to give a unity power factor fundamental current with no harmonics below switching frequency. The switching produces an output component at twice the supply frequency and the filter LF and CF is provided to absorb this current.

Although using more components than phase-angle control and requiring a complex firing control, the benefits of unity power factor, low harmonic content, and simple regeneration make this the preferred control circuit for single-phase traction.

*Figure 45.8(a)* shows part power and *Figure 45.8(b)* full power voltage and current waveforms for a four-quadrant chopper circuit. The in-phase nature of the current is apparent, as is the low harmonic content.

*Three-phase inverter* Early inverters required the use of many components and were complex, heavy and subject to failure. Developments in controlled semiconductors and



**Figure 45.8** Voltage and current waveforms of a four-quadrant chopper circuit: (a) partial power; (b) full power

improved cooling techniques have now produced small compact designs more suited for traction. Freon cooled inverter modules are used on some railways with a very low specific mass. One example, handling 1.1 MW, weighed only 140 kg.

The switching pattern of the power semiconductors is usually regulated to minimise the generation of harmonic currents at signalling frequencies.

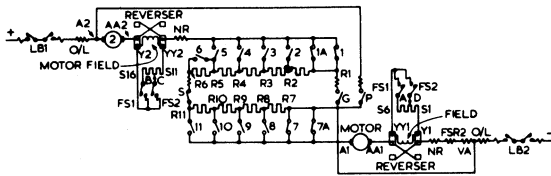
45.1.4.2 D.c. supply to train

*Electropneumatic camshaft control* The most noteworthy feature of this control unit is that the camshaft which controls the operating sequence of the accelerating contactors makes a complete revolution in one direction for the series notches, and a revolution in the reverse direction for the parallel notches, the transfer from series to parallel motor connection being made on a separate pneumatic switch unit. The initial and final positions of the camshaft are identical, so that in the case of a power interruption the equipment is ready for an immediate restart.

It will be seen that this arrangement, which is made possible by a special system of motor and resistance circuits (Figure 45.9) introduces each contactor in circuit twice during the accelerating period, once during series and once during parallel notching. Thus, when compared with control units employing separate contact systems for the series and parallel conditions, the number of accelerating notches available in a contactor group of given size and weight is almost doubled, while the simplicity of subsidiary control circuits and of mechanical construction, which are features of the pneumatic camshaft principle, are retained, with low power consumption for control apparatus.

Some equipments have 10 series and 10 parallel steps (in contrast to the five and four common with simple resistance control), making possible higher average rates of acceleration without wheel slip.

The driver's controller will have a small number of positions, and transitions between them will be regulated



		SEQUENCE TABLE																					
		STEP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
SERIES	OFF																						
	1																						
2																							
3																							
4																							
5																							
6																							
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Figure 45.9 Main-circuit diagram of a 600 V, two-motor control equipment with two field-shunt positions

by the current limit relay. Typical positions are 'off', 'shunt' (motors in series with all resistors in circuit), 'series' (motors in series with resistors out of circuit), 'parallel' (motors in parallel with resistors out of circuit), plus a number of 'weak field' positions. In urban units the control sequence lasts only for a short time and may be completed before the train has left the station.

*Thyristor regulator (chopper) control* Regulation of the average voltage applied to the traction motor is available if a thyristor switch is used to connect the supply cyclically to the motor. A thyristor carrying direct current will only switch off if the current is reduced to zero and the thyristor has a reverse voltage applied for a short time. Many circuits are in use to achieve this, the basic concept being that a charged capacitor is used as a temporary source of current, reverse biasing the thyristor to turn it off. The capacitor is switched into circuit using an auxiliary thyristor. A typical circuit is shown in Figure 45.10.

When the supply is connected, thyristor T2 is turned on to charge capacitor C via the motor path. When C is charged, the current in T2 falls and it extinguishes. Turning on thyristor T1 applies the full supply voltage to the motor and also allows the charge on C to oscillate (via L and D1) for a half-period, thereby reversing the polarity of the potential across C. When a sufficient current is flowing through the motor, thyristor T2 is turned on. Capacitor C acts as a current source for the motor and applies a reverse voltage to T1. If C has a sufficient charge, T1 will be reverse biased for long enough to be extinguished, thereby blocking the flow of forward current; C will then be charged as in the initial operation. The motor current will decay via the free-wheel diode D2. When the motor current has fallen to a selected value, T1 is again fired and the cycle repeated.

By control of the firing pulses to T1 and T2 the mean voltage applied to the motor can be regulated as the train speed changes, while maintaining motor current and tractive effort. It is customary to fire T1 at a fixed frequency, so that the input filter  $L_f C_f$  can be designed to limit the ripple currents

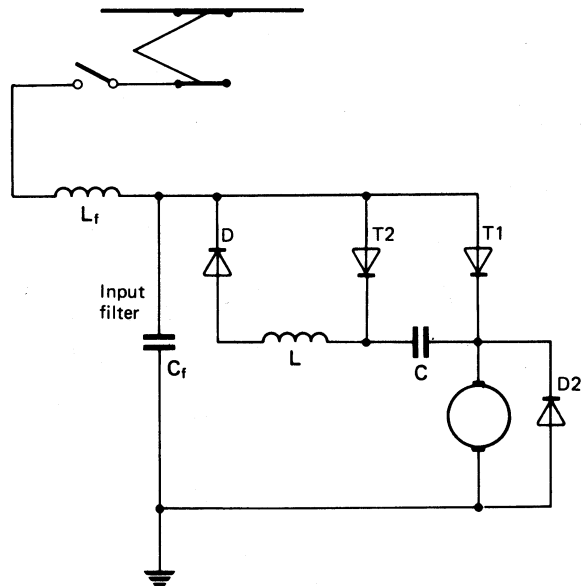


Figure 45.10 Basic circuit of thyristor chopper control

drawn from the traction supply. A fixed frequency also avoids the generation of current at track circuit frequency.

This form of control avoids the energy losses associated with rheostatic control and is particularly valuable where frequent starting is required. It is therefore used widely for urban rapid-transit systems. By reconnecting the elements of the circuit it can use the motor as a generator and convert the mechanical energy of the train during braking into electrical energy and return it to the traction supply. If the supply is not receptive, braking rheostats on the vehicle can be used.

Recent equipments have used gate turn-off thyristors which avoid the need to provide a separate thyristor-switched turnoff circuit. The chopping frequency can be varied, usually in multiple steps, to allow the wide range of output voltage to be provided. Starting is at low frequency since, at high frequency, the minimum on-time of the thyristor would deliver too high a voltage to the motor.

*Inverter* As with a.c. supply, inverters are used for power control. A simple inductor/capacitor input filter is used to isolate the inverter from transients on the power supply and to prevent switching frequency currents from flowing from the inverter into the supply.

#### 45.1.4.3 Operation of multiple unit trains, train lines

Operation of several power units from one driving cab can be provided by the use of a multi-core cable which runs the length of the train. Known systems use 27 or 36 cores to control the essential functions and return indications of response.

#### 45.1.4.4 Train line multiplex for locomotive push or pull

Where a train is to be driven from both ends but train lines have not been installed, or are expensive to provide in new vehicles, power control can be achieved using two wires only. A series of coded signals can be sent to intelligent decoders, using techniques such as time division multiplex. Actuators can be addressed individually and sent binary messages which give the necessary commands. Frequency shift keying, typically at 90/120 kHz can be used for binary codes.

#### 45.1.4.5 Driving cab

Where possible, it is desirable to use standard cab layouts for all forms and ratings of traction. Power and brake handles should be in similar places and the flexibility with which electric controls can be positioned is then an advantage.

Display of information to the driver is essential for safe and reliable operation of the train. Unambiguous displays with good lighting are required, whilst ensuring that the driver is not distracted from outside signals. Train status can be displayed on touch-sensitive screens, with selectable menus for different functions.

The increasing use of track-based signalling systems, which deliver permitted speed values to the cab, are reducing the need to observe track-side signals. They demand, however, an increase in the amount of information which has to be presented to the driver and the ergonomic design of cabs is receiving increased attention.

Closed-circuit television with visual display units can be used to monitor the surroundings, such as passenger behaviour on platforms.

### 45.1.5 Drives

The mechanical means by which the drive is taken from the motor to the axle are worthy of mention since they have

important implications for the type of motor which can be used and the environment in which the motor has to operate. A simple drive places half of the motor mass on the axle, with high consequential mechanical loading on the motor. Complex drives can isolate the motor from track stresses.

*Axle-hung geared motor* The motor is suspended partly by bearings around the driving axle and partly by a bracket resting on the bogie frame. The motor output is taken to the driving axle via a single reduction gear. This is a simple form of construction but the non-spring-borne part of the motor mass results in increased dynamic loads on the track. If high-speed motors are used an idler gear can be interposed, or a double reduction train used.

*Axle-hung direct drive* The axle can form a driven part of the motor with the electrical armature placed inside (held through the axle bearings) or outside the axle. In one version, a three-phase induction motor is formed from a wound stator held within a large-diameter tubular axle, the cage winding of the motor being fixed to the inner surface of the axle tube.

*Frame-mounted geared motor* For express locomotives and for other cases in which riding qualities are important, drives have been devised to reduce the non-spring-borne mass, to raise the mass centre and to allow for relative movement between frame-borne and axle-borne parts.

*Spring drive* This consists of a hollow shaft surrounding the driving axle and having sufficient clearance therefrom to permit the necessary relative movement between the spring-borne quill and the axle. The quill carries the gear-wheel (or a gearwheel at each end) engaging with a pinion on the motor shaft. A twin- or double-armature motor is frequently employed, and to secure flexibility the pinions may be spring cushioned. The chief feature of the drive is the method of connecting the quill to the driving axle, which is accomplished by an arrangement of circumferential springs acting between a spider on the quill and a special spoke arrangement on the driving wheel.

*Link drive* To avoid the use of springs, forms of quill drive using links (such as the Buchli drive) have been designed. The locomotive frames are within the wheel space and the motor shaft extends over the frame to a pinion engaging with a gearwheel carried in a frame-mounted bearing. The gearwheel is arranged nearly concentric with the driving wheel and outside it; the connection between the two is made by an ingenious gear-link arrangement working on to pins fixed to the driving wheel.

*Flexible-disc drive* Here the motor is mounted on the bogie frame. The armature shaft is hollow and the drive is taken through a flexible disc coupling at one end by means of a shaft passing through the armature and connecting through another flexible disc to the pinion which is carried in bearings in the gearcase.

*Alsthom drive* The drive to the wheels is by means of a hollow quill shaft and flexible links, using a 'dancing member' and rubber-bushed bearings in the links. The quill is carried in the motor frame by large diameter taper roller bearings.

*Longitudinal monomotor* The motor is arranged along the longitudinal axis of the bogie frame, driving both axles from gear outputs at both ends of the motor shaft. Bevel gears are provided on each axle, with an intermediate flexible coupling. This is used on the GEC drives for the



London Docklands light railway, with flexible couplings to allow angular movement of the axles.

*Bogie frame direct* The motor is supported from the bogie frame, with a hollow output shaft. This shaft has a sufficient internal clear diameter to accommodate the axle and the relative axle to bogie movements. Drive is taken to both the wheel discs via links. An example of this arrangement is the 650 kW, 600 rev/min induction motor drive of the Skoda prototype 85 EO locomotive.

*Bogie frame monomotor* A large single motor is mounted on the bogie frame, occupying part of the body space. Drive to the axles is via gear trains. This couples the axles together for traction purposes. It gives a low yaw inertia to the bogie. French National Railways are the main users of this system.

*Body mounted motors* Where the bogie design has to meet special targets, for example giving high speed with low track loading, the motor can be attached to the body of the vehicle. This requires a drive which can tolerate the substantial vertical and lateral relative movements between body and axle. The motor can be arranged with the drive shaft parallel to, or at right angles to, the axle. In the former case the output can be taken back across the vehicle; in the latter a splined cardan shaft can be used with universal end couplings, to drive via a bevel gear box.

*Individual wheel drives* Suspension designs have been reviewed and separate wheels, not linked via common axles, are used for special cases. The Italian AVRIL train uses a pair of 200 kW motors mounted longitudinally side by side on the body, to drive two wheels on one bogie via a cardan and bevel gear transmission. Each vehicle has two pairs of motors.

#### 45.1.6 Train resistance—motor inertia

When calculating train resistance for run timings, note that the inertia of the motors is to be added to that of the other rotating parts, and that the windage losses of the motors may be significant.

#### 45.1.7 Electric braking

The ability to use motors for braking allows a reduction in brake wear and offers the possibility of converting brake energy into useful traction energy for use by other vehicles. Electric braking has to be blended with the mechanical braking system of the train and the mechanical brake must be arranged to take over the full braking duty if the electrical mode fails.

