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DESIGN CONSIDERATIONS FOR RAPID TRANSIT

GEC Traction Limited

ENGLISH ELECTRIC AEI

Design Considerations for Rapid Transit

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A rapid transit system must be engineered as an integrated whole. No single element of the system can be taken and designed in isolation because of its pronounced interaction with the other elements—civil works, power supply, rolling stock and ventilation—and this paper attempts to emphasize the point that each factor must be considered globally and not parochially if the true overall system economics are to be correctly assessed.

In an endeavour to reduce the scope, we have firstly restricted it to dc rapid transit vehicles and then simply selected a few points which we consider to be of particular importance or interest. Nevertheless, the principles discussed can be applied to other forms of propulsion.

The various points which we have considered are set out in no particular order of merit under the sub-headings which follow. For one or two of these points we have endeavoured to give some idea of monetary value but it is dangerous to generalize, as basic costs and conditions vary widely between various organizations. Many factors demand extensive studies which will be applicable probably only to the particular rapid transit system under review.

System power supply

The value of substation output voltage chosen will have a marked effect upon the various parts of the system. In general, for a given system, raising the voltage results in fewer substations at greater spacings and a possible reduction in conductor cross section. These are now commented upon in more detail together with the effect that system voltage has upon the traction propulsion equipment.

The substations

While at first sight it would appear that the total installed capacity of the system is unaffected by substation output voltage, in practice higher voltages require an increase in the additional installed capacity which caters for substation outages. However, the fewer substations required for the higher voltage results in the more economical solution due to the reduction in substation buildings, associated land and switchgear.

Distribution

The two alternative forms of distributing the energy to the rolling stock are overhead and conductor rail.

A higher system voltage reduces the overhead conductor cross-section, always providing the mechanical requirements are met. After allowing for increased insulation weight this still results in a lighter supporting structure. For tunnel installations increasing the system voltage could result in additional cost in the civil engineering to provide the creepage required.

The conductor rail method of supplying current to the rolling stock has up to now been generally used in rapid transit systems, because of its relatively low cost and easier accommodation in tunnels. However, present environmental standards with regard to safety would require any future

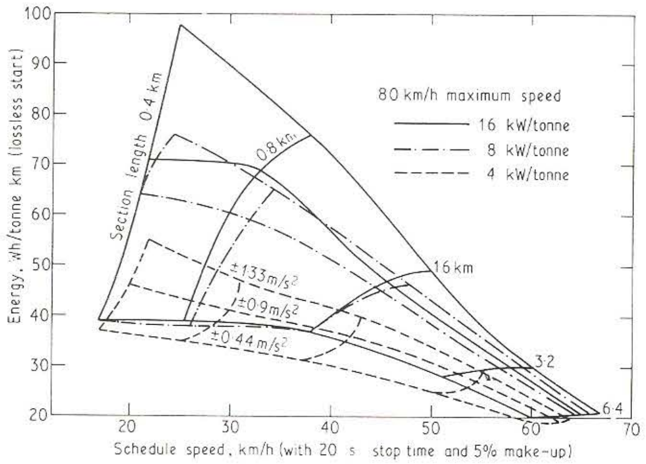


Fig 1

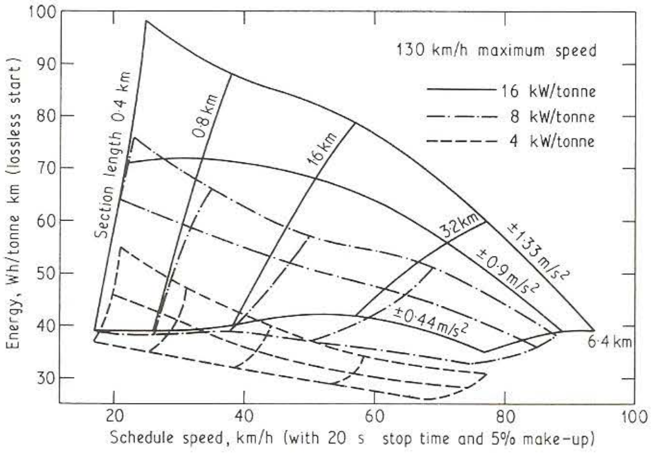


Fig 2.

Figs 1 and 2, Relationship of energy consumption and schedule speed for various section lengths, installed power and initial acceleration
Fig. 1. 80 km/h maximum speed
Fig 2. 130 km/h maximum speed

conductor rail installation to be fully guarded on open section at considerable cost.

