5 Urban railways and rapid transit systems

Early developments

During the nineteenth century, railways served almost all demands for mechanized transport, including those within urban areas. Specialized urban railways developed in the largest centres, notably the London Underground system from the opening of the Metropolitan Line in 1863. A number of main-line railway companies also developed a strong interest in suburban traffic, especially where long-distance demand was limited. Thus, the railways to the south of London displayed markedly greater interest than those to the north and west. Given the longevity of rail infrastructure, this pattern continues to affect present-day network structure, south and east London being mainly reliant on surface railways, the north and west on the Underground.

The growth of electric tramways at the turn of the twentieth century caused a rapid transfer of short-distance trips to this new mode, which offered much better accessibility and frequency than railways, whose routes had been located primarily from the viewpoint of long-distance traffic. It was the tramcar, not the railway, which gave the first opportunity to the majority of the population to make frequent use of mechanized transport. The railways responded by closing some minor routes, leading eventually to the complete closure of local systems in cities such as Stoke or Edinburgh during the 1960s.

Suburban lines were electrified to improve speeds from the first decade of the twentieth century (for example, Liverpool to Southport, Manchester to Bury, and on Tyneside). In the London region, this process greatly accelerated during the 1920s and 1930s to produce much of the present network south of the Thames. After the Second World War, this was followed by further extensions south of London, east London and Glasgow. A renewed spate of investment led to further schemes outside the South East in the 1970s, notably extensions of the Glasgow and Merseyside networks. Main-line electrification had also permitted local schemes as a by-product, notably in Manchester.

A more dramatic development was the growth of self-contained urban railway schemes, typically located underground in city centres. These are often known as ‘metros’ after the Paris system, inaugurated in 1900. Other early examples included Hamburg, New York, Chicago and Madrid. By 1940, 17 such

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systems were in operation, including Moscow, Osaka and Tokyo. A boom in metro construction then followed from the 1950s. A further 49 systems were opened by 1984, and many more since. Within Europe, successively smaller cities, such as Oslo and Marseille, have opened metros, but some of the most heavily used systems are now found in the very large cities of Asia and South America, such as Hong Kong and Mexico City. Further growth in these regions is likely to produce much of the overall increase in metros.[1]

In Britain, investment levels have been lower, but substantial improvements have been made to the London, Merseyside and Glasgow systems, and the Tyne and Wear 'Metro' has been created largely from former surface routes. Light rail has been introduced in the form of the Docklands Light Railway (DLR) and Croydon Tramlink in London, Manchester Metrolink, Midland Metro, Sheffield Supertram and Nottingham Express Transit.

In Britain, the street tramcar largely disappeared during the 1950s, and only the Blackpool system remains. However, many medium-sized cities elsewhere in Europe retained their systems, which have been developed into 'light rapid transit' networks, acting either as the major framework in the public transport systems (as in Göteborg or Hanover), or feeders to underground railways (as in Stockholm). New suburbs have been built around reserved track extensions, and older sections of the network placed on reserved track (sometimes in tunnel), so that most of the network is thus aligned.

Types of urban rail system

Four types may be distinguished, the first two using German terminology.

U-Bahn

This is an 'underground' railway, usually running within the built-up limits of a city, giving good penetration of the city centre by tunnels (however, well over half the network may, in practice, be sited on the surface, or elevated track, outside the centre). Ownership is usually vested in the city transport authority, and the network largely self-contained. Close station spacing (about 1,000 metres on average) permits a very high proportion of passengers to reach stations on foot, and all-stations operation of trains is normal. Simple fare systems, often flat rate or zonal, apply. Examples include the London Underground, Hamburg, Stockholm, Munich and New York. Although often adopted as a generic title for such systems, the Metro in Paris is in some respects untypical, with very close station spacing and short routes (apart from the RER regional system).

S-Bahn

This term denotes those routes of main-line surface railways on which a frequent service geared to local traffic is offered. Station spacing within the inner city may approximate to that of the U-Bahn, but intervals of 2–3 km are more common. Average speeds are higher, despite lower acceleration rates. Peak service levels have often been limited by lack of track capacity, although there has been a general trend to segregate such services from long-distance operations through provision of separate tracks and stations. This may be taken further, to construction of new extensions purely for such systems, including city-centre routes in tunnel; this may offer a much cheaper alternative to building a new metro, while giving many of the same benefits. Examples include Hamburg, Frankfurt, Merseyside, Cairo and Glasgow. The 'Thameslink' service, re-using an old tunnel between Farringdon and Blackfriars to create strategic cross-London links (such as Bedford–King's Cross–Gatwick) may also be placed in this category, albeit serving somewhat longer-distance traffic.