##### 45.1.7.1 Regenerative braking

The braking of heavy trains on long down gradients is materially facilitated by the use of regenerative braking, whereby some of the mechanical energy released by the train in its downward progress can be reconverted into electrical energy and returned to the supply system. For this purpose it must be possible to reconnect the traction motors as generators and control the speed by the braking torque developed. Regeneration is possible with any form of electric traction at the expense of additional weight, cost and complication. Regeneration has been most successfully employed on locomotives which have to negotiate heavy grades. Regenerative braking is also feasible in heavily loaded urban railways. If the railway system is not receptive (detected typically by a rise of voltage above a given limit), the excess energy can

either be returned to the national electrical supply or dissipated in rheostats at the railway substations. Regenerative braking can give significant reduction in overall energy consumption on urban railways, and typical figures of 15–20% are achieved on densely loaded systems. Cost savings due to reduced brake wear can be equal to energy savings.

##### 45.1.7.2 Rheostatic braking

An alternative form of electric braking, referred to as rheostatic or electrodynamic braking, is available for electric locomotives and is particularly useful for a.c. locomotives, which cannot be designed for regenerative braking as readily as those operated on d.c. systems. With this type of braking, the energy generated by the motors is dissipated in resistors. Control is usually exercised by separately exciting the motor fields, but some systems use self-excitation of the motors with main resistance switching. Owing to the large amount of energy which may have to be dissipated for considerable periods if descending a steep incline, the braking resistor is usually forced-air cooled, and special types of strip resistor units have been developed for this purpose. Where substantial rheostatic braking is required, the roof of the vehicle can sometimes be used to accommodate the rheostats.

##### 45.1.7.3 Braking using the rail

Use of the rail for braking has attractions since the thermal mass is large and new rail enters the brake zone as the train proceeds. Care needs to be taken if frequent braking takes place on the same rail since thermal stresses may become excessive, increasing the tendency of the track to buckle.

*Eddy on rail* Non-contact braking can be provided by the use of an eddy current brake acting on the rail head. A multipole array is suspended close to the rail head and a 2 m long device, with a 7 mm air gap, has developed a brake force of 14 kN at 250 km/h. The excitation power was 42 kW.

*Contact on rail* Alternatively, magnets can be arranged to make contact with the rail head when energised. Brake force depends on the coefficient of friction and forces of 5–15 kN have been found from a 2 m long unit. Power consumption is about 2 kW. Permanent magnet (neodymium) excitation is also used.

Both these methods involve substantial vertical forces.

##### 45.1.7.4 Electric actuator for mechanical brakes, motor/screw

Although brakes are normally operated by air cylinders, a motor-driven screw can be used to apply and release the brakes. This gives a substantial reduction in mass by removing air pipes and reservoirs.

#### 45.1.8 Traction vehicles

##### 45.1.8.1 D.c. locomotives

On d.c. locomotives there is almost invariably an even number of traction motors. With two motors (there are usually at least four) the simple well-known series/parallel control can be used.

In this, the motors are first connected in series with starting rheostats across the contact line and rails; the rheostats are then cut out in steps, keeping roughly constant current, until the motors are running in full series; next the motors are rearranged in parallel, again with rheostats; the rheostats are cut out in steps, leaving the motors in full parallel. Some

stages of field weakening are generally included. The power input remains roughly constant during the series notching, then jumps to twice this value during the parallel notching. With a four-motor equipment, a series/series-parallel/parallel connection can be used, giving three economical speeds (i.e. running without resistance) unless the line voltage is too high to be applied direct to a motor. In modern locomotives, chopper control of motor power is used and some locomotives have three-phase inverter/motor systems.

Italian Railways use high power 3000 V locomotives and the E 632 uses a three-bogie design to provide six driven axles. Intended for passenger service, with a top speed of 160 km/h, it weighs 105 t, is 17.8 m long, 4.3 m high and 3 m wide. Three large motors, each weighing 5400 kg and of 2000 V, 1635 kW, 1700 rev/min maximum rating, are frame mounted and drive two axles each via link drives.

Power control is by d.c. chopper, with the basic chopping frequency of 390 Hz converted to 2340 Hz at the supply by interleaving the six choppers. Harmonic current taken from the supply does not exceed 0.3 A up to 1300 Hz.

The main circuit contactors performing the functions of motor grouping, field weakening, and cutting out rheostats are operated either electromagnetically (e.g. by solenoid) or electropneumatically (electrically controlled compressed air cylinders); further, they may be grouped together and interlocked by a camshaft, or separated and individually controlled.

When a locomotive is fed from a third rail system, the inevitable gaps in the conductor rail at points and crossings (up to 150 m) cause momentary interruptions to the supply, resulting in snatching and surging of the vehicles, particularly with goods trains. This difficulty has been overcome by the Southern Region of British Rail, which has put into service 1100 kW, 600 V d.c. locomotives using a booster motor-generator in the traction motor circuit; a flywheel on the motor-generator set provides sufficient stored energy to enable the locomotive to run over a gap without perceptible reduction in torque.

Proper distribution of the weight of the apparatus in the locomotive body is an important design feature and strongly affects running qualities.

#### 45.1.8.2 *A.c. locomotives*

**Low frequency** Systems operating at 16 $\frac{2}{3}$  or 25 Hz normally use one-phase commutator motors. These require low armature voltages to achieve good efficiency and high power factor. The motors are generally connected in parallel and, except for smaller locomotives, primary tap-changing on the main transformer is used to provide a variable voltage supply to the motors. With this type of control, each accelerating notch is an economical running point. This is in contrast to the d.c. locomotive, which cannot run continuously on the resistance starting notches. To avoid jolts and momentary short circuits, preventive coils connected across successive tappings are used. Various elaborations of the simple transformer tapping system have been devised to reduce the number of tappings without reducing the number of available motor voltages. Thus, by use of a small auxiliary transformer a tapping voltage can be increased or reduced by a required amount, so that six tappings will give 18 running voltages.

**Industrial frequency** D.c. series motors are fed through a rectifier (or controlled rectifier) which is, in turn, supplied by variable voltage from a tap-changer (or fixed voltage) on the main transformer. Semiconductor rectifiers are normally

used and give reliable service when suitable protection is provided against the voltage transients which occur due to switching and other causes. Primary protection is provided by an air-blast circuit-breaker mounted on the roof, and in the case of solid state rectifiers, it is usual to protect each string of rectifiers by a fuse. A smoothing inductor is incorporated in the rectifier circuit in order to limit the ripple in the d.c. supply to the motors.

*Figure 45.11* shows the layout of a tap-changer control a.c. locomotive. Modern locomotives for 160 km/h have similar layouts but for higher speeds the motors are normally body-mounted.

A specially prepared short train of French Railways stock (two traction vehicles and three coaches of the TGV-A) attained a speed of 515 km/h in May 1990.

#### 45.1.8.3 *Multiple unit trains*

For suburban and stopping services, passenger coaches are equipped with traction apparatus placed below the floor. This leaves the body free for passengers. Both d.c. and a.c. traction supplies are used, with the 25 kV cable passing sometimes vertically through the passenger compartment from roof to transformer. Rheostat, chopper d.c. and inverter drives are used with d.c. supply and tap-changer/rectifier, controlled phase angle and inverter drives with a.c. supply. Power ratings of up to 400 kW per coach are used. These trains form the greater number of electric traction vehicles on railways.

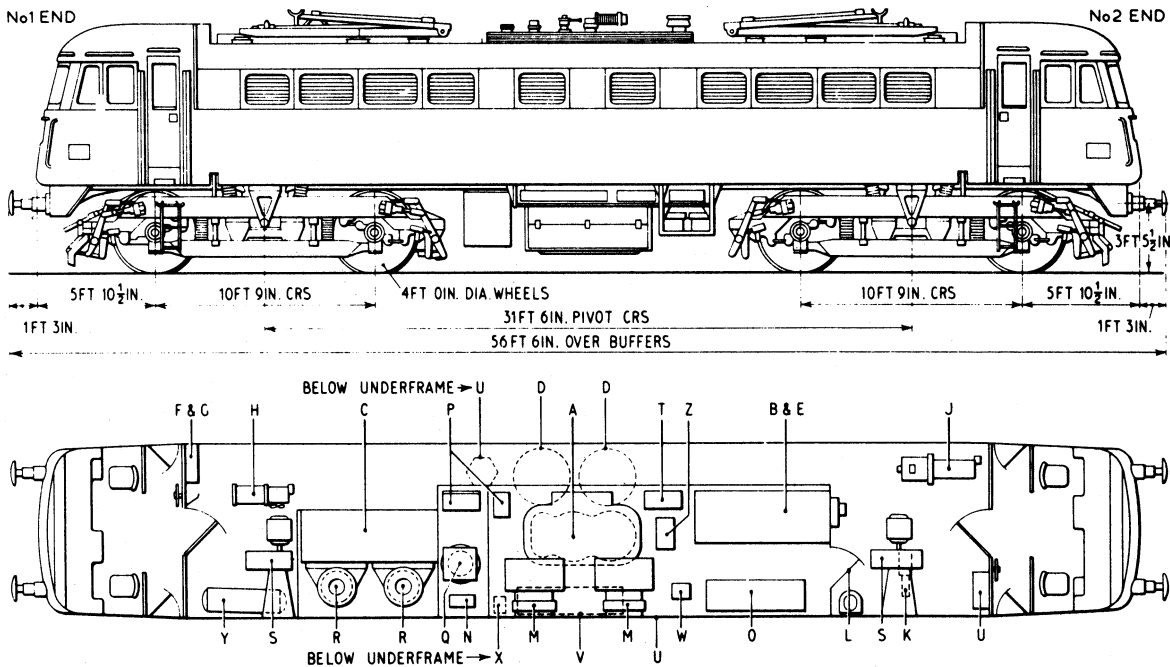
#### 45.1.9 **Battery locomotives**

These are still built and recent examples are those for the Hong Kong Mass Transit Corporation. They can operate from the 1500 V d.c. overhead or from the 750 V battery. Two 140 kW motors are installed, with three-thyristor resonant chopper control. The battery capacity is 360 A-h at the 5 h rate. Such locomotives are valuable for night-time use when the power supply is switched off for maintenance, and for shunting duties in yards which can then be left without overhead conductors.

#### 45.1.10 **Underground railways**

In city centres where a high-capacity transport system is required but where surface routes are not available, railways can be built underground to provide a rapid passenger transport. The cost of tunnelling is very high and this method is only economic for large concentrated passenger flows. The electrical supply is normally by third-rail system at about 750 V d.c.; but where tunnelling costs permit, overhead electrification at higher voltages is provided. Underground railways use the same range of electrical propulsion and control techniques as on surface railways. The acceleration of underground trains is rapid and the separation between stations is small, perhaps 800 m. Under these conditions, if rheostatic camshaft control is used, the starting sequence may be completed before the train leaves the station. Subsequent running is on the natural characteristic of the motors, with weak-field operation to extend the speed range.

In France some underground lines use rubber tyres for propulsion and guidance, running on concrete tracks. This provides high acceleration and braking, contributing to passenger capacity. The rubber tyres have a higher energy loss than steel wheels, and additional ventilation may be necessary if a line is converted to rubber-tyred operation.



**Figure 45.11** British Rail 2500 kW, 25 kV a.c. electric locomotive: A, main transformer; B, tap-changer; C, rectifier; D, smoothing inductors; E, control equipment; F, low-voltage fuses; G, fault indicator; H, main compressor; J, exhausters; K, auxiliary compressor; L, high-voltage compartment door; M, transformer coolers; N, hole storage capacitor; O, motor contactors; P, braking exciters; Q, braking resistors; R, rectifier coolers; S, motor coolers; T, auxiliary transformer; U, battery charger; V, battery; W, train heating panel; X, field divert resistor; Y, main reservoir; Z, tap-change inductor

## 45.2 Diesel-electric traction

Petrol and diesel engines have been used for traction purposes, both road and rail, for a number of years, but the extensive application of diesel-electric locomotives to railway service has only occurred since about 1935.

### 45.2.1 Locomotives

Diesel-electric locomotives may be divided into two main groups: main line and shunting. Railcars form a third group which is quite small, and in which, on the lighter cars which predominate, mechanical or hydraulic drive is more often employed.

Main-line locomotives may again be subdivided: the smaller units ranging from 450 to 750 kW, used for mixed traffic duty; and the larger units ranging from 1000 to 4000 kW for main-line service. The larger locomotives are usually arranged for multiple-unit operation and several units can be used together to haul a large train. The units are sometimes distributed throughout the train to reduce drawbar stresses and braking transients, and radio control is sometimes used to give balanced power distribution.

Diesel-electric shunting locomotives have been used for a number of years on British Rail and are mostly in the 250–350 kW range and weigh about 50 t.