From the foregoing, it will be seen that the proportion of tunnel to surface mileage of the system would be one of the principal economic factors in deciding which of the two distribution methods should be used.

Rolling stock

The effects of voltage change on the vehicle and its electrical equipment are not so clear cut and each case must be considered on its own merits. As the system voltage is increased, so the problems of insulation increase—particularly, perhaps, that of creepage. The effect is very marked at a system voltage of 3000 but at 1500—which represents the highest present thinking in rapid transit—the effect is not so marked. Normally there is likely to be some small increase in control apparatus space requirement and also in the traction motor size and weight, all of which make for some price increase. Conversely, however, using a system voltage of 1500 instead of 750 has enabled a reduction to be made in the vehicle overall control equipment size, weight and cost. This applies to an all-axles-motored scheme where, at the higher voltage, it is possible to have two adjacent vehicles semi-permanently coupled with the eight traction motors controlled in a series-parallel arrangement from a single equipment whilst still retaining an acceptable motor voltage. With eight motors in series it is, of course, essential to provide wheelslip detection and correction equipment.

Vehicle performance

The performance requirements of a railway vehicle for a given system are defined in the specification prepared by the railway authority or their consultants. The specification will describe a vehicle which will fit into one, or two, of the following categories:

Rapid transit
This will have short inter-station distances of the order of 0.8 km and will require a vehicle with high acceleration and braking rates to provide as high a schedule speed as possible. The maximum speed will be low, of the order of 80 km/h.

Suburban transit
This will have inter-station distances of the order of 4 km. Accelerating and braking rates must match the rapid transit trains with which they will have to inter run. Maximum speeds will be relatively high at 130 km/h.

Intercity transit
The trains that provide this service will run on segregated track from that of the other two types of system. Relatively low accelerating and braking rates are required, inter-station distances are long, of the order of 30 km, and high maximum speeds are specified, 160 km/h. These trains are usually locomotive hauled.

In arriving at the most economical solution for a particular system and specification, the manufacturer has to consider the various parameters, ie installed power, initial acceleration (percentage axles to be motored), energy consumption and equipment cost. This paper is concerned with the first two types of transit system referred to above, that is rapid and suburban transit. Figs 1 and 2 show the above adjustable parameters for the two types of system. Three values of installed power and three values of initial acceleration and braking are indicated. Fig 1 is for 80 km/h maximum speed and is therefore applicable to rapid transit while fig 2 at 130 km/h maximum speed is suitable for suburban duties.

The curves are used as follows—consider a rapid transit requirement of 34 km/h schedule speed and average inter-

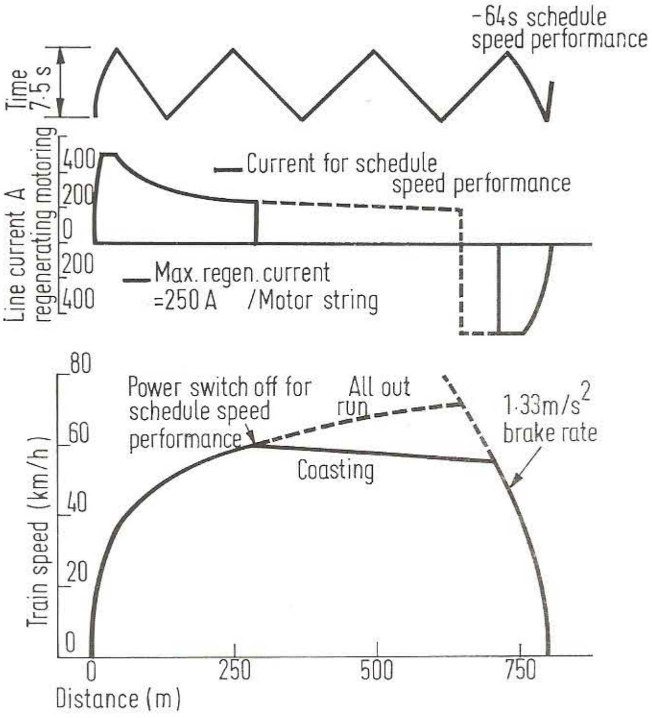
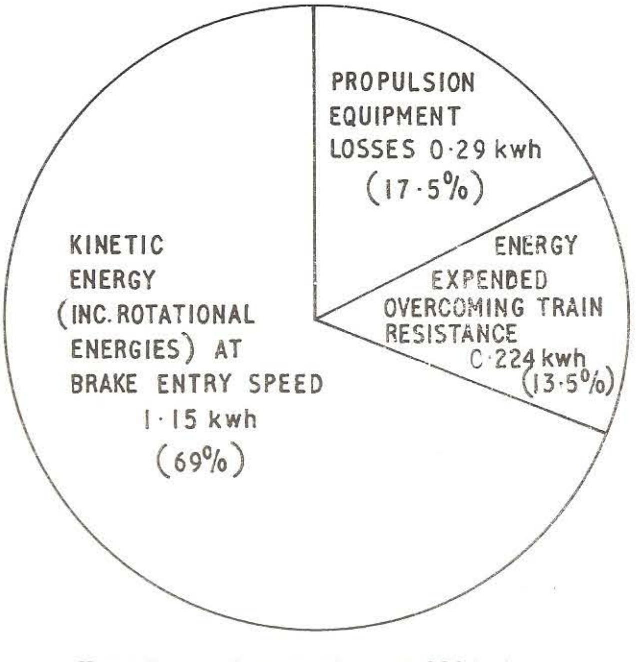