Light rapid transit (LRT) (also known as light rail)

This term is applied to electrically powered systems with characteristics similar to U-Bahn, but generally without block signalling (see below), full-height station platforms or ticket issue at all stations. Trains of up to three or four single cars, or one or two articulated cars, are usually operated. Many of the advantages of the 'heavy' U- or S-Bahn systems are given, together with better accessibility, for a much lower investment, albeit also less capacity. Except in the largest cities, such systems are generally adequate for peak flows. Most have been developed from upgraded street tramways, but entirely new systems have been opened since the 1970s, including Calgary and Edmonton (both in Canada), San Diego and St Louis (USA), Manila (Philippines) and Utrecht (Netherlands). The Tyne and Wear system uses some of the same techniques, but is closer to 'heavy' transit. The Greater Manchester 'Metrolink', opened in 1992, represented the first British example of this new generation, using street-based technology to provide a cross-city link, while incorporating through-running over former suburban lines. France offers many examples, notably the Nantes system, whose first line (opened in 1985) reintroduced the modern 'street tramway' concept, followed by others such as Grenoble, Rouen, Montpellier and Bordeaux. Current examples in Britain are in Croydon, Nottingham, Manchester, Sheffield and the West Midlands.

In some cases, tramways have been upgraded to form an intermediate stage to 'heavy' urban railways or metros. For example, the 'premetro' in Brussels comprises city-centre tunnels and stations served initially by trams, and later by conventional metro trains. In other cases, a tramway may be upgraded by extensive construction of city-centre tunnels, and some stations at which all tickets are sold prior to boarding the vehicle ('semi-metro'), for example in Stuttgart. An advantage of such systems is that trams can be diverted into relatively short sections of tunnel as they are built, rather than waiting for a major portion of the system to be completed before operations can commence.

Automated systems

For some years, control technology has made fully automated operation (with no drivers or station staff) quite feasible. A number of airport systems have been built, mainly in the United States, of which the Gatwick 'peoplemover' offers a British example, but the first such systems for general public use opened in Japan (Kobe and Osaka) in 1981. They were joined by several other Japanese systems, and the first 'VAL' in Lille, France, opened in 1983. The latter was the first to penetrate a traditional city centre, providing the same function as a traditional metro, and has operated very successfully. Further systems include the Vancouver's 'Skytrain', now being extended. In most cases, flows handled are of similar size to those suited to LRT, hence the term 'ALRT' (automated light rapid transit) being used sometimes. The DLR, the first part of which opened in 1987, also falls into this category, albeit retaining on-train 'captains' for customer contact.

The most important example is line 14 ('Meteor') of the Paris Metro opened in 1998, the first 'heavy' urban line to be fully automated, with headways potentially down to 85 seconds.[2] A number of older metro lines are now being rebuilt for fully automated operation, notably line 1 in Paris and parts of the Nürnberg system.

Basic system characteristics

Capacity

This is a function of three variables.

1 Passenger capacity of each car

Typically about 100 to 150, dependent upon the proportion of standing-to-seated passengers, level of comfort accepted, and size of car (LRT cars generally being smaller, and some 'heavy' systems, such as Hong Kong, being built to a larger track and/or loading gauge than normal). A distinction may be drawn between 'tolerable' loads, including some standing, and 'maximum crush' (with greater standing densities) at the peak: in the case of London Underground 'tube' stock, about 800 and 1,200 per train respectively. The proportion of seated passengers may be greatly increased by use of double-deck stock. This is found extensively on the Paris system for longer-distance commuting, and several other major cities, but is currently impractical in Britain due to the restricted loading gauge.

2 Average length of train

Up to ten or 12 cars may be possible in the case of S-Bahn, but U-Bahn lines are generally limited by platform length to seven or eight (although newer systems may take more), as in the case of London. For LRT, one or two articulated cars is typical, as on the Croydon and DLR systems respectively. Increasing train length is generally the cheapest and simplest method of raising capacity, where platform lengths permit – for example, expanding Jubilee Line trains from six to seven cars in January 2006 increased capacity pro rata (i.e. 17 per cent). However, on existing underground lines, extending platform length may be difficult.

3 Headway between trains

Block signalling applies to all U-Bahn and S-Bahn lines, and some newer LRT routes, implying a minimum headway of about 90 seconds. To allow some margin for minor operating delays, 120 seconds may be taken as a practical minimum with ‘fixed block’ working (i.e. 30 trains per hour).

Putting these factors together, the maximum passenger flow in one direction per hour (for a double-track route) can be estimated. For example, if each car takes 150 passengers, there are eight cars to a train and 30 trains per hour, the flow will be 150 × 8 × 30, or 36,000. In Europe, more than 25,000 is rarely required, although heavier flows may be encountered for 15–30 minute periods at the height of the peak (for example, on the Victoria Line). S-Bahn routes may have lower capacity owing to sharing of track with other services, and LRT routes a maximum of about 5,000 to 15,000 per hour. In very large cities, higher demand may be found: the Hong Kong Mass Transit Railway, for example, attains 75,000 per hour on a headway of two minutes at peaks, each eight-car train carrying 2,500.[3] RER line A in Paris attains about 65,000 passengers per hour on a two-minute headway.

