Electric braking performance of multiple unit trains

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Front cover:
The DART trains (Dublin Area Rapid Transit) are equipped with blended regenerative/rheostatic braking.

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1. INTRODUCTION

The operation of a transit system is always a compromise between two conflicting requirements, namely:—

a. high average speed, which not only improves the acceptability of rail travel to passengers, but also reduces the number of cars needed to run the service.

b. having low **energy** and **maximum demand** usage, to reduce the operating electricity costs.

Efficient usage of regenerative braking can be used to further the aims, by raising the voltage at the train power pick-up for the former and by the use of regenerative energy return for the latter. Electric braking also allows higher deceleration rates with more controlability but without increased brake maintenance.

There are two modes of electric braking, **rheostatic** and **regenerative.** The optimum choice of electric brake for a particular system depends upon the relative importance to the operator of a number of factors as well as local circumstances. The objective of this paper is to highlight some of the conflicting factors and to illustrate their inter-relationships.

2. TRAIN PERFORMANCE

Firstly let us consider the importance of braking in the overall energy consumption of a transit system.

The performance of trains can be simplified into three basic functions namely, accelerating, coasting and braking.

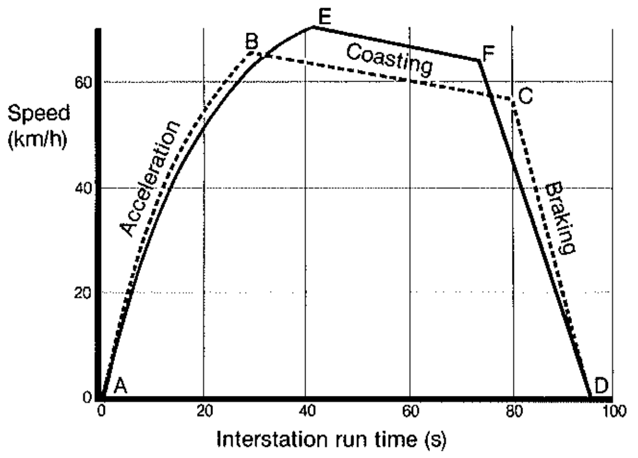


Fig. 1 Typical run curves (for the same schedule speed).

Each interstation run incorporates a period of accelerating and braking, with most **schedule speed** runs including a proportion of coasting. Fig. 1 shows a typical run curve for a particular speed. A **schedule speed** run time can be achieved in several ways ie either with high initial accelerating and braking rates (Points A, B, C and D) having a higher proportion of coasting, or with lower initial accelerating and braking rates (Points A. E. F and D) with less coasting.

Now, to a first approximation:—

Energy Input = Losses to train and frictional resistance + Kinetic energy available at brake entry.

Hence if the kinetic energy at braking entry is lower, ie a lower brake entry speed, then the energy input for the same schedule speed is lower.

Similarly for an increase in schedule speed, the brake entry speed is higher therefore requiring more energy input.

For any chosen **schedule speed,** the higher the initial accelerating and braking rates, the lower the energy consumption, ie compare points B and E for the kinetic energy at the power cut off point and points C and F for the kinetic energy at the brake entry. However, to obtain the higher acceleration rate, the current drawn from the supply has to be increased to provide more installed power thus requiring a higher peak demand.

The use of electric braking can help attain the higher schedule speeds by making better use of the available adhesion in braking as well as reducing the maintenance on the mechanical braking system created by the higher braking rates.

3. ACCELERATING AND BRAKING RATES

By maximising the accelerating and braking rates the energy consumption can be minimised. However, these levels of performance have an upper limit which again is a compromise between what can be achieved within physical constraints and initial cost.

To maximise the acceleration and braking rates the following aspects need to be considered:—

- adhesion levels
- equipment rating
- train weight
- traction motor characteristic
- percentage axles motored
- use of hump stations
- train resistance
- substation and supply network rating

and they have to be considered for the total system including any extensions which may be planned.

Adhesion levels — the higher the required adhesion level the more likelyhood there is of wheelslip and wheelslide damage to wheelsets, rails and traction motors. Under normal railway conditions the acceptable adhesion requirements vary between railway authorities, levels of up to 18 to 20% in acceleration and 9 to 15% in braking being typical.

Equipment rating — this is normally limited by thermal considerations ie on rating of equipment before a larger traction motor frame size is needed or more power semi-conductor devices are needed in the chopper.

Train weight — the lower the equipment and train weight, the less power is needed to accelerate the train, and hence the lower the energy consumption.

Traction motor characteristic — by increasing the power available at various speeds, the power rating capability of the machine is increased for higher accelerating and electrically-achieved braking performance. This may also require an increase in the propulsion equipment rating.

Percentage axles motored — by increasing the percentage of axles motored, and thus increase accelerating and electrically-achieved braking rates, the more power equipments are required necessitating an increase in initial cost.

Use of hump stations — many stations, particularly for underground stations, can be constructed with steep up-grade approaches followed by a steep down-grade on exit. This enables higher accelerating and braking rates to be achieved by the use of the train's own potential energy. This feature can often be achieved at no extra cost for the civil engineering contractor especially for tunnel sections.

Train resistance — this can be minimised by stream-lining the train sets. Also in tunnel operation, the closer the fit of the train in the tunnel, the higher the train resistance and hence higher energy losses. Conversely, the larger the tunnel, the lower the losses, but higher initial civil engineering costs are incurred.