Fig 3. Relationship of speed, time, current and distance for rapid transit vehicle over 800 m. Vehicle weight 32 t, schedule speed 34 km/h, station stop time 20 s, make up time 5%

station distances of 0.8 km. It will be seen from fig 1 that an installed power of 4 kW/tonne will not meet the specified duty. At 8 kW/tonne, the performance can be met, but with 1.33 m/sec^2 which would require all axles to be motored, whereas at 16 kW/tonne installed power, the performance can be met with only two thirds the acceleration of the train with 8 kW/tonne and therefore only two thirds of the axles of the train need be motored. The respective energies used are 52Wh/tonne and 58 Wh/tonne. From this, it will be seen that the two thirds axles motored train uses more energy but should be cheaper in capital cost and it is in equating these two factors using the energy cost in the specification that the most economical solution is obtained.

A typical rapid transit vehicle performance curve is shown in fig 3 where accelerating and regenerated currents are given. The energies relevant to this performance are shown on the energy distribution diagram, fig 4.



Total Energy Consumed – 1·664 kwh
Car Weight – 32 TONNES
Average Section Length – 800 METRES
Excluding Auxiliaries.

Fig 4. Energy distribution diagram for typical rapid transit car

Vehicle braking

The kinetic energy of a rapid transit vehicle at the instant at which it enters braking can be seen from the energy distribution diagram (fig 4) to be 69% of the total energy supplied and to lose all of this in heat either by friction braking or rheostatic braking seems an unnecessary waste. Herein, then, lies a major economic factor for serious consideration. Unfortunately, the solutions are not easy and one must be quite sure in applying them that the total costs due to the additional equipment needed do not exceed the savings made on energy and brake maintenance.

Three methods of wholly or partially combating this wastage are:

1. regeneration of current directly into the line, to be used by other vehicles;
2. storage of the braking energy into a flywheel either on or off the vehicle;
3. use of some of the heat energy of rheostatic braking for vehicle heating ('waste heat recovery').

In cases where electric braking is employed, it is not always realized by operators that the effect on traction motor design can be quite considerable. Typically, for the same motoring duty, a motor designed for electric braking would have a continuous rating some 20% higher than that designed for motoring only and, what is more important to the machine designer, would have to develop some three times the maximum power, when braking at maximum speed, than is required during the motoring mode. The use of regeneration requires serious consideration be given to line receptivity which can be of a disappointingly low order when all the vehicles are equipped with regeneration equipment and the ideal of getting back all of the braking energy by this method is unfortunately just not attainable. In order to make the best possible use of the receptivity which is available, the more advanced chopper equipments have the ability to switch virtually instantaneously between the regenerative and rheostatic braking modes and thus are able to maximize on the receptivity available at all moments of time. This would clearly be out of the question with conventional control equipment. Such a system utilizing chopper techniques is described in full in the equipment section of this paper, the circuit described is a relatively new development and it will be appreciated that full fleet experience is not yet taking place. However, to obtain some indication of the reduction in energy consumption such a control circuit would have upon a typical rapid transit system, a complex computer programme was evolved which set up a train diagram over a typical route with train accelerating and regenerating current included. Nine different service patterns were identified for the system considered over a normal day's operation, the receptivity to regenerated current was the highest, as one would expect, during peak working with 32% of the motoring energy being supplied by the trains' own kinetic energy. The lowest receptivity was early in the morning and late at night when only 15% of motoring energy was supplied from regeneration. The overall saving for a typical day's running was to reduce the energy supplied to the train for propulsion purposes by 23%—a worthwhile saving especially for an underground system which would require less ventilation equipment, and hence a further saving in energy. The other side of the coin of course is that this equipment is more expensive than the conventional equipment it replaces.