The DLR offers an interesting example, having been built to a modest capacity, partly as a means of stimulating land-use development in London Docklands, rather than catering for then-existing passenger flows. However, development occurred more rapidly than initially envisaged, thus requiring the system to be rebuilt soon after coming into operation. Initially, single articulated cars with a capacity of 220 each offered eight trips per hour on the section between the City and Canary Wharf (1,760 passengers per hour). This was increased first by expanding frequency to 16 trains per hour and doubling train length (giving 7,040 per hour). If the headway were reduced to two minutes (i.e. 30 trains per hour) this could be further increased to 13,200 passengers per hour. The system is now being upgraded for three-car trains.

It is clear from the above that the time taken to clear a block section is a critical factor. This is determined first by the length of the section (re-signalling enabling introduction of shorter sections thus becomes one means of raising capacity), and second by the average speed through the section. This will be affected by presence of station stops, whose duration (‘dwell time’) may be minimized by setting platform and train-floor heights equal, and providing a large number of doors per car, of sliding or plug form. Lower platforms on some S-Bahn and many LRT lines may cause delay. Older trams for operation on both street and in tunnel often have steps adjustable for loading at various heights. On some automated systems, a platform edge screen with sliding doors to match those on the train (as for a lift) are fitted, preventing passengers from falling on the track, and also minimizing delays; newer conventional metro lines, such as the Jubilee Line Extension (JLE) in London and Singapore Mass Rapid Transit also have this feature.

Additional time owing to stops may also be reduced by adopting higher acceleration and retardation rates to/from running speed. New stock typically attains an acceleration of around 1.2 metres/second/second, although older stock may be much slower. Higher energy consumption may be required as a result.

It will be evident from the above that one means of avoiding the need to build new tracks to raise peak capacity is to improve train performance. This may increase energy consumption and the capital cost of new rolling stock, but will generally be much cheaper than new construction.

The above statements assume implicitly that trains possess identical performance. Where speeds and acceleration rates vary, peak flows may be much lower, especially where trains with urban performance characteristics and those for long-distance work are mixed on approach tracks to main-line stations. Particular problems arise where long-distance and stopping services are mixed over the

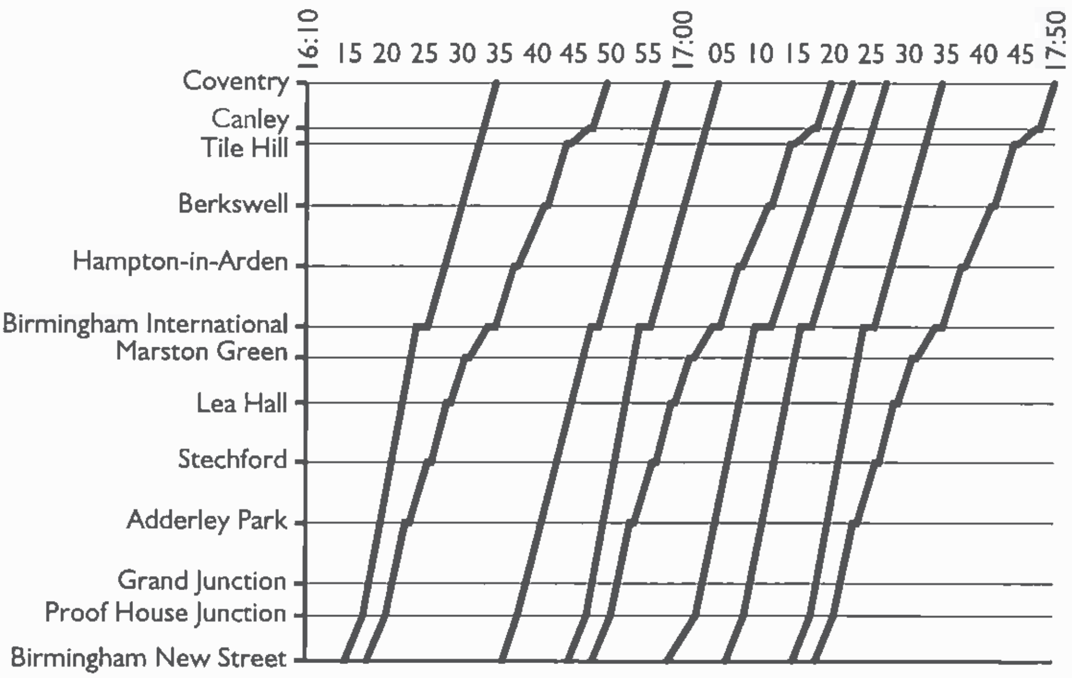


Figure 5.1 Time–distance graph of Birmingham–Coventry line. This route has been identified in several studies as one for capacity upgrading. The pattern shown is that which applied in the evening peak from Birmingham, summer 2000 timetable – by winter 2006/7 the number of trains from Birmingham in this period had increased to 11, but in the net increase was in the form of stopping trains terminating at Birmingham International, which would not obstruct paths between there and Coventry by faster trains (original graph provided by Railtrack).