Substation and supply network rating — the higher the system energy usage, the higher the continuous rating needed for the substation and supply network systems. Hence, if the total energy consumption can be reduced, lower rated trackside equipment is needed and the system can be designed accordingly. However, to reduce the energy consumption requires higher short time rated peak currents which have to be withstood by the trackside equipment as well as the traction propulsion system.

Thus, many compromise solutions have to be made between the minimisation of energy comsumption against increases in initial cost of equipment.

4. MAXIMUM DEMAND

For the economic running of a transit system, its **maximum demand** can be equally as significant as the energy usage in terms of total electricity costs. Maximum demand is a factor used by electricity supply authorities to determine their tariff charges for energy. **A user's maximum demand is a measure of the average power taken during a period when the supplier's demand is normally already high.** It is a measure of the **extra** plant needed to supply the extra demand, either specially installed or more expensive to operate, and thus the period is chosen by the supply authority.

Frequently a railway operator's maximum demand coincides with the supply authorities highest demand in which case the railway may have to pay a penalty on **all** the energy it uses. In this case it may be very advantageous to re-schedule the peak service either a few minutes earlier or later. Alternatively, any way of reducing the total energy during that period should be considered, such as extra coasting in the schedule, reduced coach heating, or maximising the use of regenerative braking.

Maximum demand is often confused with **peak demand** but they are in fact, totally different. Maximum demand is the average power (ie energy) measured during a particular period whereas peak demand is an instantaneous power figure. A higher peak demand (power in kW) gives a lower maximum demand (energy in kWH) for a particular schedule speed.

A major reduction in overall system energy consumption (and thus maximum demand) can be achieved by converting the kinetic energy the train has available at brake entry into electrical energy to supply the system.

5. BRAKING ENERGY CONVERSION TECHNIQUES

Before describing electric braking techniques, a brief description of the mechanical type braking systems traditionally used are outlined below.

5.1 Mechanical braking

Braking is simply a means of changing a train's kinetic energy from one form to another. Tread braking converts the train's kinetic energy, by the use of pneumatically applied shoe brakes, into heat which is then wasted into the atmosphere. As well as being wasteful of energy a large portion of the maintenance time and money is spent in changing brake shoes and re-profiling and scrapping tyres/wheels, the vehicles being out of service for a significant proportion of their lives. Also in hotter climates more air-conditioning is required in tunnels to extract the extra heat energy dissipated by the braking system.

Disc braking is another form of mechanical braking system where the kinetic energy is again dissipated mechanically but via pneumatically applied braking pads and wheel mounted cheek or separately mounted discs. The advantage of this type of mechanical braking is that it does not operate on the surface of the tread and thus the need for scrapping tyres/wheelsets is reduced. This form of braking system still wastes the braking energy to the atmosphere in the form of heat.

These two commonly used forms of mechanical braking systems are used to blend and supplement electric braking and provide fail safe operation under emergency conditions.

Electric braking techniques are utilised to reduce wear to the mechanical braking system and minimise maintenance as well as energy consumption and maximum demand costs.

5.2 Electric braking

Brake Entry Speed histograms, typically as shown in Fig. 2, can be predicted for particular systems by computing performance simulations of the train units using all the known system parameters including gradients, speed restrictions, station positions, train resistance, and train characteristics. For a typical application it can be seen that the mean brake entry speed is 54km/h under the schedule speed running conditions and 76km/h under the no-coasting running conditions having several maximum speed brake entries. Hence, the electric braking scheme needs to be designed to optimise electric braking for the schedule running conditions, but also be able to withstand the high speed maximum braking conditions which can be reached under all-out running conditions.

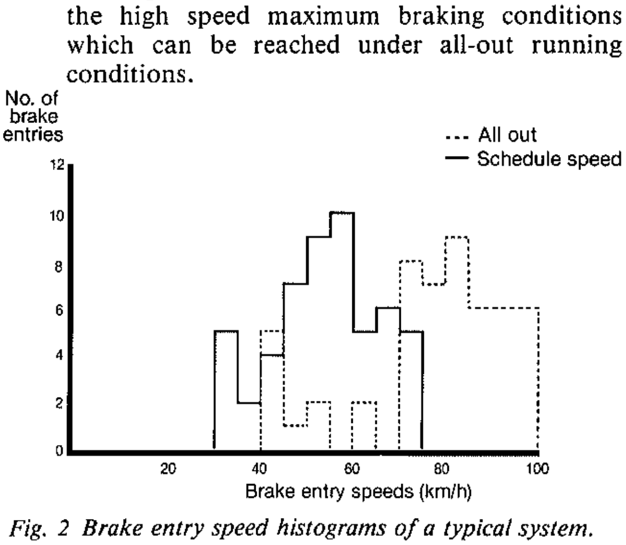


Fig. 2 Brake entry speed histograms of a typical system.