Storage flywheel

The regeneration of energy into motor driven flywheels on the vehicle solves all problems of receptivity and a certain amount of work in this area has been done. But again, all the energy cannot be recovered because of machine inefficiencies. The associated problems of vehicle weight, space and cost of this on-board arrangement somewhat naturally leads one to consider flywheels off the vehicle at, say, each station location. Some preliminary calculations we have done on this seem to indicate that it could be an economic proposition, based on a thirty year life, but the fairly heavy capital outlay would probably deter most prospective customers. This scheme envisaged an extra conductor rail or 'station rail' laid over the braking and accelerating distances into and out of each station to carry the braking and accelerating currents. On acceleration, the flywheel motor, now acting as a generator, would be arranged to raise voltage progressively so that at the end of the accelerating portion of the station rail full line voltage is achieved and the vehicle transfers to the normal third rail.

An alternative to a motor/flywheel set is a motor/synchronous machine set which, on braking, would regenerate electrically back into the supply. This also demands heavy capital outlay.

Waste heat recovery

On vehicles fitted with electric brake, it can be shown that the use of waste heat recovery on systems with climatic conditions where heating is required does represent an

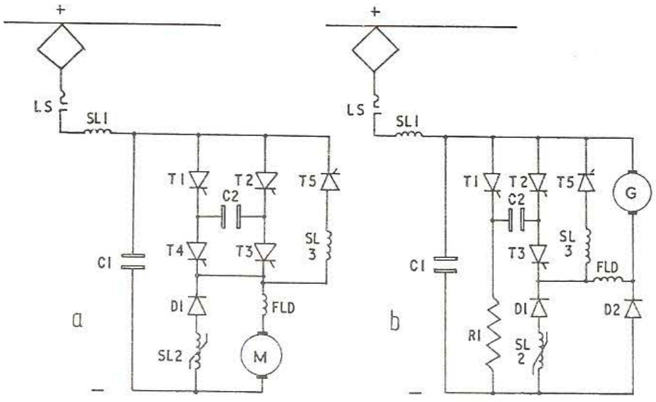


Fig 5. Schematic diagram of chopper circuit showing motoring and braking connections
a. Motoring
b. Braking

overall economy. As already shown on the diagram, fig 4, the kinetic energy represents 69% of the energy supplied to accelerate the vehicle. A high proportion of this would be dissipated in the braking resistor and hence available for coach heating. This would be equivalent to an average of 40 kW and therefore meets the requirement for vehicle heating in the UK.

The periodicity of heat release in rapid transit systems is high enough to make the scheme acceptable from a heating point of view.

From an economic point of view, this energy saving is partly offset by the higher cost of the control equipment, fans and enlarged braking resistor and the additional energy due to the increased weight and fan running costs.

Vehicle power equipment

It was shown in the vehicle performance section of this paper that, for a rapid transit train, the most efficient arrangement was obtained when all axles were motored. It was also stated earlier that system cost would be reduced as the system voltage increased. In general, it is true to say that the most economical solution will be found with the cheapest substation and distribution system, even at the expense of complicated and expensive train control equipment. An extreme example of this can be seen with the 25 kV ac schemes, and the 50 kV system now being discussed, where the vehicle carries the rectification equipment for the traction motors.

The rapid transit train is usually energized from a dc distribution system and therefore this section of the paper describes a medium voltage (1500 V) traction power equipment, with both 'chopper' and conventional types being considered.

Chopper control

The development of the chopper for controlling dc traction motors has now entered its second decade and therefore it is opportune at this juncture to briefly summarize the first ten years.

The increase in rating of thyristors to a level where it could be seen that the powers required by traction propulsion equipment were feasible, stimulated the interest of the electronic engineers in their traction application. Initially, these efforts were directed at controlling the motoring mode of the motors and making full use of the thyristor ability in the chopper circuit to give a smooth and efficient start.