same track section, a notable example in Britain being the double-track route between Coventry and Birmingham which accommodates the principal London–Birmingham services, cross-country routes and also local stopping trains. Figure 5.1 uses a time–distance graph to illustrate this.

Power supply and control

Direct current (d.c.) supply is typical, usually at 600–750 volts, via a third rail. This form of current and voltage is suitable for use on trains without rectifiers or transformers but requires the provision of substations at very frequent intervals, about every 3–5 km. For dense urban traffic, the cost of such substations is less than the extra on-train equipment, but for S-Bahn lines, especially those sharing intercity tracks, the 25 kV (25,000 V) a.c. system, favoured for long-distance movement, may be adopted as standard. Britain has standardized on this system for suburban routes in north and east London, Greater Manchester and Glasgow, whereas the London and Glasgow undergrounds, Merseyrail and the network south of the Thames are based on third-rail d.c. A third option is 1,500 d.c. by overhead supply, requiring about half as many substations as third-rail voltages, but using 750 V motors in parallel; this has been adopted for the Tyne and Wear Metro and also on the Hong Kong Mass Transit Railway.

Current to electric motors was traditionally controlled by the 'series-resistor' system (banks of resistances connected in series, which are successively switched out as acceleration occurs. A further sequence may be inserted by connecting the motors in series during the first stage of acceleration, and then in parallel).

The series-resistor system is very well-established and reliable, but involves a waste of energy as the resistances are heated (warming the passenger saloon is one use for this by-product in cool climates). The alternative solid-state electronic systems, used on all new stock, now represent an increasing proportion of the fleet total. In the acceleration phase, waste of energy is avoided and smoother performance given, of particular value where high acceleration rates are required. Provided that problems caused by high-frequency interference from the gating pulses to telecommunications equipment can be overcome, this system offers clear advantages. It also makes the use of regenerative braking (see below) much easier.

Electric urban trains are almost entirely of the multiple-unit form, in which the switchgear is carried on each power car, which picks up current direct from the third-rail or overhead, being operated by controls from the driving car. A high proportion of axles in the train can be motored where high acceleration is required, without reducing passenger capacity, as all motors and control gear are mounted under the floor. Some 'push–pull' working using separate locomotives linked to a control cab in the car at the opposite end of the train is also found, notably on SNCF lines in Paris and – using diesel locomotives – the 'GO Transit' suburban lines in Toronto.

Energy consumption

This is determined by two main factors.

1 Acceleration
Energy used is proportional to the mass of the train (including payload) multiplied by the square of the maximum speed attained.

2 Overcoming rolling resistance
Energy is used while accelerating and maintaining a steady speed, and is proportional to mass.

Aerodynamic resistance is of little importance at the fairly low speeds attained by urban railways, although critical for intercity modes. However, it is a factor in tunnels, where little clearance is provided between train and tunnel, creating a 'piston' effect. The need for frequent bursts of high acceleration, owing to close station spacing, may lead to higher energy consumption; high acceleration may itself impose a weight penalty, owing to the higher proportion of motored axles (up to 100 per cent for rates of 1.0 metres/second/second and above) thus required. Kemp indicates current good practice of about 0.030 kW/h per seat-km for electric suburban stock.[4]

The energy required for the acceleration phase is often the greater part of total consumption, especially where stations are less than 1,000 metres apart. Since it is proportional to mass, and urban rail stock is heavy relative to road vehicles, much of the expected energy advantage that one would expect vis-à-vis buses owing to lower rolling resistance disappears. Except where very high load factors are attained, energy consumption per passenger-km may be higher for urban rail than bus, as appears to be the case in Britain. A typical unladen weight per passenger space for a bus is about 125 kg, that for 'heavy' urban rail stock is about 250 kg.

Many techniques for reducing rail energy consumption are available:

1 A downward gradient

On leaving a station at about 1 in 20 (5 per cent) this aids acceleration, and retardation is likewise aided by an upward gradient on entering. This is used on some London 'tube' lines, but for subway or surface routes such frequent variation in vertical alignment is less easy to incorporate.