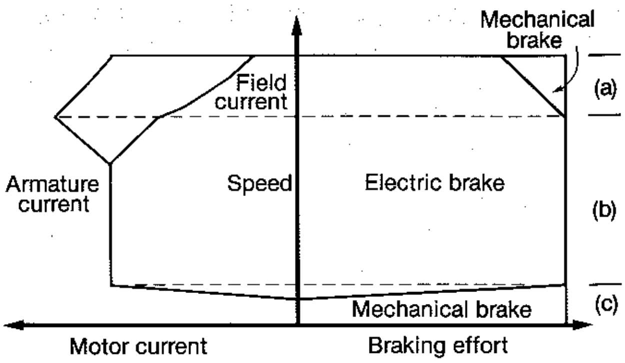


Fig. 3 Typical electric braking envelope.

As seen in Fig. 3, electric braking normally consists of three areas:—

(a) high speed braking, which may be limited by motor commutation or pinion stress levels on the armature shaft.

(b) medium speed braking, which may be limited by either equipment ratings or adhesion limits.

and

(c) low speed braking, at which the electric brakes fade.

For the high speed conditions, (a), the railway authority may require full blending with the mechanical brake to maintain the deceleration/braking effort constant or may prefer electric braking only, thus reducing the friction braking to a minimum and maximising the electric brake, but having a shortfall in high speed braking effort. Normally the former consideration is applicable with modern Automatic Train Protection (ATP) and Automatic Train Operation (ATO) systems which require constant deceleration rates from all brake entry speeds.

For the medium speed conditions, (b), friction braking is not normally required.

For the low speed conditions, (c), the electrical braking can no longer be maintained and is thus faded in a controlled manner, the friction brake being blended to maintain the braking effort without appreciable jerk. For series-controlled schemes electric brake normally fades from speeds between 15 and 10 km/h, whilst for separately excited braking schemes fade speeds of below 10 km/h can be achieved.

Tread braking rather than disc braking is more advantageous for the low speed braking blending duty since the wheel surfaces are roughened enabling better adhesion levels to be obtained between wheel tread and rail. A direct consequence is the reduced risk of wheelslip during acceleration as well as wheelslide in braking.

Until now no mention has been made of the two different types of electric braking namely, rheostatic and regenerative.

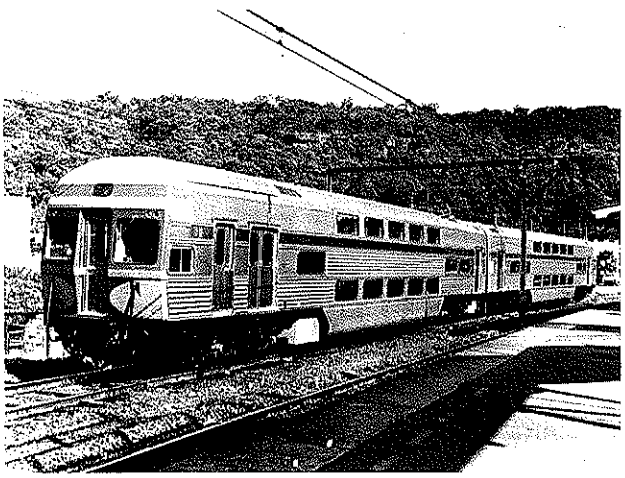
5.2.1 Rheostatic braking

During electric braking the traction motors are re-connected to act as generators. Under rheostatic braking the energy is still dissipated as heat, but through on-board resistances, and hence this provides a tremendous advantage to operators in reduced mechanical maintenance of the brakegear. There is not just a saving of man-hours in working on the brakegear and wheelsets themselves, but also the train can be released for revenue-earning service for much longer periods, having shorter maintenance outages.

On camshaft controlled trains the braking resistance is progressively taken out of the armature circuit as the train speed is reduced. On a chopper controlled train the braking current is maintained constant by the use of the chopper and series armature resistances to dissipate the motor voltages.

Energy dissipated in rheostatic braking resistances may not necessarily be wasted since it can be used to heat the passenger accommodation in cold weather by the use of **waste heat recovery** systems. The Tyne and Wear units have a system of waste heat recovery where the resistor banks are split on to each car of the articulated unit, the A end housing the acceleration resistors, the B end housing the braking resistors. A waste heat recovery system enables the heat produced by the on-board resistors to be mixed and blended with ambient air to a temperature which is suitable for heating the passenger saloon. An auxiliary heater is used to top-up heat if the brake resistor heat is insufficient. Indirectly, therefore, it reduces the total energy consumption of the train system, being a combination of propulsion and auxiliaries, which in this case includes the 1500V auxiliary saloon heaters, thus providing a double financial benefit in terms of overall energy consumption and maximum demand.

On a mixed train it is only economical to use waste heat recovery on the motor cars, the trailers needing to be heated by conventional means. Even so, experience has shown that significant benefits can be gained, these being more significant in the lower temperature areas of the world.



Multiple unit for inter-urban service in the New South Wales and fitted with regenerative brake.

5.2.2 Regenerative braking

Regenerative braking has long been the aim of multiple-unit fleet operators. Regenerative braking has been used in practice on camshaft controlled stock for over 50 years now, but because it can require skill on the part of the driver and also in time to set-up, it was only practical for vehicles braking on long inclines such as in New South Wales, Australia from the Blue Mountains to the coast. Recent developments with semi-conductor devices, however, have made it possible for regenerative braking to be fitted to rapid transit trains, which have frequent stops, thus making the maximum use of this stopping-brake energy to provide a high proportion of the power required for acceleration.