As these techniques and the thyristors developed, it became apparent that the fast response of the thyristors in the chopper circuit was of the same order as the transient behaviour of the traction supply system and that, at last, a control element was available that would realize the ambitions of earlier traction engineers to regenerate the train kinetic energy. Furthermore, the 'dc transformer' effect of the chopper circuit, that is its ability to transform the reducing voltage from the traction motor as the speed fell to that of the line supply, meant that even more of the train kinetic energy could be regenerated than with previous control systems.

A chopper control system which incorporates the above features and represents the latest thinking in chopper circuits is described in Appendix I.

The circuit shown in fig 5 uses an 'H' configuration during motoring and a modification of the 'H' circuit during braking. This enables current sharing during acceleration to be carried out on a time basis and a combination of regenerative and rheostatic braking to be employed during retardation, the relative amount of each being varied during each cycle as required by the receptivity of the system to regeneration.

'Conventional' equipment

It is now generally accepted that the camshaft provides the most economical and reliable solution to this type of equipment. The circuits used are well known and it is therefore not proposed to describe them in this paper; reference was, however, made earlier to a scheme where, when all axles were motored, it was possible to control the eight motors of a two car unit with one control equipment.

Fig 6 shows a circuit where motoring only is provided, an example of which has just been delivered to the Danish State Railways for trials on their Copenhagen 'S' system. The scheme uses a parallel motor circuit which allows the motor currently in use on the Copenhagen system to be retained. A feature of the scheme is that only one power connection is necessary between the two motor coaches and this is under the protection of the linebreaker and overload circuit.

It is possible to devise a braking scheme from the above circuit, but the complication of motors in parallel during braking could be significantly simplified by having the four

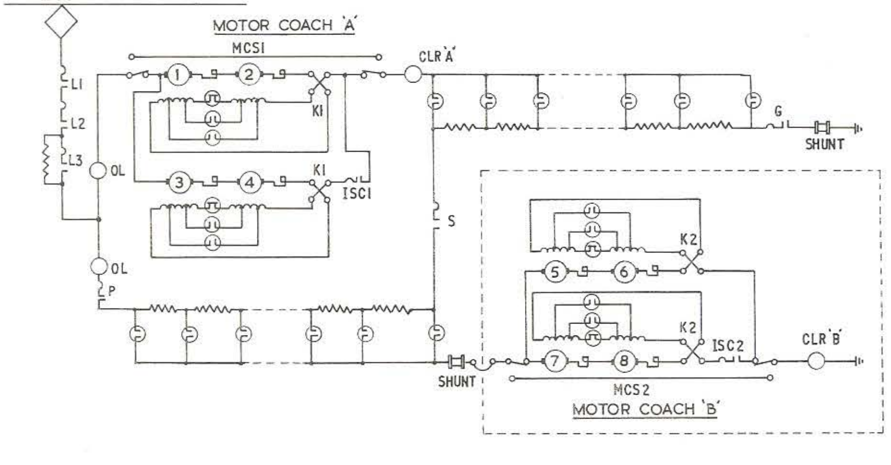
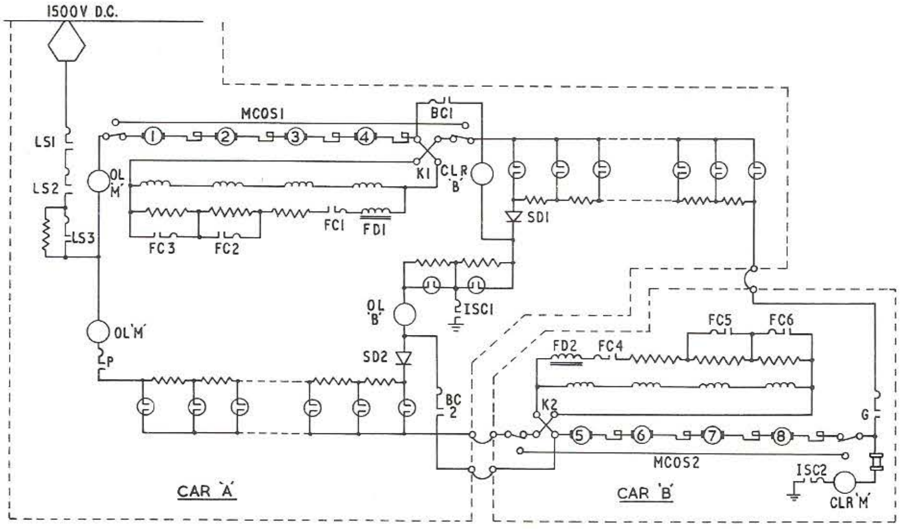


Fig 6. Conventional control equipment, motoring only, with one control equipment controlling two motor cars

Fig 7. *Conventional control equipment, motoring and rheostatic brake, with one control equipment controlling two motor cars*



motors on a motor coach connected in series. Such a scheme is shown on fig 7, where it will be seen that familiar 'cross-field' braking circuit is obtained at the expense of three 'protected' power connections between the two motor coaches.