### 45.2.2 Design

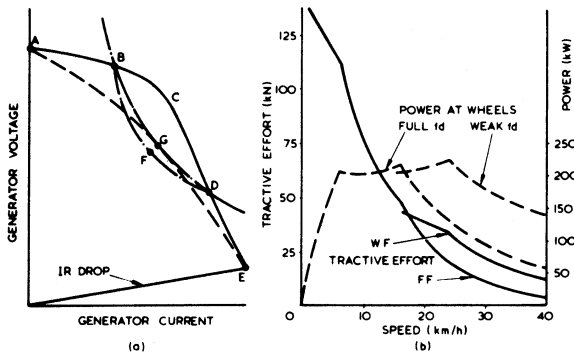
The diesel engine is primarily a constant-speed, constant-power unit, and it is necessary to convert this to a

variable speed, constant power at the wheels of the locomotive. The characteristic of the series d.c. motor is ideal for traction, since it provides a falling torque with increasing speed; by varying the voltage applied to the motor the torque-speed product can be made to match the constant power of the engine. The generator, which becomes in effect a flexible power link between the engine and the motors, provides the necessary current at varying voltage.

The essence of the problem of diesel-electric equipment design is to match the generator output curve to the engine power curve. The typical generator characteristic at constant (maximum) engine speed in *Figure 45.12(a)* is shown by the curve ABCDE.

The voltage-current curve for constant input power at this speed is BGD. Between B and D the two do not match and engine speed falls to give the relation BFD, with loss of power. In a shunting locomotive the speed drop produces output-input balance. Alternatively, the voltage-current characteristic of the generator may be made to follow the curve AGE, but full engine power can then only be developed at G, with loss of tractive effort for other operating conditions (*Figure 45.12(b)*).

For main line locomotives it is desirable that full engine power be maintained over a wide range of train speeds. The diesel engine has an optimum operating zone in which the fuel efficiency is highest. For any desired output power there is therefore an optimum diesel engine rotational speed. The load regulation system normally responds to the setting by the driver of a desired engine speed. The excitation of the generator is then adjusted so that the optimum output power is taken from the diesel engine. If the train load



**Figure 45.12** Diesel-electric characteristics: (a) voltage–current characteristics for: ABCDE, generator at constant maximum speed; BDG, constant generator input power at constant maximum speed; BFD, reduced speed. (b) Performance of 300 kW, 50 ton shunting locomotive (traction 280 kW, auxiliaries 20 kW, two motors with double reduction gearing)

reduces, the generator will run at a high-voltage, low-current condition delivering part power.

### 45.2.3 Electrical equipment

Electrical equipment consists essentially of a main traction generator, one or two auxiliary machines, a number of traction motors and the control equipment necessary for both main and auxiliary circuits. On large main line locomotives the auxiliary supply has to provide for compressors, traction motor blowers, lighting, heating, control and similar requirements. A battery is usually included to provide stand-by power and starting.

#### 45.2.3.1 Generator or alternator

The generator armature is usually coupled direct to the engine crankshaft with a single bearing in the generator end housing. The auxiliary generator may be overhung from the main generator or in some cases driven together with an exciter by belts. Since the generator is a variable-voltage machine, the maximum voltage is arranged so as to obtain the most economical use of materials and the lowest  $I^2R$  losses. The maximum voltage is usually limited to 1000 V and normal operation is around 600 V.

#### 45.2.3.2 Motors

Motors are of series type and are generally similar to those used on d.c. electric trains and locomotives. They are usually built for operation at the full generator voltage but in some cases may be connected permanently two in series. The size of motor is determined largely by the maximum tractive effort required and bears little relation to the power capacity of the diesel engine.

#### 45.2.3.3 Control

The control equipment on a diesel-electric locomotive is concerned mainly with the following functions.

**Engine-speed control** The varying requirements of railway service make it necessary for the engine to have some speed

control so that it can operate when required at reduced speed and power. In its simplest form a hand-operated lever, which alters the governor setting, provides a range of speeds between idling and full speed. No more is required on locomotives of the shunting type.

**Generator-field control** On large locomotives a speed-sensitive device is used to adjust the generator field to match the engine power.

**Motor control** Motors are normally connected in parallel and this provides the simplest arrangement. In certain cases, however, series/parallel control may be necessary to give the required locomotive characteristics and provision must be made for changing over the motor connections. A reverser is required for changing direction of running, and diverter contactors may be provided if the fields have to be shunted to give top-speed running.

**Driver's controls** On a typical shunting locomotive three control levels are provided on each side of the cab so that the driver has alternative driving positions. A time delay in the operation of the dead-man pedal is introduced so that the driver can change over from one operating position to the other without shutting off power. The engine, or master, control is used to start and stop the engine, and provides for engine testing with the locomotive at rest. A reversing lever with an off position determines the direction of movement of the locomotive. Finally, a power controller gives the driver complete control over all locomotive movement. Initial movement of this control lever prepares the power circuits and brings on generator excitation with the engine running at minimum operating speed. Further movement strengthens the generator field and finally brings the engine up to full speed.

The arrangement for main line locomotives is similar, except that a single driving position at each end of the locomotives is provided, with facilities for multiple-unit operation when double heading is required.

#### 45.2.3.4 Starting

The usual method is to start the engine from the battery by motoring the main generator, using a special starting winding. Compressed air starting is occasionally employed, but it involves the use of a compressor for charging the air cylinders. Bendix starters, similar to the type used on motor-car engines and operated from a 24 V battery, are used on some American locomotives. In the case of most shunting locomotives it is usual to make provision for tow starting in an emergency if the battery is too far discharged to motor the generator for normal starting. This involves connecting one or more of the motors so that they act as generators to motor the main generator and thus start the engine. Although emergency starting is seldom required, it is a useful provision, since another locomotive is usually available and starting can be effected with very little delay.

#### 45.2.3.5 Mechanical design

The design of diesel-electric locomotives follows very much the same lines as that of normal electric locomotives; main line locomotives, particularly, use axle-hung motors and bogies which are generally similar.

## 45.3 Systems, EMC and standards

### 45.3.1 Novel systems

#### 45.3.1.1 Magnetic levitation

Research work on high-speed maglev trains has continued for several years but no public service is in operation. Two types have been taken to full-scale tests, one using controlled magnets working in attraction, the other using fixed magnets working in repulsion. Attraction systems such as the TransRapid 07, built in Germany, use a series of steel-cored magnets placed below a laminated suspension rail. The TR07 has a three-phase winding embedded in the track rail and this interacts with the vehicle magnets to provide propulsion and braking. Separate magnets give lateral guidance. The vehicle sits on a T-shaped beam. No sliding contacts are used, the traction power being supplied to the track and the vehicle auxiliaries being powered via induction pick-up from the track.

The MLU 002 of Japan National Railways uses superconducting magnets interacting in repulsion with wound coils fixed to the U-shaped track, to provide lift, guidance and traction/braking. The vehicle has wheels since levitation in repulsion is not available at low speed. No sliding contacts are required.

One maglev system is in public service at Birmingham International Airport, UK, offering a 600m link from airport to railway station. The 6t vehicle uses attraction magnets (which also provide guidance) with linear motor propulsion and braking. Power is supplied via sliding contacts to on-board power control for this 50 km/h vehicle.

An M-Bahn system is in use, in which permanent magnets exert an upwards force greater than the mass of the vehicle, the surplus force being taken on rollers. Other rollers provide guidance and others carry the vehicle across gaps in the magnets. Windings in the track give three-phase synchronous motor drive and braking.

The US Government has launched a maglev Initiative to produce a 480 km/h vehicle using American technology. The first full sized components are due for testing in late 1993.

#### 45.3.1.2 Monorail

Systems using a single beam for the track, termed monorails, are in use. The Alweg design is most common, with rubber tyres used for support and guidance. Power is collected by sliding contact and the support wheels are powered.

### 45.3.2 Coaching stock

Modern passenger coaches use significant amounts of electrical energy. Environmental comfort requires heating and air conditioning, and many other amenities and essential services have to be provided. Power is supplied via train lines from the locomotive or from the local multiple-unit power source. Train-line voltages are typically 1000 V single phase 16 $\frac{2}{3}$  or 50 Hz, or 750 V d.c. On multisystem vehicles, d.c. voltages of 1500 or 3000 V are used. Depending on whether a.c. or d.c. supply is used, a transformer and/or inverter is used to supply those auxiliaries which require a.c. feeds.

*Heating* Resistor heating banks are provided, with thermostat control of air temperature. A coach may have 40 kW installed for this duty.

*Air conditioning and pressure ventilation* Power for the refrigerant compressor is required and an inverter is usually

used to convert the train-line supply to three phase for this motor. A rating of 26 kVA may be required. The fans for air circulation could consume 6 kVA.

*Lighting* Fluorescent lighting is standard, supplied from inverters which produce high-frequency a.c. to reduce mass and avoid flicker effects.

*Toilet wash water and hand dryer* Hot water is required for toilets and a 1.5 kW heater is usual. If a hot air hand dryer is installed, the electrical load may be 4 kW.

*Shavers, public address, telephone and audio visual service* A number of small amenity loads may need to be supplied.

*Battery and battery charger* To ensure lighting in emergencies and sustain ventilation under fault conditions, a vehicle battery is fitted. This is typically 24 V, 440 A-h, and requires a battery charger. This charger is usually fed from a high voltage train line.

*Power doors* It is advantageous for train operation if doors are power operated. Electric or air motors can be used for doors. Audible warning of door closure should be provided.

*Passenger information* Display panels may be provided within the vehicle to announce the next station and provide route information. Train services can be publicised. Liquid crystal displays (l.c.d.), light-emitting diodes or visual-display units are available options. External displays of route information can be generated by two-state dot arrays of electro-mechanical discs which have black and coloured sides.

*Servicing information* Vehicle status can be monitored by transducers and fault condition data can be stored in a micro-processor memory, for interrogation by maintenance staff. An l.c.d. can be used to indicate areas requiring attention.

### 45.3.3 Electromagnetic compatibility

Electrified railways must be bonded to earth so that dangerous voltages are not produced during short-circuit conditions. The spacing and type of bond depends on the rating of the system and the distance from the feeding point.

Traction currents must not induce dangerous voltages in nearby conductors and conductor geometries are arranged as required. Leakage of d.c. current can cause corrosion to pipes and cables and bonding must be adequate to keep voltages below safe levels. In practice, when the railway has designed its systems to prevent damage to itself, nearby apparatus is normally safe. Regular inspection of safety measures is required.

Sliding current collection of power normally involves the generation of some radiofrequency noise and filters may have to be added if disturbance is caused.

### 45.3.4 System simulation

With the advent of fast computers, simulation of train movements on actual track layouts is feasible and can be used to study the electrical aspects of introducing a new service or rolling stock. Colour graphics are used to observe train movement and energy use.

### 45.3.5 Standards

Although railways tend to use their own standards and specifications when purchasing equipment, a number of standards exist. These include those listed below.

45.3.5.1 *British standards*

BS 173	Specification of rotating electric machines for traction
BS 2618	Electric traction equipment
BS 3403	Tachometer and speedometer apparatus
BS 4999	Rotating machines

*Railway Industry Association* 6 Buckingham Gate, London SW1 6JP, UK. Technical Specifications have been prepared in collaboration between railways and manufacturers. These include:

BRB/LUL/RIA 12	Protection of traction electronic equipment from transients in d.c. control systems
BRB/LUL/RIA 13	General specification for electrical equipment used on traction and rolling stock
BRB/LUL/RIA 18	Interference testing for electronic equipment used on traction and rolling stock
BRB/LUL/TG 22	Technical guide on e.m.c. for electronic equipment used on traction and rolling stock

45.3.5.2 *International electrotechnical commission*

A number of leaflets have been issued, giving guidance for the design of traction apparatus. These specify limits such as working voltages and permitted harmonic currents.

IEC 77	Rules for electric traction equipment
IEC 165	Rules for testing electric rolling stock
IEC 310	Traction transformers and reactors
IEC 322	Ohmic resistors
IEC 349	Rotating electrical machines
IEC 411	Power converters for electric traction
IEC 494	Pantographs of electric rolling stock
IEC 563	Limiting temperatures of electrical equipment
IEC 571	Electronic equipment on rail vehicles
IEC 631	Characteristics and tests of electrodynamic and electromagnetic braking systems
IEC 638	Criteria for assessing commutation of traction machines
IEC 737	Measures for limiting disturbance of light current installations by electric traction
IEC 801	Immunity to electromagnetic disturbance

## 45.4 Railway signalling and control

The purpose of railway signalling is to control the passage of trains such that they may run at speed by maintaining a safe adequate distance between following trains and safeguarding their movement at junctions. Inherent in any system, therefore, must be the ability to detect the presence of all trains and vehicles and a means to ensure separation between them.

The basis of modern signalling is the electrical track circuit to detect the presence not only of trains but also of single vehicles. A track-circuit equipment must detect the presence of a vehicle presenting a maximum resistance of  $0.5\ \Omega$  between rails, a figure taking account of contact effects due to rusty rail surfaces and other features. There are several forms of track circuit, and their principles are considered first in relation to the simplest d.c. track circuit.