Operators with fleets fitted with rheostatic braking have grown accustomed to specifying **maximum electric braking** in their specifications for new rolling stock. Now that regenerative braking is available to them they are tempted to add **with maximum regeneration.** These two points at first appear to be similar, but in fact, they are partially contradictory.

During regenerative braking the voltage across the traction motors is limited by the supply voltage and thus to provide adequate braking at high speeds, where the powers involved can be several times the maximum motoring power, high currents must be generated or the additional voltage must be dissipated across a series armature resistance. Thus, a compromise needs to be made between the use of series armature resistances to increase the allowable motor voltage within the supply voltage limitations and the currents which can be maintained within the device rating of the chopper.

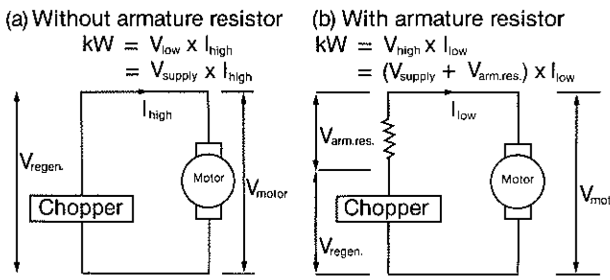


Fig. 4 Regenerative braking schemes.

With Reference to Fig. 4.

kW brake = Volts × Amps

Either (a) kW = Volts Supply × Amp High

or (b) kW = (Volts Supply + Volts Armature Resistance) × Amps Low

For option (a), if the current is increased, the chopper equipment ratings increase, involving larger devices or more strings of parallel power semi-conductor devices. For option (b), if the voltage across the motor is increased then a higher value of armature resistance (with its associated control equipment) is required for full electric braking requirements at maximum speed.

Seoul Subway Cars.

The Seoul Metro cars are an example of a regenerative only braking scheme without the use of series armature resistances. The air brakes are used to replace the regenerative brakes on loss of receptivity and blend at higher speeds where the regenerative brake does not provide sufficient braking efforts.

With present semi-conductor devices and traction motors, for full electric braking requirements at maximum speed, the preferred option is to allow the voltage generated to increase and drop the additional voltage across a series armature resistance, but maximising the current returned to the supply within the power semi-conductor device ratings.

The armature resistance is only kept in circuit if the traction motor voltage is above the supply voltage. For example from a top-speed full-brake entry the armature resistance is in circuit. As the train speed decreases, the power from the motors decreases and since the voltage across the supply and armature resistance is constant, the regenerative power, and thus current, must reduce. To optimise the regenerative current the armature resistance must be progressively shorted out thus reducing the power lost in the series armature resistance.

The stages of armature resistance are removed at speeds when the motor voltage equals the supply voltage plus the remainder of the armature resistance voltage drop, the last stage being removed when the voltage being produced by the motors equals the supply voltage.

Dublin Area Rapid Transit.

In the case of the Dublin Area Rapid Transit two car units, the braking circuits were chosen to ensure that electric braking in the motor car always takes preference over the mechanical brakes of the trailer. As much as possible of the available electric braking effort is offered for regeneration within the physical constraints applicable. A study was undertaken to determine the optimum number of series armature resistance stages for the most cost beneficial operation of the railway system. The study showed that two steps were an ideal solution. If more resistance steps were used then more energy would have been available for regeneration but the extra complexity would have had penalties in terms of first cost, maintenance, weight and volume.

Fig. 5 outlines the following criteria for the number of series armature resistor steps:—

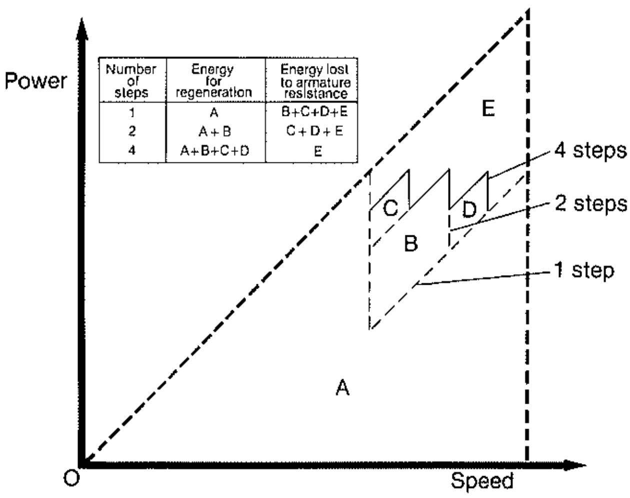


Fig. 5 Regenerative brake envelopes using series armature resistors.

For a single step of armature resistance

— a larger rated and heavier armature resistance is required to dissipate the energy created by the resistance (areas B, C, D and E).

— less regenerative energy (area A only) is available since more energy is lost in the series armature resistor (areas B, C, D and E).

— a single contactor and associated control electronics is required.

— there is a smaller initial equipment cost.

For numerous steps of armature resistance, say 4 steps

— a smaller rated series armature resistance and thus lighter in weight is required to dissipate (area E).

— a higher regenerative energy is provided (areas A, B, C and D) than with a lower number of steps option.

— four contactors and associated control electronics are required, needing more space and weight in the equipment case.

— there is a higher initial equipment cost.