2 Reduced unladen weight of train

Older motor cars may weigh as much as 45 tonnes, but stock delivered from the 1970s onwards was much lighter. Use of stainless steel instead of conventional construction can bring the weight of a trailer car to about 25 tonnes. Further reductions may be obtained through aluminium or light alloy construction. More dramatic savings were obtained in London Underground's D78 District

Line stock, in which use of longer cars, and a lower weight per car, enabled a saving of 40 per cent, through a six-car train of 146 tonnes replacing a seven-car train of 242 tonnes. Using longer cars (within limits imposed by the loading gauge) enables the number of bogies to be reduced, in addition to savings from lower body weight. Where longer cars are not feasible, articulation of adjoining cars over common bogies achieves a similar gain, as in the Tyne and Wear Metro stock (an articulated set weighing 38 tonnes), or three-car sets as on the Hamburg U-Bahn.

The stock placed in service on London Underground's Central Line from 1993 uses large welded aluminium extrusions to give a weight of only 24 tonnes per car, all of which are motored.

However, when the high energy requirements for aluminium production are borne in mind, it is only for vehicles operating high distances each year that net overall energy saving is obtained.

A worrying development in recent years has been a shift towards heavier rolling stock, especially that used by TOCs in Britain. This has come about partly through the weight of additional features (such as air conditioning), but also less attention to the importance of weight as a design criterion. Ford[5] provides recent examples, such as an increase of 21 per cent in the weight of a four-car electric multiple unit (class 360 versus class 317) and 43 per cent in a three-car diesel unit (class 185 versus class 158).

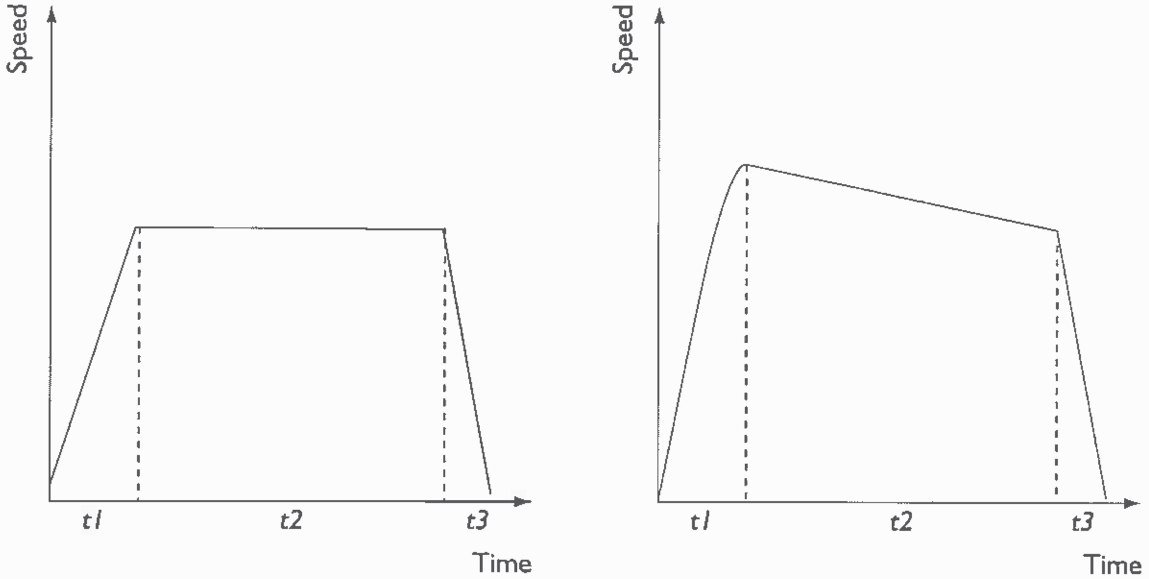
3 *Reduced length of train*

Some systems run shorter trains at off-peak periods. However, since the cost of electricity is determined largely by the peak (see below), this is probably more useful in reducing maintenance costs.

4 *Coasting*

By cutting off power after the initial acceleration phase, energy consumption can be reduced substantially as rolling resistance has to be overcome only during the acceleration phase, i.e. that shown as phase t_1 in Figure 5.2. Where constant speed is maintained during phase t_2 a trapezoidal speed-time curve results, but an irregular curve is produced when coasting is used, as shown in Figure 5.2(b). The area under the curve represents distance (i.e. speed × time). By using a higher initial acceleration rate the station-to-station trip may be completed in the same time, even with coasting.