The fundamental philosophy of all signalling systems is that they should *fail safe*, i.e. fail to a more restrictive condition. Solid-state devices are used extensively for supervisory and information purposes, and are being introduced

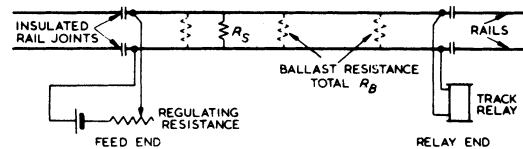


Figure 45.13 D.c. track circuit

for safety functions such as track circuits, the transmission of vital controls and interlocking.

### 45.4.1 D.c. track circuit

The track circuit (*Figure 45.13*) is formed by a section of the track normally isolated electrically from adjacent sections by insulated rail joints. Ordinary joints within the section are bridged by metallic bonds. Feed-end and relay-end connections are made to the rails close to the insulated joints. The rail resistance is small enough for the rails to be considered as equipotential bus-bars between which is a distributed ballast resistance  $R_B$ . The ballast resistance is the critical variable in the track-circuit performance: it varies from day to day, being low in wet conditions, high in dry and totally frozen conditions. It varies also with the type of track. Modern track is laid on reinforced-concrete sleepers, and it is necessary to ensure that the rail is isolated electrically from the sleeper. The fixings for the rail are metallic and thus the rail has to rest on an insulating pad and the clips holding down the rail are separated from the rail by insulating material. Insulation break down can cause a failure, the source of which is difficult to locate. The type of ballast may be significant. Stone ballast (preferably granite) has good resistivity; but in some areas ash ballast is found, and this can make reliable track-circuit conditions difficult to achieve. Low-resistance ballast conditions occur where the track is adjacent to the sea or is carried through under-sea tunnels. A good track under the worst conditions may have a ballast resistance of  $14\text{--}20\ \Omega$  per 1000 m; but on poor track it may be as low as  $0.5\ \Omega$  per 1000 m.

Track-circuit adjustment must take account of variation in the battery voltage. The cell shown in *Figure 45.13* can be a trickle-charged cell which, if of the lead-acid type, has a voltage range of  $1.8\text{--}2.5\ \text{V}$ . If a guaranteed mains supply is available, the battery can be replaced by a transformer and rectifier.

#### 45.4.1.1 Track relay

Standard d.c. track relays have a resistance of  $4\ \Omega$  (although there are many of  $2.25$  or  $9\ \Omega$  in service). The significant characteristics are: (a) *drop-away voltage*, at which the energised contacts 'break', when, after the relay has been energised, the voltage is reduced; and (b) *pick-up voltage*, at which the energised contacts 'make' when, after the relay has been de-energised, the voltage is increased. The drop-away voltage is a minimum of 68% of the pick-up voltage. Associated with these voltages is the train-shunt resistance  $R_S$ : (1) the *drop shunt* is the maximum resistance that produces track-relay drop-away conditions; and (2) the *pick-up shunt* is the minimum resistance such that the relay just picks up.

In practice the pick-up shunt is greater than the drop shunt and as long as this is a practical resistance the track circuit will work. If not, the track circuit will fail to re-energise.

In setting up the track circuit, the regulating resistance is adjusted for maximum battery voltage and maximum ballast

resistance such that with a drop shunt of, say,  $0.5\ \Omega$  the track relay is de-energised. Then it is necessary to check that the track relay will re-energise with minimum battery voltage and minimum ballast resistance. If the pick-up shunt is relatively high, say  $10\ \Omega$ , then the conditions only need to become a little more critical for the track circuit to fail to re-energise. In this case, assuming that no fault exists, the selected length of track circuit is too great. On the other hand, if the pick-up shunt is relatively low under these conditions, increasing the regulating resistance will give economies of power, which is important where primary cells are used, as it gives them longer operating life.

It is normally possible to work track circuits successfully with ballast resistances down to  $2\ \Omega$ . The length of track to which this corresponds depends on the ballast conductivity: on good ballast a length of 1–2 km is typical.

#### 45.4.1.2 Fail-safe conditions

To prove the track clear, the track relay must be energised. It will de-energise if: (a) the power supply fails; (b) a disconnection occurs in the feed-end or relay-end connections, or in the rails (e.g. a rail removed); or (c) a short-circuit occurs on the track. As the de-energised state is taken to mean that a train is present, the fail-safe principle is achieved.

A wrong-side fail condition could occur if the voltage were excessive. The possibility that this condition could occur owing to a voltage from an adjacent track is eliminated where possible by reversing the supply polarity at each pair of insulated rail joints: then, should the joint insulation fail, both track circuits will fail safe. The staggered-polarity principle is applied to pointwork, where the requirements can be complicated.

#### 45.4.1.3 Operation

The d.c. track-circuit system is reliable and economical. In certain circumstances relay timings of successive track circuits may become critical. When the supply voltage is high, the track relay may pick up faster than it drops away (which may take as long as 2 s), and in consequence a short train or single locomotive may be 'lost' for a brief time.

The d.c. track circuit will work satisfactorily in a.c. traction areas. It is necessary to ensure that the track relay is a.c. immune, to guard against false energisation from traction currents. For the same reason it is not possible to use d.c. track circuits in d.c. electrified areas and, hence, a.c. track circuits are used.

### 45.4.2 A.c. track circuit

The track circuit is fed by a transformer which isolates the power supply from the track. The track relay, a double-element device, has a 'local' winding connection to the same supply as the feed-end equipment (normally at 110 V), and a 'control' winding fed through the track circuit. This makes possible reliable operation with less track power.

#### 45.4.2.1 Track relay

The two-position a.c. relay is an induction device, which is in principle the same as an induction-disc wattmeter. An aluminium vane lies in the magnetic fields produced by two electromagnets (Figure 45.14); one, the 'local' magnet (Q), is energised at voltage  $V_q$  from the main transformer, and the other, the 'control' magnet (R), at voltage  $V_r$  from the track circuit. The torque is proportional to  $V_q V_r \sin \theta$ , where  $\theta$  is the angle between the voltage phasors. If  $V_q$  is large, a

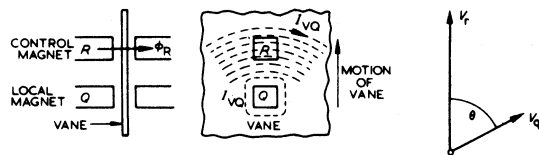


Figure 45.14 Principle of a.c. track relay

relatively small  $V_r$  can ensure operation of the relay, the angle  $\theta$  being adjusted by a variation in the current-limiting devices.

#### 45.4.2.2 Capacitor feed

In a capacitor-fed track circuit a 1:1 isolating transformer feeds the track through a variable capacitor (Figure 45.15). The advantage is that there is little loss in the feed and no path for d.c. traction currents.

#### 45.4.2.3 Impedance bonds

On electrified lines where both rails are used for traction return currents, impedance bonds are used to provide a low-resistance path for the traction current (d.c.) but a high impedance to track-circuit currents (a.c.). A simple bond is shown in Figure 45.16(a): it consists of a few turns, centre-tapped, on a laminated ferromagnetic core. Balanced traction currents give zero effective magnetomotive force (m.m.f.); but unbalance up to 20% is mitigated by the provision of an air gap in the core. The d.c. resistance of an impedance bond may be about  $0.4\ m\Omega$  and its impedance of the order of  $0.5\ \Omega$  at 50 Hz.

### 45.4.3 Jointless track circuit

In modern rail track designed with continuous welded rail, there are no joints: concrete sleepers and careful installation allow thermal expansion and contraction stresses to be accommodated.

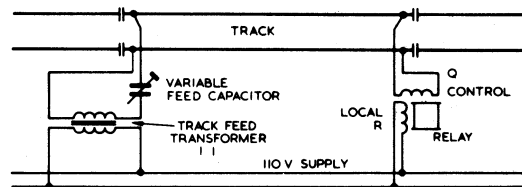


Figure 45.15 Capacitor-fed track circuit

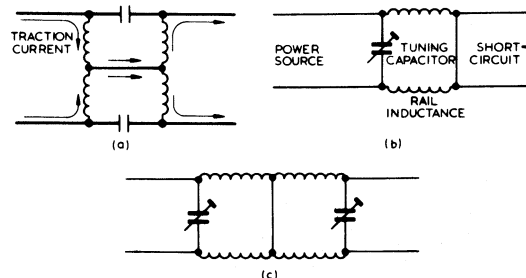


Figure 45.16 Impedance bond and tuned sectionalisation

#### 45.4.3.1 Audio-frequency circuits

One method of achieving electrical separation between adjacent track circuits on jointless track relies upon tuning a short length of track using two series-resonant tuning circuits. The short circuit and rails have inductance that can produce a resonant circuit with a parallel-connected capacitor, as shown in *Figure 45.16(b)*. With this arrangement no power from the source on the left can reach the receiver on the right. If two adjacent track circuits are required, it is possible to tune from both sides as in (c). A tuned length of typically 20 m results with this arrangement. The obvious disadvantage is that vehicles near to the short circuit may not be detected.

One form (*Figure 45.17*) uses a series circuit in resonance at a given frequency. Adjacent track circuits operate at different frequencies, and their limits are achieved as follows. At a frequency  $f_1$ , components  $C_2$  and  $L_6$  are in series resonance, short circuiting  $C_3$  and presenting (ideally) zero impedance across EF, while  $C_1$  is such that the whole circuit is in parallel resonance and of high impedance: thus, the end of track circuit  $f_1$  is defined. At a different frequency  $f_2$  (with  $C_2$  and  $L_6$  now off-resonance and of high impedance),  $C_1$  and  $L_5$  are series resonant short circuiting AB, and  $C_3$  is such that the whole circuit is antiresonant, so defining the limit of track circuit  $f_2$ . The rails contribute inductances  $L_1$  to  $L_4$  to the network. Transmitter and receiver units are connected to the network through the track transformers.

Operating frequencies are a compromise between capacitor size and maximum track circuit length. With one transmitter and one receiver at opposite ends, track circuits between 50 and 1000 m in length can be operated at frequencies in the range 1.5–2.6 kHz. If a track transformer coupled with a transmitter is placed at the centre and a receiver at each end, the length of the track circuit can be doubled. Adjacent track circuits are allocated different frequencies, as are parallel track circuits on multitracked lines.

#### 45.4.4 Other forms of track circuit

##### 45.4.4.1 Coded circuits

Coded pulses (on-off or frequency-shift) may be superimposed on track circuits designed for the purpose, and detected by the receivers or by pick-up coils at the front of a train. The system can be used for train control.

##### 45.4.4.2 Impulse circuits

Where wheel contact is bad, as on rusted rails or on gradients and curves where locomotives use sanding to improve adhesion, non-detection can be overcome by using high-voltage pulses detectable by the receiver.

##### 45.4.4.3 Reed circuits

Mechanically coupled reed filters at each end of the track circuit ensure that only the desired frequency is fed to the

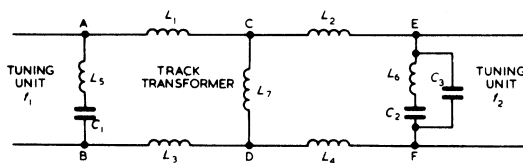


Figure 45.17 Jointless track circuits for adjacent sections

track circuit and that the relay responds only to the correct frequency. The range of frequencies used is 360–400 Hz (but avoiding multiples of 50 Hz) allowing the circuit to be suitable for use in areas where both a.c. and d.c. traction are employed. By using different frequencies for successive tracks and for each parallel track on multiple lines, false operation due to failure of insulated rail joints and diverse feed paths through the traction system is avoided.

##### 45.4.4.4 Overlay circuits

In all cases the relay is de-energised in the presence of a train. Sometimes interlocking controls require a train to be detected at a given spot to operate some function. This may be done by providing an 'overlay' circuit which energises when a train is present, additional to the normal track circuit. Frequencies in the range 20–40 kHz can be used, but the attenuation is such that detection is possible only for distances up to about 50 m.

#### 45.4.5 Other means of vehicle detection

In addition to track circuits, various methods are available to detect the presence of a vehicle. The mechanical action of a wheel flange on the arm of a treadle is used to close electrical contacts and register that a train has passed a particular location. This method is used in association with track circuits as a diverse means of safely operating automatic level crossings. To save track-circuiting long stretches of lightly used line a system of axle counting is used. The passing of a vehicle is detected by the change in magnetic flux around a transducer caused by a vehicle wheel as it passes. When connected to an evaluator unit two such transducers can be used to count axles in and out of a section of line. Besides long stretches of single line, axle counters find use in special circumstances where track circuits are not suited, such as on lines prone to flooding and slab track formations.

#### 45.4.6 Multiple-aspect signalling

Colour light signals are used to display a simple and logical set of indications to drivers. The displays are the same by day and night and the lens system is designed to give long-range viewing and good penetration in fog. Two groups of signal exist; main signals which are used for main line and high-speed moves and position light signals designed for controlling shunting and low-speed moves (*Figure 45.18*).