5.2.3 Regenerative/rheostatic braking on chopper controlled trains

On chopper controlled trains the chopper controls the motor current to produce all the required braking effort within the motor limitations. Rheostatic operation of the traction motors is only used if the supply is non-receptive to the regenerated energy, ie the supply voltage is higher than a predetermined level, the energy being diverted into an on-board braking resistor on a chopper cycle-by-cycle basis. The supply voltage is constantly monitored so that the instant the supply becomes receptive, ie the supply voltage falls below a predetermined level, the chopper equipment reverts back from its rheostatic mode to its regenerative mode, thus maximising the energy return.

The Dublin Area Rapid Transit 2-car units are an example of a chopper controlled unit having fully blended regenerative and rheostatic brake.

A choice of either a full-time or a short-time rated rheostatic brake can be provided. A short-time rated resistor can provide say 2 seconds of rheostatic brake after which time if the supply is still non-receptive, the rheostatic brake will have sufficient capacity to allow the motor car mechanical brakes to replace the electric brake in a jerk-free manner. The short-time rheostatic resistance is additionally protected by an electronic temperature detection system which shuts down the electric brake on excessive outlet air temperature from the braking resistors.

6. RECEPTIVITY AND REGENERABILITY OF RAILWAY SYSTEMS

In theory, a large part of the energy, which is used to accelerate the train, could be returned to the supply during regenerative braking since the losses from windage, mechanical friction and train resistance are only a small part of the total. Practice is very different, however, since energy can only be regenerated if the supply is receptive.

Fig. 6 shows an energy against time curve for a typical interstation cycle including the train's own auxiliary loading.

It can be seen that the period during which regenerated energy is being offered is only a small proportion of the total time, approximately 12% in this example.

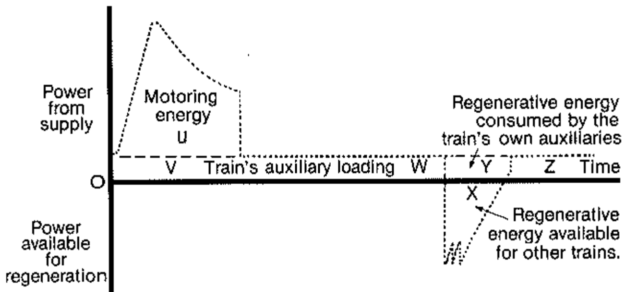


Fig. 6 Typical power consumption requirements for a regenerative chopper controlled train.

The **receptivity** of a system is defined as:—

$$\frac{\text{energy actually regenerated into the system}}{\text{energy available for regeneration.}}$$

The **regenerability** is defined as:—

$$\frac{\text{energy actually regenerated into the system}}{\text{energy used in motoring.}}$$

Both receptivity and regenerability are used to define a system's suitability for regeneration.

With reference to Fig. 6, the receptivity and regenerability of a system is based on three types of energies.

(i) variable load — ie when trains accelerate (Area U).
(ii) base load — ie train auxiliary loadings (Areas V, W, Y, Z).
(iii) regeneration load — ie when trains brake in the regeneration mode (Area X, Y)

Areas X and Y together are the maximum theoretical regenerative energies available from each train set. Area Y is used to supply the train's own auxiliaries, Area X is the regenerative energy available for other train sets to use. The proportion of the available energy consumed by other train sets will vary depending on the type of service being operated, the interval between trains and the size of auxiliary loading such as air-conditioning.

By simulating the whole railway network of trains the receptivity and regenerability for various headways on the system can be computed. Fig. 7 shows the results of computer simulations for receptivity of various headways on an intensive all-axles motored system. For an all-axles motored vehicle the full regenerability can be as high as 60%. This together with a 2 minute headway receptivity of say 83.5%, taken from Fig. 7 could lead to a nett saving of 50% of the motoring energy. Thus the regenerative braking will enable the trains to run the same schedule speed with half of the motoring energy input from the system when compared with non-regenerative stock. There is also a very significant saving in maximum demand as well as in perceived energy consumption.

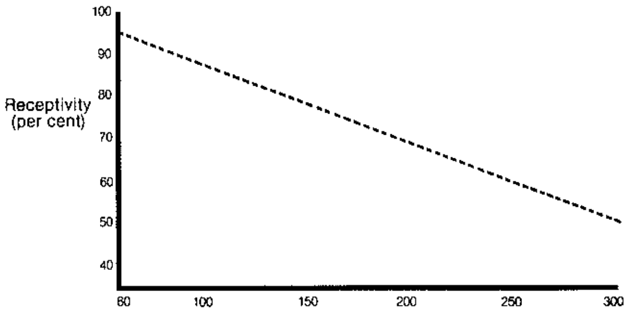


Fig. 7 Computer simulated receptivity study.

7. BRAKE BLENDING

The previous section describes the situation of all-axles motored stock. The energy savings for rolling stock with a lower percentage of axles motored are reduced since there are additional losses to the non-motored axle air brakes but the savings are still significant for half-axles motored stock and above, in particular if preference-type braking schemes are applied as described below.

Electric braking can be used on trains which include a mixture of motor cars and trailer cars in their make-up. The usual practice is to blend the electric brake on the motor cars with the mechanical brakes on the same cars, the trailer car having mechanical braking only, each car braking its own weight. Priority is given to the electric brake on a motor car only basis. However, the latest schemes maximise electric braking further, the motor cars electric brake also retarding all or part of the weight of the trailer cars.