The above two schemes present the most economical means of obtaining an 'all-axles' motored two-car unit. One disadvantage occurs during motor cut-out operation where, with these schemes, the remaining motors on the car with a faulty motor have to be disconnected.

Vehicle mechanical design

The vital factor here as affecting system economics is that of weight. The only advantage of weight is for adhesion but, in the rapid transit world, the solution to any problem of adhesion is not to increase weight but to increase the percentage of motored axles.

Weight is of much greater moment in rapid transit operation than for main line due to the very repetitive requirement of accelerating the mass and then destroying the kinetic energy in braking.

Most operators in their specifications now attach a penalty figure for weight, related directly to the energy cost taken over the life of the vehicle. The figure varies, of course, depending on the cost of energy to the system and other factors, but it is typically of the order of £1000 per tonne for a rapid transit system.

This process of weight saving can, economically, only be taken to the stage where lightweight building techniques start to cost more per tonne than the penalty figure, but this at least should help establish the type of construction which can be justified. In a world where energy costs are rising at a greater rate than the general inflationary rate, this would seem to indicate a progressive move toward ultra-lightweight techniques.

Vehicle auxiliary equipment

Air conditioning

Air conditioning is a feature of modern life with considerable sales appeal. When applied to rapid transit trains, however, it is absolutely vital to study the disadvantages as well as the merits. Apart from price, the technical disadvantages are real as the considerable size, weight and power consumption of modern equipments (typically 25 kW per car) have a very direct effect and complication on the vehicle design. Fitting air conditioning to trains which operate underground presents a further disadvantage in that the increased power consumption is dissipated in the tunnel. So, although the passengers are cooler, the tunnel is hotter or, alternatively, the ventilation system capacity has to be increased. If the feature helps to attract custom to the service then this, of course, could be a real point of advantage.

On the other hand in certain tropical areas where air conditioning is now almost a necessity, it is interesting to note that the energy consumption of such plant can equal that of the propulsion equipment.

Miscellaneous

Vehicle width and tunnel diameter

The London tube system is as good an example as one will find of minimum tunnel diameter and piston-fit vehicle, the origin being the basic one of cost of tunnelling.

For some of the newer metros under consideration, however, there has been some reappraisal of this fundamental concept and tunnels of fairly large diameter are proposed. The logic is that as the tunnel diameter increases, for a given passenger flow, the vehicle width increases and therefore the train length decreases. Associated with this, the station length also decreases. It is the cost reduction associated with these two items when compared with the extra tunnelling costs that decides the most economic solution. Calculations, the results of which are shown on fig 8, have indicated that the optimum is of about 5 m which is, in fact, the diameter proposed for Hong Kong.

Steel vs rubber wheels

This subject is interesting and controversial from the technical standpoint and perhaps even more so from an economic point of view because it represents one of the difficult cases where pollution and environmental factors have to be assigned a monetary value before any strictly logical economic appraisal can be made.

Reduction of noise is the one main factor claimed as an advantage of the rubber tyred vehicle. All other aspects, such as complexity and cost of running gear, complexity and cost of tracks, energy consumption, tunnel heating, etc, are against it. We have somehow to weigh all these disadvantages against the one potential advantage of noise reduction.