##### 45.4.6.1 Main signals

Main signals are arranged to show four basic indications or aspects:

Red: stop, danger

Yellow: caution, be prepared to stop at next signal

Double yellow: preliminary caution, be prepared to find next signal exhibiting a single yellow light

Green: clear, next signal exhibiting a proceed aspect

These various aspects are used according to the density of traffic and are arranged to form two-, three- or four-aspect systems.

##### 45.4.6.2 Terminology

**Braking distance** The service braking distance is the minimum spacing between the first caution signal that a driver sees and the red aspect to which it refers. From this distance



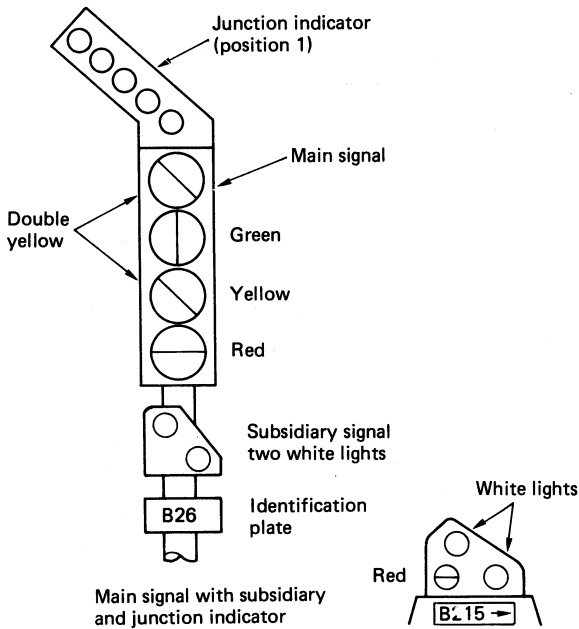


Figure 45.18 Signals

trains running at their maximum permissible speed can stop by normal service (not emergency) braking before reaching a signal at danger. The distance is derived according to maximum line speed, gradient and deceleration rate of the trains.

**Sighting distance** A driver on approaching a caution signal will act to reduce the speed of his train at a sighting distance from that signal.

**Overlap** It is practice in Britain to provide a short length of line beyond a signal to act as an 'overlap' in the event of a train overrunning a signal at danger. Normally a distance of 183 m is provided at multiple-aspect signals.

**Headway** This is the separation (in time or distance) between successive trains travelling at the same speed such that the following train can maintain speed.

45.4.6.3 Two-aspect signalling

Used on lines with low traffic density the two-aspect system divides the line into sections (Figure 45.19), each of which is protected by a red/green stop signal (B and D). At braking distance to the rear of each stop signal is a yellow/green repeater (A and C) to advise drivers in advance of the state of the stop signal to which it refers. Before a stop signal is

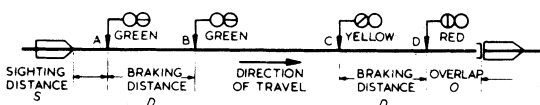


Figure 45.19 Two-aspect signalling

allowed to show clear (B) the line ahead must be clear to the overlap beyond the next stop signal (D). The repeater (A) changes from yellow to green at the same time.

45.4.6.4 Three-aspect signalling

Where greater traffic density is required the line must be divided into smaller sections. A stage is reached where the repeater for one stop signal falls close to the stop signal in rear. The two functions are then combined to give one signal capable of displaying stop, caution and clear (Figure 45.20). Each signal is at least full service braking distance from the next. Signal B changes from red to yellow when the rear of the leading train passes the overlap of signal C. Signal A changes from yellow to green at the same time. The headway can now be defined: if the following train is to run at normal speed it must not approach closer to A than its sighting distance before A clears to green. For a train of length  $L$  running at speed  $V$ , the headway distance  $H$  and time  $T$  are

$$H = S + 2D + O + L \quad \text{and} \quad T = H/V \quad (45.1)$$

where  $S$  is the sighting distance,  $D$  the braking distance and  $O$  the overlap. Three-aspect signalling is usual on lines carrying medium-density traffic and can cope with trains at 5 min intervals.

45.4.6.5 Four-aspect signalling

When a three-aspect system is unable to give adequate headways in an area of dense traffic, a fourth aspect (double yellow) is introduced (Figure 45.21). This allows signals to be placed at half braking distance, a driver being warned initially of a red signal ahead by the double yellow aspect. The headway can now be defined as:

$$H = S + 1\frac{1}{2}D + O + L \quad \text{or} \quad T = H/V \quad (45.2)$$

In practice, a four-aspect system gives around 30% greater capacity than a three-aspect system. As  $D \propto V^2$  approximately, then a train travelling at 0.7 of the maximum line speed requires only one-half of the braking distance afforded by the system, thereby allowing the driver to effectively ignore the double yellow. This means that

$$H = (S + D + O + L) \quad (45.3)$$

and, therefore, greater capacity.

If one lamp of a double yellow fails, it leaves the greater restriction of single yellow, failing safe.

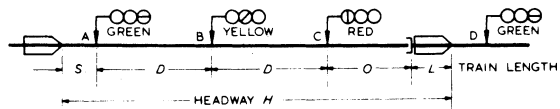


Figure 45.20 Three-aspect signalling

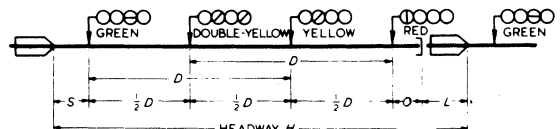


Figure 45.21 Four-aspect signalling

45.4.6.6 Position light signals

These signals are used to control movements into and out of sidings, between running lines and into occupied platforms. The 'stop' indication is given by a red and white light displayed horizontally, the 'proceed' by two white lights inclined at 45°. Where a position light signal is associated with a main signal it is positioned either beneath or to the side of the main aspects. When at 'stop' it displays no indication, the main red performing this function. When showing 'proceed' the two inclined white lights illuminate and the red of the main signal remains lit.

45.4.7 Signalling for junctions

British railway practice is to employ a route style of signalling whereby a driver is informed of the direction in which the route is set ahead. Where speeds are in excess of 64 km/h the routing is given by a junction indicator mounted above the main aspects.

The indicator shows a row of five white lights in the general direction of the route to be taken. Where multiple routes exist, up to six indicator positions are available (Figure 45.22). An indicator must be proved alight (at least three lights) before the main signal may show a 'proceed' aspect. The main (highest speed) route is not provided with an indication.

Most diverging junctions have speed restrictions lower than for the main route, and the usual practice is to prevent the junction indicator and signal from clearing until the train has passed the previous signal, thereby enforcing the driver to begin braking. This is known as 'approach release from red'.

In many situations this is over-restrictive and so a system known as 'approach release from yellow' is applied (Figure 45.23). In this instance the signal beyond the junction (D) is held at red allowing the junction signal itself to show a single

yellow with junction indicator (C). The signal in rear of the junction signal (B) is then arranged to show flashing single yellow to inform the driver that the junction signal is showing a 'proceed' aspect for the divergence. The driver may then slow his train for the turnout. Once the train has passed the flashing yellow signal, signal D is allowed to show a 'proceed' aspect (provided the line ahead is clear) enabling C to improve to double yellow or green. In four-aspect territory, signal A will be fitted with a flashing double yellow.

In and around stations and other locations where the line speed is 64 km/h or less, letter or number indicators are used to identify the route with the characters formed by a selection of optical fibres lit from a single source.

45.4.8 Coloured light signals

Each aspect is provided with its own lamp and lens unit. A double-lens optical system giving an 8° beam angle is employed. The 212 mm diameter outer lens is of clear glass, and has a downward-deflecting sector for close-up visibility. The 139 mm inner lens is coloured according to the aspect to be displayed. The units are set 279 mm apart in the vertical plane, are provided with hoods to screen off sunlight, and backed by matt black plates to give a dark background.

Double-filament tripole lamps are used rated at 12 V 24/24 W normally operated at 11.5 V to prolong filament life without undue loss of light flux. The main filament (with a guaranteed normal life of 1000 h) is detected by a current-sensing relay which switches the supply to the auxiliary filament if failure of the main is detected. The changeover is indicated to the control centre in order that the lamp can be replaced before complete failure.

A transformer is associated with each lamp, the feed circuit being 110 V a.c. allowing signals to be controlled from a distance. In 25 kV a.c. traction areas this is limited to 200 m to guard against false illumination brought about by induction into the cable from the traction system.

45.4.9 Signal-aspect controls

Before a signal is allowed to show a 'proceed' aspect the line ahead must be clear, including the overlap at the next signal and the next signal must be alight. The actual aspect displayed is reliant upon the aspect being shown by the next signal such that the correct sequence is always shown approaching a red signal. Therefore in four-aspect territory the sequence is green, double yellow, yellow, red.

On open track the passage of a train will replace signals to danger behind it and allow them to clear again as it progresses. At least one red indication will protect the train and be preceded by the relevant caution aspects. In areas where pointwork and diverging routes exist the signals are still replaced to danger automatically behind each train but movement of the points and selection of routes is performed by a control centre.

45.4.10 Point operation

In modern power signalling, points are moved by equipment on the ground controlled electrically. There are two forms of operation in widespread use: electric and hydraulic.

45.4.10.1 Electric

The drive machine is a d.c. split-field motor to reduce the possibility of false operation due to electromagnetic interference. The control circuits are preferably four wire.

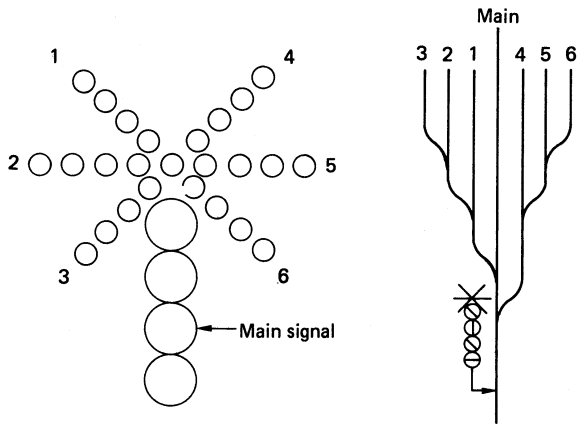


Figure 45.22 Junction indicators

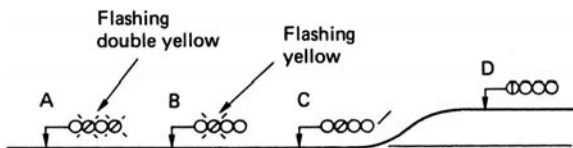


Figure 45.23 Approach release from yellow

Control is through a contactor designed to pass a control current up to 10 A at 120 V. There are separate contactor relays for the two operations: when the signalling controls require a point to be moved, then the appropriate contactor is energised first, proving that its complementary contactor is de-energised. The power is then applied to the motor. For passenger train movements it is necessary to ensure both that the point is detected in its correct position and that it is also mechanically locked. The first operation of the point machine is to unbolt this lock, then to move the point switches in the required direction and rebolt the lock. As this is completed, the point machine windings are cut off by special contacts within the machine and a special electrical snubbing circuit is brought into use by another set of contacts to prevent the motor from over-running. Also operated by the point machine contacts is a detection circuit which uses a three-position a.c. relay or two neutral polar relays: this circuit detects the point machine normal or reverse setting, including the detection of the mechanical bolt in its locked position. When the detection is in correspondence with the point machine calling, the point contactor is de-energised.

Normal operation takes about 3 s. A clutch is provided to slip if, owing to poor adjustment or an obstruction, the point machine is unable to make its full travel; and to protect the motor, a timing circuit will disconnect the machine.

#### 45.4.10.2 Hydraulic clamp lock

The purpose of point (switch) mechanisms is to ensure that the switch mates with the stock rail without gap. A positive and definite method is to clamp the two together by an electrically controlled hydraulically operated unit. Each unit has its own electrohydraulic power pack, and control from the hydraulic unit is by means of valves which actuate two pistons, one for movement to the normal and the second for movement to the reverse position. When the movement is completed, the control circuit is de-energised. The locking of the points is achieved by the clamping mechanism, which will only make in its correct position if the switch is properly against its stock rail. Thus, in operation the clamp is unlocked, and the switches are moved and then clamped. The units include detection contacts which operate a detection circuit similar to that for a point machine.

#### 45.4.11 The modern control centre

The control of railway signalling is today brought together into large centres responsible for the supervision of many miles of line over a wide area. The latest of these exploit microprocessor technology to its best advantage. Known as 'integrated electronic control centres' (i.e.c.c.s) they contain not only the means to manually monitor and control the railway system but also features such as automatic route setting and interfaces to adjacent control centres and information systems.

The i.e.c.c. consists basically of a number of processor modules configured on two local area networks. The networks and modules are duplicated for availability. The segregation of the system into separate networks (signalling and information) provides control over the amount of data flowing in the signalling network, in order to ensure quick response times. The response times in the information network are less critical. All of the modules are based on versa module eurocard (VME) bus architecture.