Electric braking can be blended by two methods:—

1. fully blended — if at any speed there is any shortfall of electric braking, when compared with the total braking demand, the mechanical brake is blended with the electric brake to maintain the deceleration and braking effort.
2. partially blended — the electric brake provides the full braking effort demanded, but on the loss of electric brake at fade or if the electric brake fails to build up to the required level, the mechanical brakes provide full braking effort.

The control of the braking schemes can be divided into two main categories namely, digital and analogue.

7.1 Digital Control

For digital control systems the electrical control circuits usually comprise of two or more train wires, being connected throughout a train, which are energised and de-energised by means of cam-switches to apply and release the brake on all vehicles simultaneously. This form of control permits the brake to be graduated 'on' and 'off' in steps and may be used when the brake is to be operated from either a driver's brake controller or a combined traction and braking controller.

Fig. 8 shows an example of the digital type of control scheme which has been supplied to Dublin Area Rapid Transit which incorporates a '7 + 7' scheme on each married pair of motor and trailer cars. The train has 13 steps of service braking and so as to maximise the use of electric brake the four train wires are energised/de-energised in sequence as shown noting that the first six notches are electric only, providing full motor car electric braking in notch 7. Notch 7 to 13 have full motor car electric braking, the trailer car mechanical braking being progressively increased.

Brake Notch	Train Wires				Braking effort	(x proportion on car weight)
	1	2	3	4	MC	TC
0	x	x	x	x	0	0
1	x	x	o	x	1/7th	0
2	x	o	o	x	2/7th	0
3	x	o	o	o	3/7th	0
4	o	x	o	o	4/7th	0
5	x	x	o	o	5/7th	0
6	x	x	x	o	6/7th	0
7	o	x	x	x	Full	1/7th
8	o	x	x	o	Full	2/7th
9	o	o	x	o	Full	3/7th
10	o	o	x	x	Full	4/7th
11	o	x	o	x	Full	5/7th
12	o	o	o	x	Full	6/7th
Full service	o	o	o	o	Full	Full

x denotes energised
o denotes de-energised

Fig. 8 Brake notching sequence on the Dublin Area Rapid Transit Train Sets.

This sequence enables trains requiring some holding brake, say notch 4, to be braked all-electrically on the motor car thus making best use of the electric braking capability.

The deceleration rates for each braking notch are shown on Fig. 9 showing the effect of load weighing.

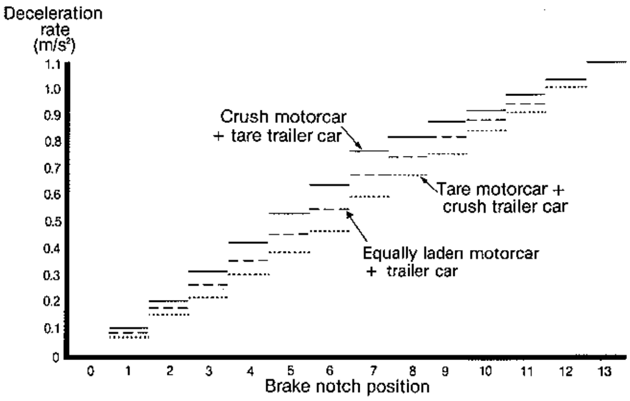


Fig. 9 Deceleration rates on the Dublin Area Rapid Transit Units.

7.2 Analogue Control

In the case of analogue systems, the electrical control is usually by means of a wire connected throughout the train to form a continuous loop to which a pulse width modulated (PWM) signal, or variable current is applied to operate the braking system. This arrangement provides stepless control of the brake and is normally adopted when the traction equipment requires the same type of control, the two systems being operated from a combined braking and traction controller.

The following example provides a method suitable for the analogue control of a 6 car train set having 4 motor cars and 2 driving trailer cars. The braking control system ensures that at all times the electric brake takes preference over the mechanical brake, but if there is any shortfall in braking performance, this is made up using mechanical brakes, the mechanical braking duty being shared equally between all cars in relation to their weight. To achieve this aim a closed loop system similar to that shown in Fig. 10 could be used.

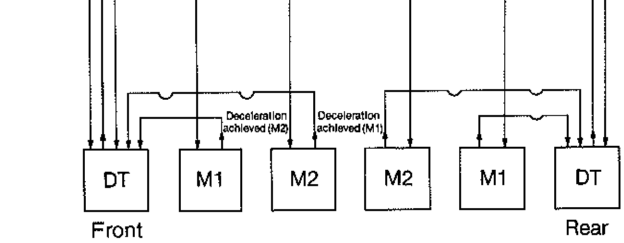


Fig. 10 Brake control system.

The deceleration demand from the driver or ATO system is first compared against a feedback signal which is proportional to the sum of the decelerations achieved on all 6 cars as measured by the leading car microprocessor. The error signal generated by this comparison is amplified and subjected to limits to produce a **deceleration required** signal. This signal is then encoded as a PWM signal for transmission down the train to each car. The duty cycle of the PWM signal is allowed to change linearly from 5% to 95% and is encoded so that a duty cycle of 5% to 50% gives zero to full electric brake but a duty cycle of 50% to 95% gives zero to full additional air brake.