For example, if we consider the energy consumption factor only, it can be calculated that, for a typical rapid transit

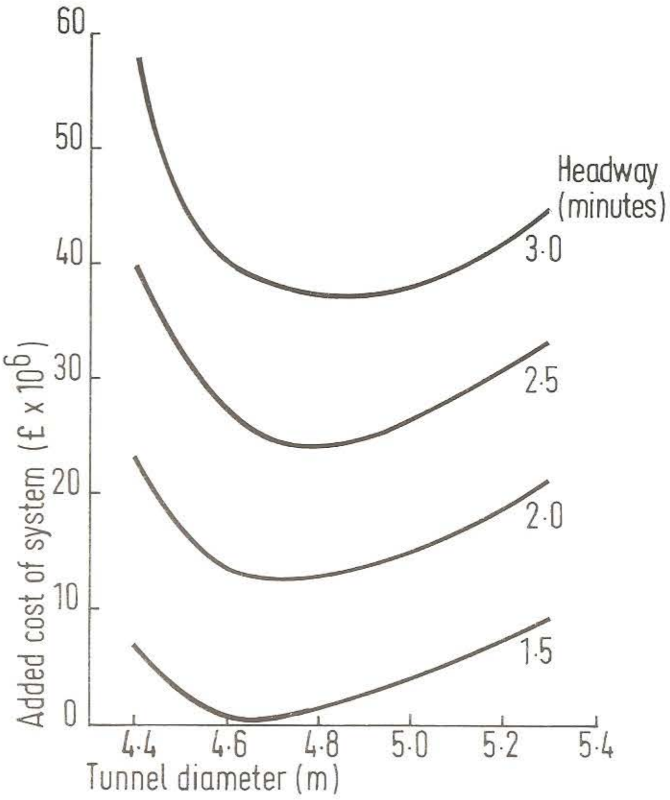


Fig 8. Effect of tunnel diameter on system cost for 25 km underground system with following characteristic: 60 000 passengers/h for structures; 47 000 passengers/h for trains; 26 underground stations; 34 km/h schedule speed; twin bored tunnel in amenable soil conditions

vehicle, the energy consumed in overcoming a rubber tyred vehicle's resistance to motion is of the order 1.1 kW h/car km, compared with 0.28 kWh/car km for a steel tyred car. This means that a 32 t rapid transit car operating on a system with 0.8 km inter-station distance and a schedule speed of 34 km/h will consume 1.66 kW h/car km if fitted with steel tyres (from fig 1) and 2.48 kW h/car km if rubber tyres are used.

These figures refer to surface operating stock and show that trains running with rubber tyres will consume some 49% more energy than the equivalent steel tyred train. Apart from the additional energy cost to operate the trains, those operators with extensive underground services will also be concerned with the effect of this increase in energy on tunnel temperatures.

Off train control

A system worthy of consideration is that of 'off-train' control with the minimum of control equipment being fitted to the vehicles and just one control equipment per track at each station. It will be appreciated that a train travels 20 metres to reach full voltage on the motors and that the accelerating equipment is only required during this period.

The system would comprise a station conductor rail, in addition to the normal supply rail, which would be energized from a thyristor bridge connected to the station three phase supply. Initially, the traction motors would be energized from the station conductor rail until full voltage is reached at which point the on-board switchgear would connect them to the normal conductor rail. The traction power for the remainder of the journey is obtained from the normal conductor rail.

On the broad basis that there are usually more powered vehicles than stations in a rapid transit system, there could be some economic merit in this system, but the subject has not been studied in adequate depth.

Conclusions

In the introduction, it was stated that one must consider each system on its own and not attempt to give a generalized opinion on the optimum design. This should remain the fundamental approach. Nevertheless, it would appear from the factors discussed in the paper that, for many applications, the optimum economic design would be a 1500 V dc single control equipment associating two or more motor cars.

However, local conditions, as indicated in the specifications for a particular railway, could require some modification of the above. For example:

1. inter running with existing main line system;
2. train headway for the specified passenger movement;
3. environmental considerations such as climatic conditions and noise pollution;
4. energy costs;
5. maintenance costs.

Developments are, however, in hand, as indicated in this paper, aimed at reducing the energy consumption of a railway system. The results of these are awaited with interest, but, in applying them to a practical situation, it will be essential to ensure that the extra capital cost does not exceed the cost of the energy saved.

Acknowledgments

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Appendix 1

Motoring (fig 5a)

The required accelerating current is obtained by applying line voltage to the motor for short periods of time at a constant repetition rate. The time during which voltage is being applied is called the 'on' time and this is variable over a wide range. The greater the 'on' time, the higher is the mean motor voltage, so that, to maintain the acceleration of the train constant, a signal from the motor current controls the rate at which the thryistor 'on' time is increased.

The chopper circuit for motoring is shown on fig 5a, from which it will be seen that line voltage is applied to the traction motor whenever there is a conducting path through the thyristor network formed by T1, T2, T3, T4 and C2.