The man-machine interface is provided by the signalman's display system (s.d.s.). One is provided for each

signalman up to a maximum of three per i.e.c.c. Each is housed in a workstation comprising a number of high-resolution graphic monitors, keyboard and trackerball. The graphic monitors depict the relevant control area using a special character set to display the track layout, points, signals, etc. Overview and detail screens are available plus a general-purpose display. Command input lines, output messages and alarms are handled by the general-purpose display which can also show simplified real-time movements on map displays of adjacent workstation or control areas.

Other modules include solid-state interlocking (s.s.i.) (see Section 45.4.12.1), automatic route setting (a.r.s.), timetable processor (t.t.p.), external communication system (e.c.s.), gateway system (g.w.s.), and system monitor (i.s.m.) (Figure 45.24).

The a.r.s. package is designed to set routes automatically in response to the approach of trains based on data available from the timetable processor. Out of sequence and late running are catered for with operating strategies designed to minimise delays and deviation whenever a conflict occurs. The signalman remains in control at all times and may set routes ahead of a.r.s. or restrict its sphere of operation. Certain shunt routes and unscheduled movements require manual route setting. This is achieved using the trackerball and associated control buttons.

The signalman uses the trackerball to position a cursor over the symbol of the signal from which the route is to be set, then presses a 'set' button. He then moves the cursor so that it is positioned over the signal at the end of the route and again presses the 'set' button. A correctly set route is shown by the normally grey track layout changing to white. The progress of the train is shown by occupation of each track circuit which is indicated by turning the relevant portion of track display red. The four-digit train description number is also displayed in line with the 'red track occupied' indication.

Actual signal indications are displayed on the graphic screens as are point positions, level-crossing and other ancillary functions. Signal, point and track-circuit names are displayed optionally upon request by the signalman.

Trackerball control is exercised over individual points and is used for many of the routine commands, aided by a set of icons depicted at the bottom of each graphic display. The keyboard is used to set up train descriptions and to interrogate the system. Additionally it is available as a fallback mode of operation should the trackerball fail.

The timetable processor holds the various timetables appropriate to particular days of the week, downloaded from the national train service data base. Local details and short-term alterations are handled by input at a local level to ensure that the information passed to the a.r.s. processor is current. The t.t.p. also makes its contents available to the information network to assist in the running of passenger-information displays.

The gateway system is tasked with handling the interface between the signalling and information networks. It regulates the exchange of traffic between the two networks, isolating the response-critical signalling network from heavy demands of information. Incoming information from outside the i.e.c.c. area that is required by the s.d.s.s. is passed into the network by the g.w.s.

System monitoring, status and fault reporting are handled by the i.s.m. which provides for a technician's interrogation facility. Time synchronisation is performed by the i.s.m. in conjunction with the Rugby radio clock.

In order to interface to other control areas or subsystems, an external communications system is provided to translate message formats to and from these connected systems.

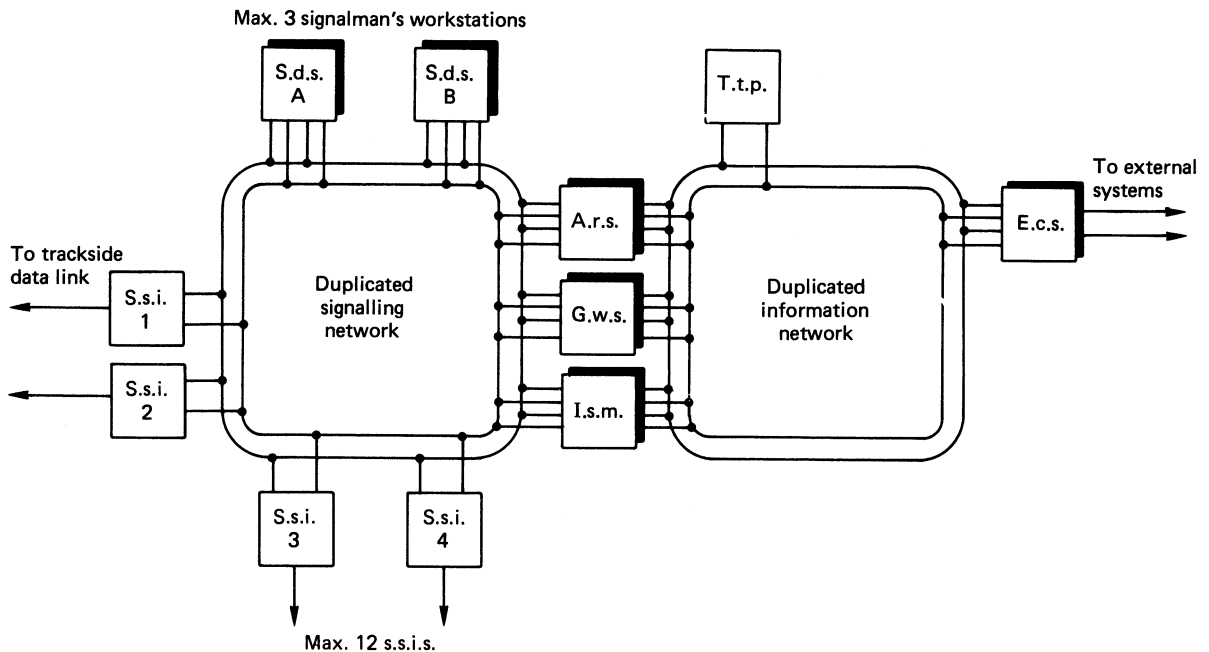


Figure 45.24 I.e.c.c. network

#### 45.4.12 Interlocking equipment

It is necessary to ensure, before a signal clears, that the route has its points in the correct position and that there is no possibility of a train being signalled in an opposing direction. Equally, once a train has been signalled, there must be no possibility of a point in that signalled route being moved or another movement being signalled against the first-signalled move.

A signalled route generally extends from one signal to the next. In it there will probably be a number of track circuits, and a point in one of the middle track circuits. The control of that point is fundamental to the safe passage of trains: (1) the point will be locked in position by occupation of the track circuit that includes it; (2) when the signal has been operated and cleared, it must be locked; (3) if after (2) the signal has to be restored to 'danger' (e.g. in emergency), then the point must be kept locked for a time sufficient for an approaching train to stop—the time normally allowed is 2 min minimum and 4 min maximum, depending on the spacing of the signals to the rear; and (4) when a train has passed a signal which had cleared, on occupation of the first track circuit and subsequently others, the signal would revert to 'danger' and it would be necessary to ensure that the points are still locked for these movements. But there might be movements in opposite or other directions through these track circuits, in which case point locking may not be necessary. Thus, locking by these track circuits is conditional: it is called 'route locking' and is often designed to incorporate the other features listed above; and it is essentially a part of any electrical interlocking system. Another important feature is that of sectional release whereby, as a train clears each track circuit and the sections ahead are still locked, the locking of points in those track circuits that have been occupied and cleared can be released.

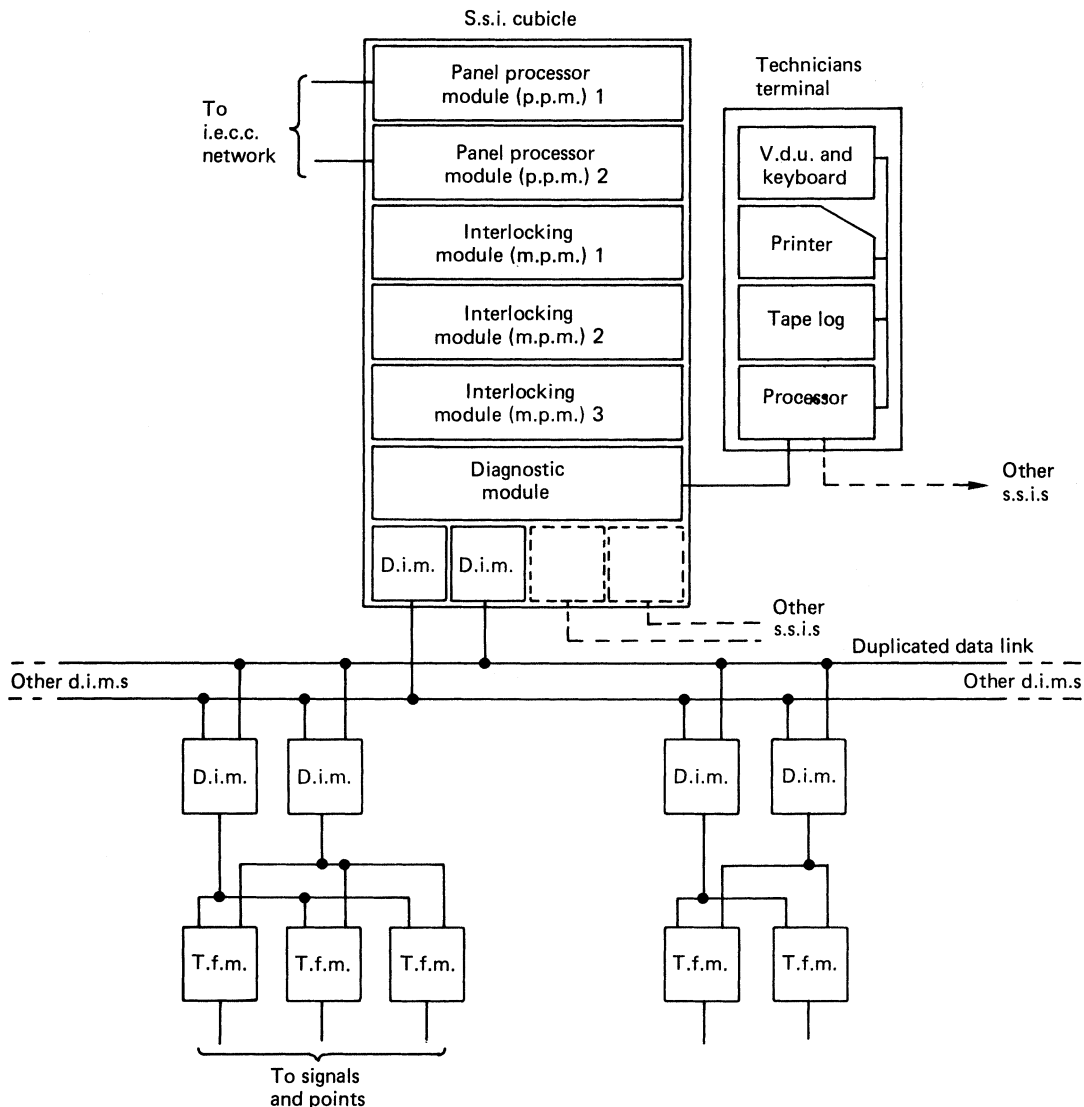
##### 45.4.12.1 Solid state interlocking

Whilst a number of older systems remain in use, nowadays safety logic required by railway signalling is performed by solid state interlocking (s.s.i.), which is a purpose-built microprocessor-based system. Safety is provided by redundancy, the s.s.i. employing a two-out-of-three voting arrangement.

The interlocking is usually sited at the control centre and communicates with trackside equipment via a data link and trackside functional modules (Figure 45.25). The area of control is limited by the density of trackside equipment but single s.s.i. modules can be connected to form multiple interlockings to control larger layouts. Interface to the signalman's control and display system is via a standard RS422 link driver from panel processor modules which are duplicated to provide fault tolerance.

The interlocking program is data driven and comprises two parts. There is a fixed program written in assembler which has a modular structure to enable clear validation, and geographic data which configure the interlocking for its specific location. Each of the panel processors and the triplicated multiprocessor interlocking modules are fitted with an interchangeable memory module which contains the fixed program and geographic data in erasable programmable read only memory (EPROM).

The three multiprocessor modules which perform the interlocking logic tasks are identical and run the same program. They form a two-out-of-three majority voting system and each contains a redundancy management device which monitors output states, system states and program memory comparing with the other two units. A faulty module can be disconnected by its own or either of the other two management devices allowing the remaining two modules to continue operating as a two-out-of-two redundant system.



**Figure 45.25** Scheme of solid-state interlocking. D.i.m., data link module; t.f.m., trackside functional module

without a reduction in safety. If a further fault occurs in either of these remaining modules a complete system shut-down is invoked and signals are retained at red.

Connection to the lineside equipment is made through trackside functional modules (t.f.m.s) connected to a duplicated data cable via data link modules which handle the communications. The integrity of the complete system relies upon the safe transmission of data between the interlocking and t.f.m.s and on each t.f.m. performing in a fail-safe manner. Data are transmitted at a rate of 10 kbaud in each direction in the form of telegrams addressed to and from each t.f.m. Up to 63 t.f.m.s can be addressed by one interlocking, each being polled and reply received in turn. Telegrams take the form of Manchester II code containing direction, addresses, identity, status, signalling controls and parity.