Owing to the low rolling resistance on steel rail, loss of speed through coasting is marginal. For example, if two stations are 750 metres apart, and a train accelerates at 0.49 metres/second/second (m/s/s) and decelerates (phase t_3) at –0.75 m/s/s, then at a steady speed of 9.89 m/s during phase t_1 the trip takes 92.5 seconds. If the train is allowed to 'coast' during phase t_2, losing speed at –0.025 m/s/s, the same distance is covered in 98 seconds, an increase of only 5.5 seconds, or about 6 per cent – yet an energy saving of about 25 per cent would



(a) Simplified trapezoidal form, train running at steady speed after acceleration period

(b) Form in which a higher rate of acceleration is followed by a 'coasting' period

t1 – time during which train accelerates
t2 – time during which train runs at steady speed or 'coasts'
t3 – time during which train decelerates

Figure 5.2 Energy consumption curves for urban rail services.

be obtained. The additional journey time between stations might be offset by reducing station dwell time.

5 *Use of regenerative braking*

With friction braking, kinetic energy is converted wastefully into heat and noise. The electric motor of the train may be used as a form of retarder, generating current in this process. The simpler form is known as 'rheostatic braking', in which the current is fed into resistors to produce heat. This reduces wear and tear on the friction braking system, and the heat may be used inside the car where climate requires. Better use of the current may be made by feeding it back into the power supply for use by other trains, known as 'regenerative braking'. In theory, savings of up to 30 per cent or more in net energy requirements may be obtained, although in practice this may be limited by factors such as the acceptability of regenerated current at substations, and number of other trains on the system at any one time that can use the regenerated supply. This has limited the net gain in most cases to around 15–20 per cent, but with more comprehensive system design to make better use of regenerative motor characteristics from the outset, gains closer to the theoretical maximum may be expected. Regeneration has been made much easier through the use of solid-state technology, and is now general on new systems. Substations on the Sheffield Supertram are designed to accept regenerated current.

The combined impacts are considerable – for example, in the case of Hong Kong it was found to be worth retrofitting solid-state equipment in place of the series-resistor control initially fitted, resulting in energy consumption falling by 50 per cent, with a payback period of under seven years.[6]

In Britain, a more conservative approach was adopted by manufacturers and operators, and only with the introduction of the 'Networker' class 465 in 1992 and the Central Line stock for London Underground in 1993 did it become standard for new stock. Even so, much of the stock thus fitted was not initially operated in this mode, due to inability of the supply system to accept regenerated current. The 'averaging out' of electricity charges to operators through charges passed on by Network Rail also reduced incentives to regenerate current, although the revised track access charging structure from 2001 gave an incentive to operate stock fitted for regeneration. Only very recently (from 2006) has regeneration been used extensively (80 per cent of the suitably-fitted AC emu stock by May 2007[7]), giving potential savings of about 20 per cent.

6 *Other forms of energy storage*

As in the case of buses, energy may also be stored on the vehicle itself through high-speed flywheels or batteries, thus overcoming the problem of finding other trains to use regenerated current. Rail vehicles can incorporate the weight and bulk of such equipment more readily than buses, but conventional regeneration is probably more practical. Flywheels have also been used to store regenerated current at a substation on the Tokyo network, thus overcoming the problem of feeding it back into the main supply system.

Putting all these factors together, one can see scope for reducing energy consumption on some older systems by up to 50 per cent, mainly through a combination of reduced stock weight and use of regenerative braking. The main constraint in many cases is the rate of renewal of rolling stock. Longevity of rail stock makes it possible to aim for lives as high as 35–40 years (with mid-life refurbishment), but in consequence the rate at which energy-saving technology can be introduced is very slow. If energy costs rise, a more rapid rate of renewal may be justified.

Internal layout of rolling stock

For many years, a pattern of three or four sliding doors on each side of the car, with a high proportion of standing space, has characterized U-Bahn stock. Seating is often arranged longitudinally to assist this. In some recent London Underground stock a single-section sliding door has replaced the traditional double-leaf door (for example, D78 stock on the District Line), giving reduced maintenance costs without significant extra dwell time. High rates of acceleration necessitate a larger number of grab rails.

For S-Bahn services, a higher proportion of seats and fewer doors are usually provided. This difference can be observed in London by comparing the C69 Circle Line stock (with four sets of double doors per car to permit rapid loading), with the A60 stock on the Metropolitan Line to the north-west of London (with three sets of doors and 'five across' seating).

The sliding-door layout permits driver control, and with certain other modifications (notably mirror or closed-circuit TV display at platform ends) enables driver-only operation (DOO) to be introduced. In Britain, it has applied from the start on the rebuilt Glasgow Underground, Tyne and Wear Metro and Manchester Metrolink. It applies to a number of TOC suburban and all London Underground lines, and is being extended. On heavy rail systems, the driver remains responsible only for driving as such, and on new light rail systems all fare collection is likewise removed from the driver's responsibility.

Where double-deck stock is used, as in Paris, this takes the form of an entry vestibule over each bogie, with steps into upper and lower saloons, the latter within a well section of the chassis.