The 'deceleration-required' signal is first decoded on each motor car by the microprocessor control system and then modified according to vehicle weight to produce an electric brake demand signal for the chopper servo system and, if the input PWM duty cycle is over 50%, an air brake demand signal for the air brakes. Each mircoprocessor control system calculates the total deceleration achieved by that vehicle, ie the sum of mechanical and electric braking achieved, and passes this data back over an inter-car wire to the nearest driving trailer again using PWM techniques.

The driving trailer car at the rear of the train set receives the deceleration achieved on its two neighbouring motor cars and sums these with its own deceleration achieved, if any, from the mechanical brakes. The resultant summed signal is then transmitted to the leading driving trailer car.

The leading driving trailer car receives the deceleration achieved of its two neighbouring motor cars (and the three rear cars via the rear driving trailer) and sums these with its own deceleration achieved. The resultant summed signal is now equal to the deceleration achieved on all 6 cars and forms the feedback signal to control the deceleration-required signal.

When the driver or ATO system starts to demand a particular deceleration rate the feedback signal will be zero and hence the 'deceleration-required' signal ramps to the maximum. The system then brings both the mechanical and electrical brakes into operation on all the cars. As the electric brake is established on the motor cars, the feedback signal will start to increase in value and so reduce the deceleration required signal. Once electric brake has established on all motor cars, the deceleration demand signal will reach a balancing value.

If this balancing value is below the mechanical brake threshold, ie 50% PWM signal, then all braking will be electric. When full electrical brake has been reached on all motor cars and the driver or ATO system still requires more brake, then the deceleration required signal will increase over the mechanical brake threshold level and so mechanical brakes will be applied on all 6 cars. The mechanical brake will be fully blended with the electric brake on the motor cars up to the maximum braking levels allowable.

8. BRAKING ENVELOPE

Electric braking is a complex subject but Fig. 11 shows in diagramatic form how the braking power is typically dissipated by a chopper controlled stock.

Some railway authorities may consider increasing braking rates, say from BR1 to BR2 to achieve a higher schedule speed advantageous in terms of minimising energy consumption. However, increasing the braking rate will, in fact, reduce the amount of regenerated energy, since the saving of energy input during motoring is small compared with the extra braking energy which is dissipated in the mechanical brakes unless the requested adhesion level on the motor car is increased (which in turn increases the likelihood of wheelslide). By similar means the effects of other changes, such as motor characteristics, the number of armature resistor steps, motor commutation limits, adhesion levels etc can be compared.