The t.f.m.s contain two processors working in a two-out-of-two voting arrangement for safety, availability being less stringent than for the central interlocking.

The modules act as a serial/parallel multiplexer taking control commands from the interlocking and turning these into outputs to directly drive signal lamps and electro-hydraulic clamp locks or point machines via contactors. Other equipment is interfaced via relays driven from outputs of the t.f.m.s. Likewise, inputs from lineside equipment such as track circuits, point detection and lamp proving are converted to serial data and transmitted back to the s.s.i. (Figure 45.26).

Finally, a diagnostic processor is connected to a technician's terminal to provide comprehensive fault reporting and maintenance support.

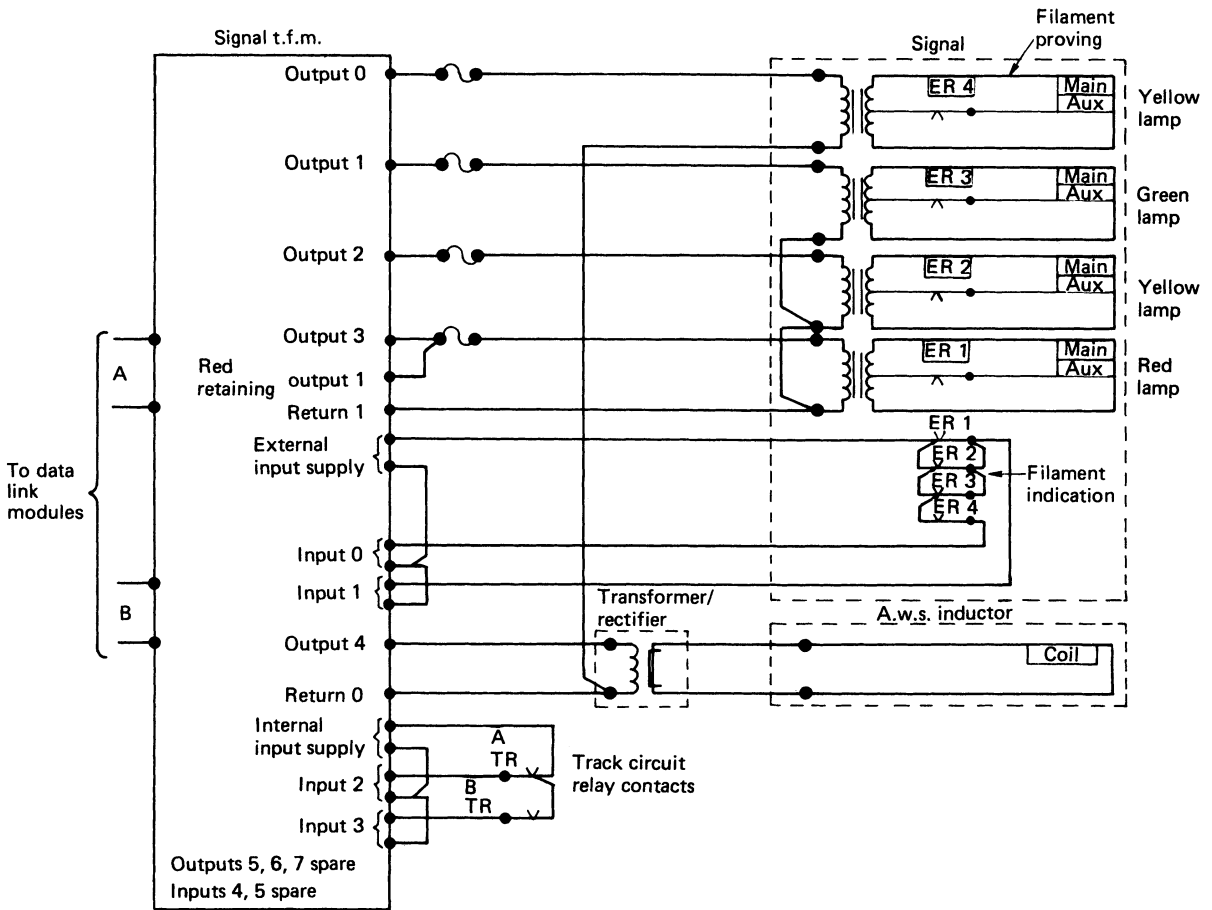


Figure 45.26 Typical trackside functional module connections

### 45.4.13 Automatic warning system

The standard British Rail form of in-cab signal, fitted to around 70% of the network, is intermittent in operation and gives only two indications, 'caution' and 'clear'.

Two different audible sounds can be given to the driver. If the signal ahead is showing green, an electric bell rings for approximately 1 s; but if the signal displays any other aspect a horn sounds continuously until the driver makes an acknowledgement. If the driver fails to acknowledge, a full brake application is automatically initiated. When the driver makes an acknowledgement, a visual indicator operates to remind him of the fact that he has received and acknowledged this warning, and the indication remains displayed until it is cancelled on approaching the next fitted signal.

#### 45.4.13.1 Track equipment

The link between the track and locomotive or vehicle is magnetic, the track being fitted with two inductors, the first one to be passed over being a permanent magnet and the second an electromagnet. The magnet centres of these

two inductors are 787 mm apart. The magnets have a vertical axis, the permanent magnet having its south pole uppermost and the electromagnet, when energised, having its north pole uppermost. The electromagnet is only energised when the signal ahead is clear (green). The inductors are usually fitted about 183 m on the approach side of the signal with their upper surface at rail level. They are sufficiently powerful to operate the equipment on the locomotive or vehicle through a 165 mm air gap at speeds up to 240 km/h. The permanent inductor has a magnet of Alcomax II, fitted with mild-steel spreader plates, top and bottom, to give a projected flux curve that is of sufficient intensity to operate the vehicle equipment over a horizontal distance of 250 mm measured at a height of 165 mm above the top of the inductor casing. The electro-inductor coil has two windings, and the core is similarly fitted with spreader plates to give a flux curve like that of the permanent inductor. The two coils can be connected in series or parallel for 24 or 12 V d.c., the nominal coil consumption being 9 W.

Permanent magnets are also fitted on the approach to permanent and temporary speed restrictions to give a warning and to provoke a response from drivers.

### 45.4.13.2 Rolling-stock equipment

Rolling-stock equipment has various forms for diesel and electric locomotives hauling vacuum-braked trains, diesel multiple-unit trains with vacuum brakes, and diesel or electric multiple-unit trains with air brakes.

On the underside of the locomotive or vehicle is a receiver responding to the magnetic flux from the track inductors. It consists of a permanent-magnet armature, centrally pivoted and lying between soft-iron poles. The armature carries a flexible beryllium-copper contact strip to act as a single-pole changeover switch when the armature moves under the influence of the south and north poles of the inductors. Its own magnetism holds it in one or other of the two positions against the vibration of the vehicle. A coil wound round one of the poles is energised by the driver when acknowledging a warning indication, the magnetic field causing the armature to return to the normal position from which it had been moved by the flux from the permanent inductor. If the signal has been clear, the receiver armature after being thrown by the south pole of the permanent inductor will be automatically restored by the north pole of the now energised electro-inductor, no acknowledgement by the driver being required.

Power for the automatic warning system (a.w.s.) apparatus is provided from the vehicle battery through a static voltage converter, which serves to isolate the a.w.s. equipment electrically from the driving control and lighting circuits and to provide the correct voltages (12 V for the main circuits and 40 V for the acknowledging or re-setting circuits). Normal power consumption is about 4 W with a peak of 12 W for a few seconds on receiving a signal from the track.

The 'caution' indication is either a vacuum or compressed-air operated horn controlled by an electropneumatic (e.p.) valve normally energised. A second e.p. valve, similarly energised and mounted in the same unit, is used to control the a.w.s. brake valve. On passing over a permanent-way inductor with the electro-inductor de-energised, the breaking of the normal receiver contact de-energises the e.p. relay, which, in turn, energises both e.p. valves. The horn immediately sounds and the brake valve begins to release in the air/vacuum system. Within about 3 s the valve releases fully and a brake application is made to bring the train to a stand.

The driver can acknowledge and re-set the equipment by pressing a re-set plunger within the 3 s period and maintain control of the train. The visual indicator changes to a black and yellow display to act as a reminder that a 'caution' signal has been passed.

### 45.4.13.3 Mechanical safeguards

On double-ended locomotives and multiple-unit trains, means have to be provided to isolate the a.w.s. equipment in all drivers' cabs except that from which the train is being driven. For vacuum braked stock, a combined electrical and vacuum switch is provided with a loose handle which is carried by the driver. When the driver enters a cab, he inserts the handle into the switch and turns it to close the necessary electrical contacts, which puts supply to the a.w.s. apparatus and opens the a.w.s. brake valve to the train pipe. The handle cannot be removed without first switching off to isolate. To ensure that the driver inserts the loose handle and switches in the a.w.s., additional contacts are provided through which the supply to the main driving controls is taken. The train cannot be moved unless these contacts are made. This switch also carries a second fixed handle, which is sealed in the running position. In case of a failure of the a.w.s. apparatus which would apply a permanent brake, this

seal can be broken and the handle moved to isolate the a.w.s. equipment and yet allow the train to be moved.

On air-braked trains the same principles apply, but the independent a.w.s. loose handle is dispensed with and the switching effected by operation of the driver's brake control key.

### 45.4.13.4 Bi-directional lines

Where a line is used for signalled moves in both directions steps have to be taken to suppress the permanent magnets which are passed over in the wrong direction. This is achieved by switching on a suppressor unit comprising an inductance forming part of the permanent magnet. When switched on a magnetic field is produced that is equal and opposite to that of the permanent magnet. Having said this many lines now fitted with a simplified form of bi-directional signalling do not have this feature built into the a.w.s. track equipment. In these cases the driver must cancel and ignore the warnings received that do not apply to his direction of travel.

### 45.4.14 Automatic train protection

Although the a.w.s. has made an important contribution to increasing the safety record of British Rail, it cannot ensure that drivers respond correctly to a caution signal or warning of a speed restriction. A programme of fitting automatic train protection (a.t.p.) has therefore been embarked upon. Like a.w.s. the a.t.p. system is intermittent, in that information is passed to the train at fixed locations. However, the amount of information passed between track and train is sufficient to allow complete speed supervision at all times.

The trackside equipment comprises beacons, usually fitted adjacent to signals, into which are encoded data relevant to the route ahead. These data comprise such items as: present position, distance to 'danger' signal, overlap at signal, gradient, maximum line speed, distance to next speed restriction, value of next speed restriction and its length. Variable information such as signal aspect and route information is determined by selection from the signal controls. The data are encoded into a telegram and presented to the track beacon which comprises either a cable loop laid between the rails or a transponder mounted on a sleeper. On passing over a beacon the train-borne receiver passes the telegram to the on-board processor.

#### 45.4.14.1 Speed supervision

The on-board processor is responsible for taking the trackside messages and other train-carried inputs such as speed and direction and generating supervision curves to ensure that the train does not exceed speed limits or pass a signal at 'danger'. A certain amount of fixed train-carried data is required to enable the processor to make the right calculations. This includes: length of train, maximum permitted speed, and braking capability. These are entered by the driver at the start of the journey. When all signals are at 'clear' and no speed restrictions exist in the immediate route ahead the processor will supervise the train speed to ensure that the driver does not attempt to exceed the maximum line speed or maximum permitted speed of the train, whichever is the lower. When approaching a speed restriction or signal at 'danger' the processor calculates a series of braking curves down to the target speed at the signal or restriction. There are four curves (*Figure 45.27*).