Signalling and control

A system simpler than that found on main-line railways can be used, owing to regular timetable patterns and lesser variation in speeds, braking distances, etc. The network of most U-Bahn systems is fairly simple, with few junctions and crossing points only at terminals or certain intermediate stations. S-Bahn may be somewhat more complex, owing to mixing with other rail traffic, but even in this case, tracks are often largely segregated from parallel main lines (between Euston and Watford, for example).

A semi-automatic sequence of trains can be programmed, with manual control as an override to handle exceptions and emergencies. An entire network can thus be controlled from a single centre, such as that on the Tyne and Wear Metro.

As on main-line railways, the basic signalling system is that of block working. A train may not enter a block section until the previous train has cleared it. Figure 5.3 shows this in simplified form. The train in section A cannot enter section B until the train in that section has entered section C. The minimum length of block section is normally at least equal to the minimum safe braking distance from the maximum speed permitted, where signals are of the simple 'two aspect' (red/green) type.

The presence of the train in a section is monitored either by a low-voltage 'track circuit' current fed through the running rails (a.c. where traction is d.c., and vice versa), or axle-counters to check train length at the beginning and end of each section (as in the recent Portsmouth area re-signalling scheme).

Complete automation of 'heavy' urban railways is possible. To date, this has mainly taken the form of automatic control of the train running between stations, with the driver remaining responsible for starting the trains, as on the Victoria Line in London and the Paris Metro. High-frequency pulses through

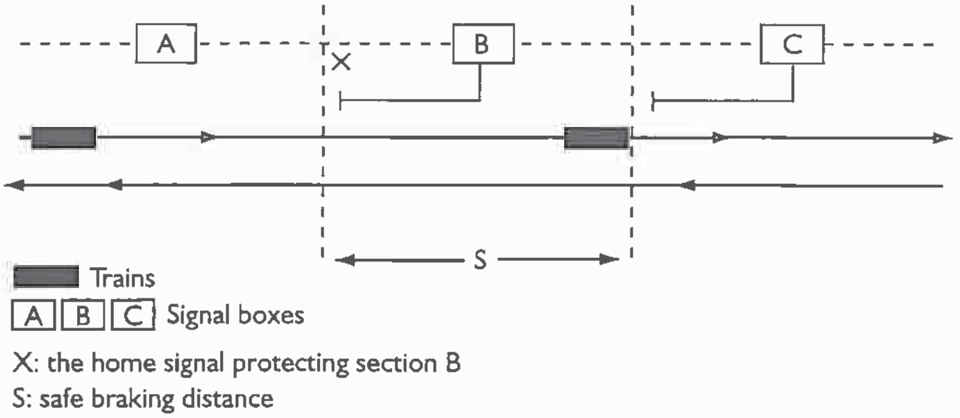


Figure 5.3 Block section signalling.

the traction supply determine rates of acceleration, maximum speed and retardation. A more efficient cycle can thus be followed – for example, to make the best use of opportunities for coasting described above.

French systems have pioneered full automation of heavy metros, beginning with the 'MAGGALY' system on Lyon's Line D in 1992. This also incorporates 'moving block' signalling (as distinct from the 'fixed block' described above), enabling spacing of trains related to braking distance for the speed currently performed. This was followed by the 'Meteor' line in Paris in 1998, as described earlier.

Information from track circuits and control centres can also be used to activate platform indicators, which display a real-time estimate of the number of minutes in which the train is due. This information has been found to be acceptably accurate and of considerable help to passengers.

Stations and interchanges

Much of the high labour productivity resulting from one person driving a train with over 1,000 passengers on a heavy transit system may be offset by the need to staff stations throughout the day. Ticket issue may be automated to a large extent by use of machines designed to cover all destinations and ticket types. Cash sales may be further reduced by pre-sale of travelcards and stored-value tickets, which are decremented on use. On some older systems, station staff are retained to handle some types of ticket issue and provide for emergencies, as in London, but complete destaffing is technically feasible, as the Tyne and Wear Metro has demonstrated since opening in 1980. Ticket inspection may be automated by use of barriers which read magnetically-encoded or contactless smartcard tickets, checking their validity, and if necessary re-encoding. If a complete 'closed-entry' system is used, then a record is obtained of both ends of the trip on the rail network and a deduction made from stored-value tickets to allow for distance/zones covered and rate applied (e.g. peak or off-peak), as in the case of the London Oyster card. However, there are some cases of a move back to fuller staffing, in order to minimize fraudulent travel and assist passenger security.

On some systems, a simpler approach is adopted, as on the DLR, where the passenger is required to hold a valid ticket on entering the platform, but not to pass through a barrier as such. Strict enforcement through random inspections is a necessary feature on such systems, backed up by penalty fares and fines. Reliable ticket-issuing machines, to ensure that all passengers have had the opportunity of buying a ticket before commencing their journey, are also essential.