The sequence of events is as follows:

1. Thyristors T2 and T4 are energized and motor current flows momentarily through T2, C2, T4 until C2 is charged to line voltage with its RH plate being positive.
2. Thyristors T2 and T3 are energized, causing line voltage to be applied to the motor.
3. When the motor has reached the required value, thyristor T1 is energized, so that the voltage charge on C2 causes thyristor T2 to be reverse biased and to cease to conduct. The circuit T1, C2, T3, remains in a conducting state until the commutating capacitor C2 is fully charged with its LH plate now positive.
4. Steps 1 to 3 above complete the first cycle of chopper operation. The second cycle follows steps 1 to 3 except that T1 replaces T2 and T3 replaces T4 and the charge on C2 is in the reverse direction.

Step 2 is commenced at fixed intervals of time to start the 'on' period, with step 3 being initiated to end the 'on' period of conduction. The time interval between steps 2 and 3 determines the mean value of the traction motor voltage.

It will be appreciated that the 'on' time cannot be reduced to zero, as is required during the initial accelerating period. To achieve this, two modifications to the above sequence of events are necessary. Firstly, direct application of line voltage to the traction motor, ie step 2, is dispensed with and steps 1 and 3 only are used. Secondly, shortly after step 1 (and step 3), thyristor T5 is energized, to divert some of the energy from the capacitor through the choke SL3 to the line.

Progression to the full firing sequence as described above is a gradual one under the control of the traction motor current.

Braking (fig 5b)

The components of the motoring circuit, as shown on fig 5a, are rearranged to give the braking circuit as shown in fig 5b by means of grouping contractors.

The braking scheme is based on the use of a weakened field at high speed braking, yet retains the advantage of the dc chopper's ability to store and let fly energy at low speeds (sometimes referred to as flywheeling), the storing being done in the inductance of the motor windings. The circuit also provides integrated regenerative and rheostatic braking at speeds below that at which full excitation of the motors is reached. The ratio of rheostatic to regenerative energy is assessed each cycle and may be varied according to the receptiveness of the line.

There are two basic states for the armature and field, one is the build-up of armature and field currents via T2 and T3 and the other is the generation of energy from the armature and field.

During a braking application from high speed, the motor and chopper may have to deal with three different conditions of field excitation. At high speeds, weak field control is used in which the T2 and T3 conduction times are small. In some conditions, T5 will also be operating to reduce the field current still further. Control over this range is usually on a constant power basis until the required brake rate is reached. As the speed starts to fall, the conduction times of T2 and T3 are progressively increased, until the full field is reached.

At medium speeds, the conduction of T2 and T3 is further increased, still keeping a constant braking power but with full excitation and an increasing armature current. Because the motor mean generated emf is less than the line voltage, the 'store and let fly' technique is used to transform the power into a higher voltage form which can then be returned to the supply.

At low speeds, the 'on' time of T2 and T3 is increased still further. This portion of the braking is at constant retardation. As above the 'store and let fly' technique is used, keeping a constant armature current until, at very low speed, the motors are virtually short circuited.

There are two ways in which the electrical energy produced can be absorbed. If the supply is receptive, the energy can be regenerated via diodes D1 and D2. In the event of the supply system being unreceptive, the energy is dissipated rheostatically via T1.

The sequence of events is as follows.

1. Thyristors T2 and T3 are energized, causing current to flow around the circuit consisting of the traction motor field and armature and thyristors T2 and T3. Commutating capacitor C2 is charged with its RH plate becoming positive via the circuit T2, C2, R1, D2 from the traction motor armature. At high motor speeds, where the field current is less than the armature current, the difference flows through diode D2 to the external circuit.
2. When the required armature current is reached, thyristor T1 is energized, causing T2 to be reverse biased and therefore cease to conduct. The field current now flows through T1, C2 and T3 until C2 is fully charged and T3 ceases to conduct. The field current now flows through D1 and associated choke SL2. The armature is now generating into the braking resistor R1 via thyristor T1.
3. If the line is receptive, as indicated by the line voltage, then T2 is energized immediately following step 2 above, so that the charge on C2 causes T1 to turn off. C2 is now fully charged via T2 and R1 so that its RH plate is positive.
4. If, however, the line voltage indicates that the line is non-receptive to generated current, step 2 is continued to the end of the cycle with the generated energy being dissipated into the train-borne braking resistor.

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