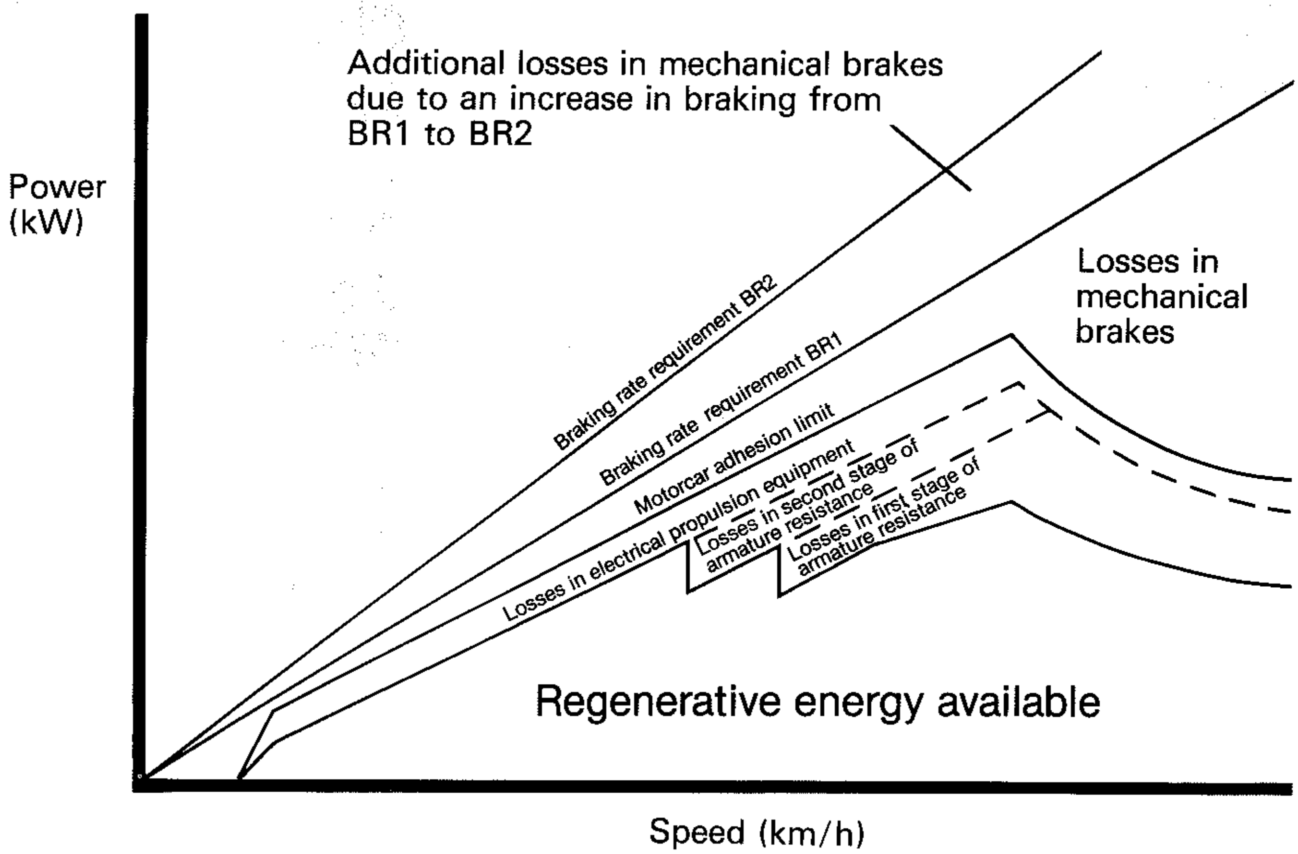
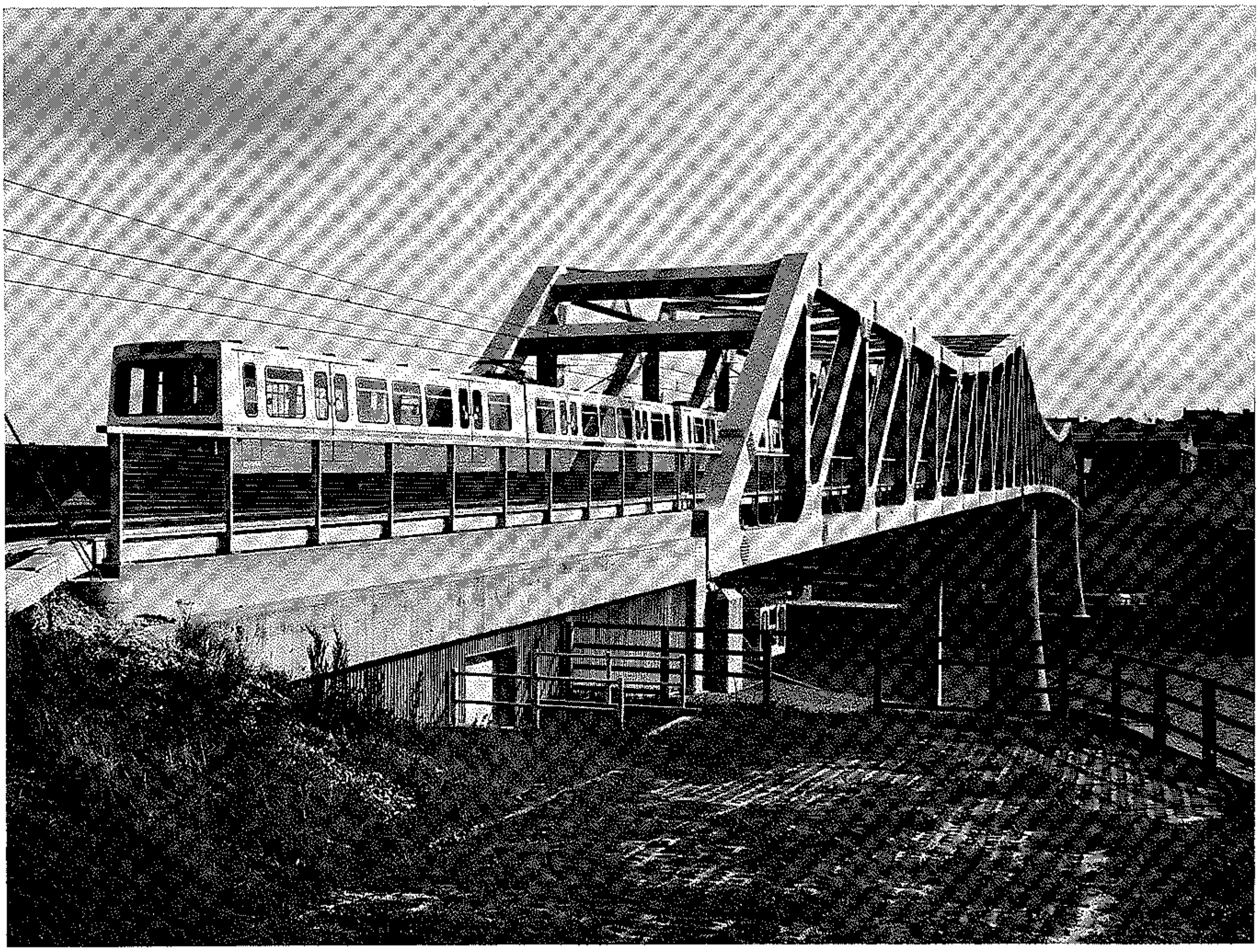


Fig. 11 Typical braking power envelope against speed.

9. CONCLUSION

The development of power semi-conductor devices and microprocessors has provided the technology to make full use of converting the train's kinetic energy in electrical power during braking. The efficient use of this available brake energy can be fully utilised to reduce the overall energy consumption and maximum demand of a railway system and/or improve the train performance at similar energy input levels from the supply within the limitations of the variables involved.

Electric braking has also provided the means for increasing the times between maintenance outages thus enabling the railway to be run more efficiently.



The Tyne & Wear Metro cars are equipped with rheostatic braking and waste-heat recovery for saloon heating.

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