In designing stations, it is desirable to minimize the number of changes of level, and make such changes as are necessary easier by use of escalators and lifts. The latter may also improve access for the disabled. Conflicting pedestrian flows should be prevented by use of separate passageways where possible. Well-lit passages and platforms, with no 'blind spots', are desirable.

Escalator width required for one person is about 60cm, 80cm with luggage, or about 1 metre to allow overtaking. In order to reduce energy consumption created by continuous operation, escalators may be activated by passengers breaking a photo-electric beam. Increased emphasis is now being placed on accessibility for elderly and disabled users, and provision of lifts in addition to escalators is now normal practice on new lines (such as the Jubilee Line Extension in London).

Passages and other entrances to the platform should be located at different points on successive stations so as to distribute passenger loadings throughout the train. If only one entry can be provided, the mid-point is best, or if two (or separate entry and exit), then at quarter-length from each end. The situation to be avoided if possible is the repetition of the same entry/exit positions at successive stations, which result in some parts of the train being overcrowded, others almost empty. The terminal layout is particularly unsuited to suburban operation, as boarding passengers may concentrate at only one end of the train, while seats at the other remain empty. Further arguments for through-running in place of terminal working may be found in Chapter 6. In some cases, platform width may be a constraint, notably on the deep-level tube lines in London, in that passengers from one train may not be able to clear the platform before the next has entered at peak times, and other aspects of the station layout may impose constraints (for example, at Victoria on the Victoria Line: substantial rebuilding of this station with an additional ticket hall, escalators and passenger circulating areas is now proposed).

Where different routes can be arranged to run parallel at an interchange, cross-platform passenger movement may be possible, as at Oxford Circus (Victoria/Bakerloo Lines) or Hammersmith (District/Piccadilly Lines) in London.

Track and structures

The cross-sectional area of rolling stock is determined primarily by the height of standing passengers, use of standard track gauge, and the clearance required for motors and equipment below the train floor. A square cross-section of about 3 metres is typical. Where power is supplied from overhead wires, a vertical clearance of about 4.5 metres may be required. More limited clearances may apply to light rail systems, and on automated systems such as VAL (Lille) a narrower vehicle width can be adopted to reduce tunnelling costs; the high frequency possible with unmanned trains provides capacity to compensate for the reduced size of each car. On curves, swept area is a function of radius, body width and length. Shorter vehicles, or tapered ends, may be adopted (as on street tramways) to reduce lateral clearances.

Surface tracks may be relatively simple, although use of continuously welded rail is now common as a means of ensuring a smoother ride. Conventional rail track with sleepers and ballast is generally used, although grooved rail is still used on street tramway sections of light railways, and concrete slab-base track is now used on new tunnel sections, to reduce subsequent maintenance costs and access delays. Tramways continue to operate through pedestrianized areas, and new light rail alignments of this sort are now accepted, as in Manchester. Bremen in north Germany was the first major city to pedestrianize its centre in the early 1960s, and the trams remain the only vehicles in major shopping streets. The swept area of cars is indicated by distinctively coloured paving.

Where land is not available, the cheapest alternative alignment is an elevated structure. This may also be a means of avoiding conflict on the same level with other modes. This solution was common on early systems – the DLR partly follows such an alignment first built in 1840 – and substantial sections remain in New York and Paris. However, the environmental effects of such structures are often criticized. Newer elevated structures, using concrete, are much less intrusive, and noise levels may be reduced by adoption of rubber-tyred stock, as on the Marseille and Lille systems.

An underground alignment became necessary in the largest cities because of the high land costs and environmental effects of elevated structures. Most systems are subways, i.e. usually aligned not more than ten metres below the surface and built on the 'cut and cover' principle, often along existing major roads. The first London lines, such as the Metropolitan, were of this pattern, but at an early stage opportunities at this level were restricted by existing railways, sewers and the Thames. The deep-level tubes such as the Bakerloo were therefore built by shield tunnelling, of about 3.5 metres diameter. Reduced cross-sectional area limits train capacity and room for motors, etc.

The depth required for access by escalator or lift, instead of a short flight of stairs, increases passenger access time, which will itself deter use especially for short trips. Hence, this alignment should only be adopted if unavoidable. A subway alignment, even if incurring more disruption during the construction phase, is generally preferable. Whereas the sub-surface metro in Paris is appropriate for short trips, the deep-level tubes in London require bus duplication for such travel. Londoners' habit of referring to all underground railways as 'tubes' is inaccurate in their own city, and even more so in respect of others, Moscow being the only other major example.

government's decision to drop support for schemes in Leeds, Liverpool, Bristol and Portsmouth.

Notes

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References and suggested reading

Frequent coverage of urban rail developments is given in *Modern Railways* and *Railway Gazette International*, with further coverage of light rail system developments in *Tramways and Urban Transit* – all monthly.

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