The basic curve is derived from the distance required to slow the train  $D_b$  from its present speed  $V$  to the target

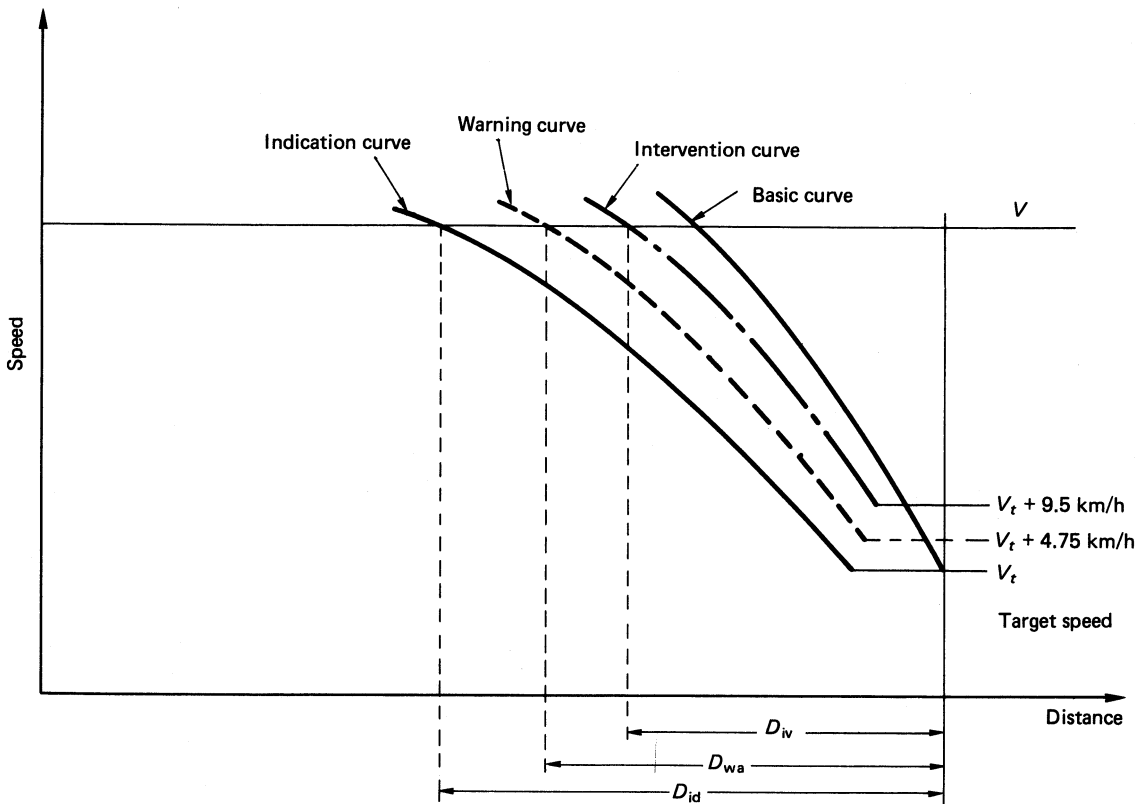


Figure 45.27 Automatic-train-protection generated curves

speed  $V_t$  where  $B$  is the deceleration on level track brought about by service braking and  $I$  is the deceleration resulting from the gradient:

$$D_b = (V^2 - V_t^2)/2(B + I) \quad (45.4) \Leftarrow$$

In order that the on-board processor can intervene in the event that a train is not being braked sufficiently early, account must be taken of the time required for full service brake force to build up. A second (intervention) curve is therefore derived from the basic curve displaced by the distance travelled at constant speed during the time it would take for the brakes to be fully applied. This distance  $D_i$  is derived from the formula

$$D_i = D_b + VT_b \quad (45.5) \Leftarrow$$

where  $T_b$  is the time taken to build up full service brake force. In the normal course of events the system should not be called upon to intervene as the driver will control braking well before any overspeed is detected. To advise the driver should he come close to invoking intervention a third (warning) curve is generated. The warning is based upon giving a constant warning time  $T_w$  and, therefore, the displacement of this curve from the intervention curve is the sum of  $T_w$  and the time taken for the brakes to fully apply  $T_b$ . The warning curve is thus derived from the formula

$$D_w = D_b + V(2T_b + T_w) \quad (45.6) \Leftarrow$$

The driver requires his indication of target speed to be updated such that he is able to react before receiving a warning from the system and so a fourth (indication) curve

is used to update the cab display. Again a constant time  $T_{id}$  is allowed for the driver to react to the change of indication and so the distance from target at which the curve begins  $D_{id}$  is defined as

$$D_{id} = D_b + V(2T_b + T_w + T_{id}) \quad (45.7) \Leftarrow$$

The warning and intervention curves result in being 4.75 and 9.5 km/h above the indication curve, respectively.

In order to allow trains to draw up to a signal at red or to pass a previously red signal which has improved to proceed, trains are not supervised to an absolute stop. The release speed is determined by the length of the overlap  $D_o$  such that should a train pass a red signal it can still be brought to rest in the overlap. If the release speed is known as  $V_{max}$  and the time taken for the emergency brakes to be applied  $T_{be}$  then

$$V_{max} = \sqrt{2(B + I)D_o} - 2(B + I)T_{be} \quad (45.8) \Leftarrow$$

#### 45.4.14.2 Driver's interface

The driver's interface comprises green and yellow lights around the dial of a conventional analogue speedometer. The green lights indicate permitted speed and the yellow lights release speed. A three-character alpha-numeric display gives details of status and actions of the system. Four push buttons are supplied to cater for switching on, shunting, passing signals at danger, and regaining control after intervention. A separate keypad and display are used for entering train data. Various audible tones alert the driver to changes of state.



#### 45.4.15 Signal power supply

As industrial power supply reliability cannot be guaranteed, all signal systems have stand-by arrangements. For isolated signals and light loads, the stand-by is in the form of trickle-charged batteries. Where a.c. is essential, inverters have been used. The normal provision for major power signalling systems is a stand-by diesel-engine/generator set. It is accepted that the set may take up to 7 s to be ready for load. Transfer back to normal supply is done manually. An acceptable main power variation is  $\pm 10\%$  in voltage and  $\pm 2$  Hz in frequency. The stand-by equipment is designed to detect wider variations and take over the load in such a case.

A normal power distribution system is based on 650 V a.c. In densely signalled areas ring mains are used, and in all other areas spur mains are used. Power supplies are sited at suitable points according to loads but, on average, power supplies are required, with associated stand-by equipment, every 16 km.

The basic signalling equipment operates at voltages of 110 V a.c. for signals and track-circuit equipment, 50 V, 24 V and 12 V d.c. for relays, and 120 V d.c. for point machines. Transformers are provided at suitable intervals to give 110 V from the 650 V main, and the other voltages used are obtained from the 110 V a.c. Batteries are normally used on telecommunications equipment and at automatic level crossings, the latter to ensure continued operation on safety grounds. In certain track layouts it is possible to operate 12 point machines at once and this would require a large transformer rectifier. As it is only an intermittent load a small transformer rectifier and heavy-duty battery are used to overcome this heavy peaking.

All signalling circuits other than track circuits are insulated from earth.

#### 45.4.16 Protecting signalling against traction currents

A.c. traction systems are unbalanced, and as much as 50% of the return current may reach the substations through the earth, and signalling circuits are subject to induction. In order that induced voltages will not exceed the International Consultative Committee for Telephone & Telegraph (CCITT) limits of 60 V normal and 430 V under fault conditions, circuits are restricted to a length of 2 km, and in the presence of a.c. traction use a.c.-immune d.c. relays.

Connection to colour light signals is restricted to 200 m in electrified areas. Point machines are d.c. operated with a.c.-immune motors and contactors, the latter being located near the machines. For track circuits, a.c. feed is used on d.c. electrified lines and d.c. on a.c. lines. A.c. track circuits operating at frequencies of  $83\frac{1}{3}$  Hz or at frequencies which are not a multiple of 50 Hz are acceptable for both forms of traction electrification.

#### 45.4.17 Level crossings

The railway has an obligation to protect road users at level crossings on public highways. Traditionally this was done with gates, but currently there are six main ways of achieving modernised protection. These comprise automatic half barrier (a.h.b.), automatic open crossing (locally monitored) (a.o.c.l.), automatic barrier crossing (locally monitored) (a.b.c.l.), manually controlled barrier crossing (m.c.b.), trainman-operated barrier (t.o.b.) and miniature warning lights (m.w.l.).

All these crossing types, with the exception of m.w.l., are fitted with road-traffic signals. These comprise one yellow and twin red flashing lights located in each of the four corners of the crossing facing oncoming traffic. Additional units are provided for side roads as necessary. Other fixed

road signs and audible warnings are provided according to the particular type of crossing and the number of lines crossed.

The road signals are lit on initiation of the crossing and show a yellow light for 3 s followed by alternate red flashing lights at a rate of 80 flashes per minute. The red signals continue to flash throughout the operation of the crossing until the train is clear and, if there are barriers, until these have begun to rise.

##### 45.4.17.1 Automatic half barrier

These are controlled automatically by the approach of trains through track circuits and treadles. Barriers are provided on each nearside road approach only with red and white booms which carry two red lights.

A minimum of 27 s warning is given before the fastest train arrives. At initiation the yellow aspects show for 3 s followed by the flashing red for 7 s before the barriers lower. With the lowering taking 5 s the barriers are down for a minimum of 12 s. No indication of the crossing is given to the train driver but operation and power status together with emergency telephones are monitored from a supervising control centre.

The maximum line speed where a.h.b.s are installed must not exceed 160 km/h and on multiple lines the barriers must remain up for at least 5 s before a second train initiates operation. If this period cannot be achieved the barriers remain down until the second train clears the crossing.

##### 45.4.17.2 Automatic open crossing (locally monitored)

These are controlled in a similar manner to a.h.b.s but no barriers are provided. A minimum of 27 s of warning time is given and the lights must remain extinguished for at least 10 s before a second train initiates operation on an adjoining line. In this instance a separate road signal on each side of the crossing flashes red with the words 'another train coming'. The equipment and power supply are monitored by the train driver through a rail signal. This normally exhibits a flashing red indication which changes to flashing white once the red road signals are correctly lit. Should the red lamps in one road signal fail, or a failure of the main power supply occur, the rail signal will not show the proceed aspect. The driver is then authorised to pass over the crossing at caution once he is sure it is safe to do so.

Each a.o.c.l. is restricted to a speed dependent upon local sighting conditions but always within the maximum of 88 km/h. Before reaching the crossing and sighting the rail signal the driver will pass an 'advanced warning board' at braking distance followed by a crossing speed board advising of the speed restriction.

##### 45.4.17.3 Automatic barrier crossing (locally monitored)

This system is similar in operation to an a.o.c.l. with the addition of road barriers but without emergency telephones. It is similarly subject to a speed restriction based on local conditions. The train driver receives the same trackside approach boards and monitors the operation of the crossing via the red and white flashing rail signal. During a failure situation the barriers remain raised. A plunger is provided for the driver to lower the barriers in this situation before entering the crossing.

##### 45.4.17.4 Manually controlled barrier crossing

This type of installation is provided with full barrier protection which closes off the whole road. The barriers are normally fitted with skirts and the usual yellow and flashing

red signals are shown to road users. Whilst in the lowered position the barriers are locked down.

There are several variations on the style of control but each essentially requires an operator to ensure that the barriers are lowered and that the crossing is clear before a train is allowed to approach. Controlled signals are, therefore, provided on each rail approach interlocked with the level crossing.

There are no restrictions on train speed, traffic levels or the number of lines passing over the crossing. Typically operation will be performed by a signalman or crossing keeper adjacent or near to the crossing or remotely by the aid of closed-circuit television. Automatic raising is often fitted and in many instances automatic lowering, whereby an approaching train initiates operation. Before the signals can be cleared for a rail movement, however, the operator must always confirm that the crossing is clear.

#### 45.4.17.5 *Trainman operated barrier*

Used on rural lines, the train driver is responsible for operating the crossing from a switch or push button which he can reach from the driving cab. A flashing red and white rail signal indicates the status of the road signals and barriers before the driver ensures that the crossing is clear and then proceeds. A special signal is located beyond the crossing to indicate to the driver that the barriers have raised automatically behind the train. If they fail to rise the train must stop and the crew raise them manually.

#### 45.4.17.6 *Miniature warning lights*

This type of installation is used for footpath crossings or minor level crossings where user operated gates or barriers are fitted. Red and green lights are provided for users on each side of the crossing, operated by the approach of trains. Users may only cross when the green light is showing. No indications are given to the train driver.

#### 45.4.18 **Train to signal box radio**

To facilitate driver-only operation of suburban passenger trains a system of 'train to signal box radio' is implemented on appropriate routes. This allows for secure direct voice communication between the signalman and driver and for the exchange of fixed data messages.

Each signal box or control centre is equipped with a management processor and one or more signalman's processors each with interfaces comprising a visual display unit (v.d.u.), keyboard and audio equipment. Radio coverage is provided by a number of fixed radio stations along the length of the railway under control. These are connected back to the signalman's processor by four-wire circuits. Coverage through tunnels is maintained by using leaky co-axial cables or directional antennae. The signalman has control of the system at all times, his v.d.u. advising of all incoming calls and alarms and echoing his inputs from the keyboard. The fixed stations transmit on two frequencies, a nationwide signalling (or control) channel used to establish calls and a discrete traffic channel assigned to the area. The system is allocated 19 traffic channels in the ultra-high frequency (u.h.f.) band. To prevent cross-talk between areas continuous tone controlled signalling system (c.t.c.s.s.) is employed. Each base station is allotted a time slot in which to transmit. Synchronisation of time is handled by the management processor from reference to the Rugby radio clock. The train-carried equipment comprises a transmitter, receiver and control equipment. The cab interface includes a keypad and alpha-numeric display.

The system aids safety and operating by giving direct communication during all times without the need for drivers to leave their train and contact the control centre via signal post telephones. When stopped at a signal a driver can for instance send a 'waiting at signal' data message by operation of a function key. The signalman can respond to this with the instruction 'wait' by pressing a function key. This message is then displayed on the driver's display in his cab.

The management processor is kept informed of train whereabouts by the signalling system and is thus able to identify each caller by the train running identity and pinpoint the location of the train.

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