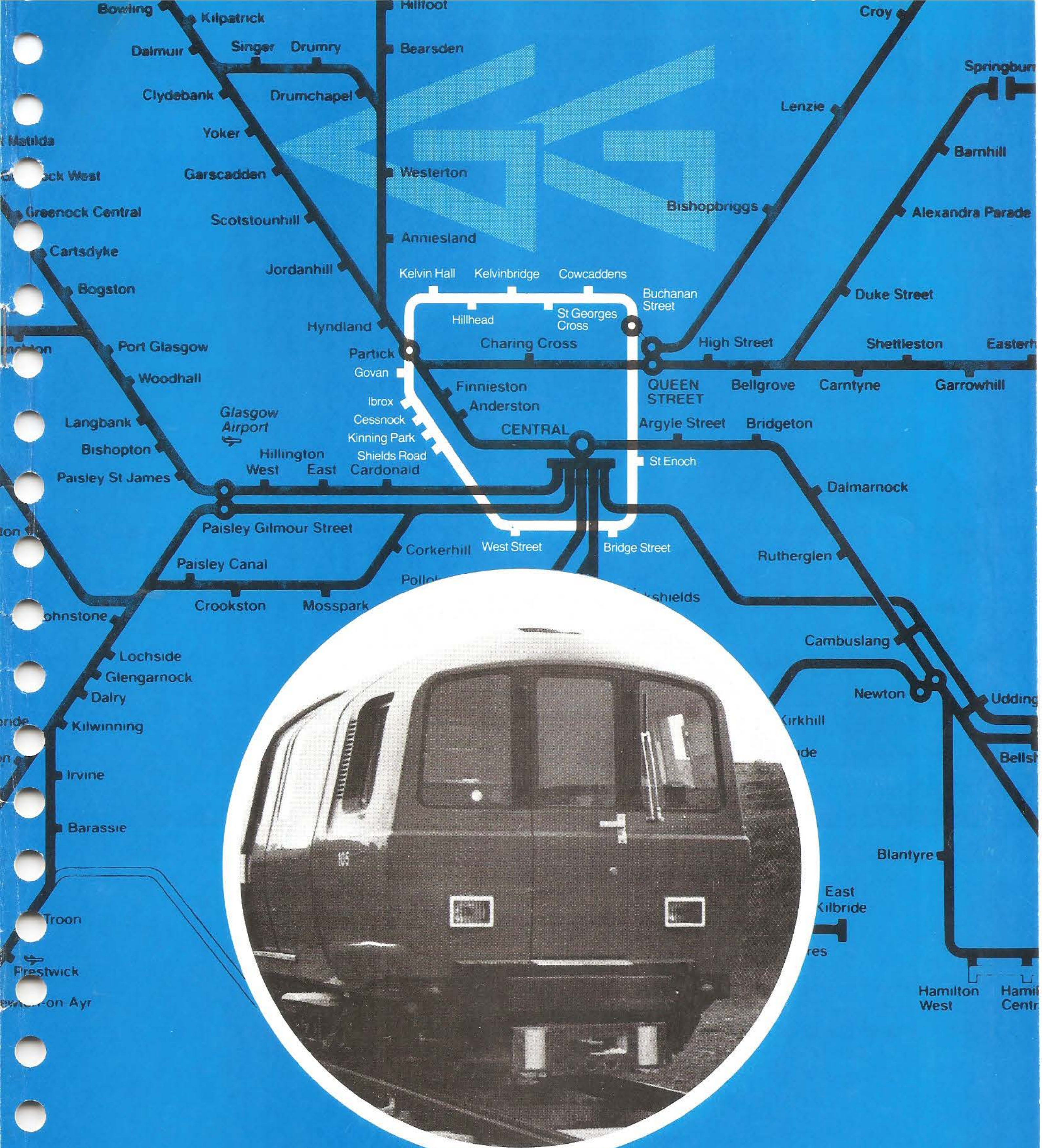


Equipment for

GLASGOW UNDERGROUND

GEC TRACTION

GLASGOW UNDERGROUND

The Glasgow subway was opened to traffic in 1897 as a cable hauled railway and was converted to electric operation in the 1930's but still using the original rolling stock. These original vehicles in fact continued in service until the late 1970's by which time a decision had been taken to completely refurbish and rebuild the entire railway including the provision of new rolling stock. A total of 33 new cars were ordered from Metro-Cammel by the new operating authority, the Greater Glasgow Passenger Transport Executive. The electrical propulsion equipment in turn was ordered from GEC Traction, one of whose predecessors (Metropolitan Vickers) had provided the electric equipment for the conversions carried out in the 1930's.

With the introduction of the new rolling stock the opportunity was taken to introduce a number of changes and improvements:–

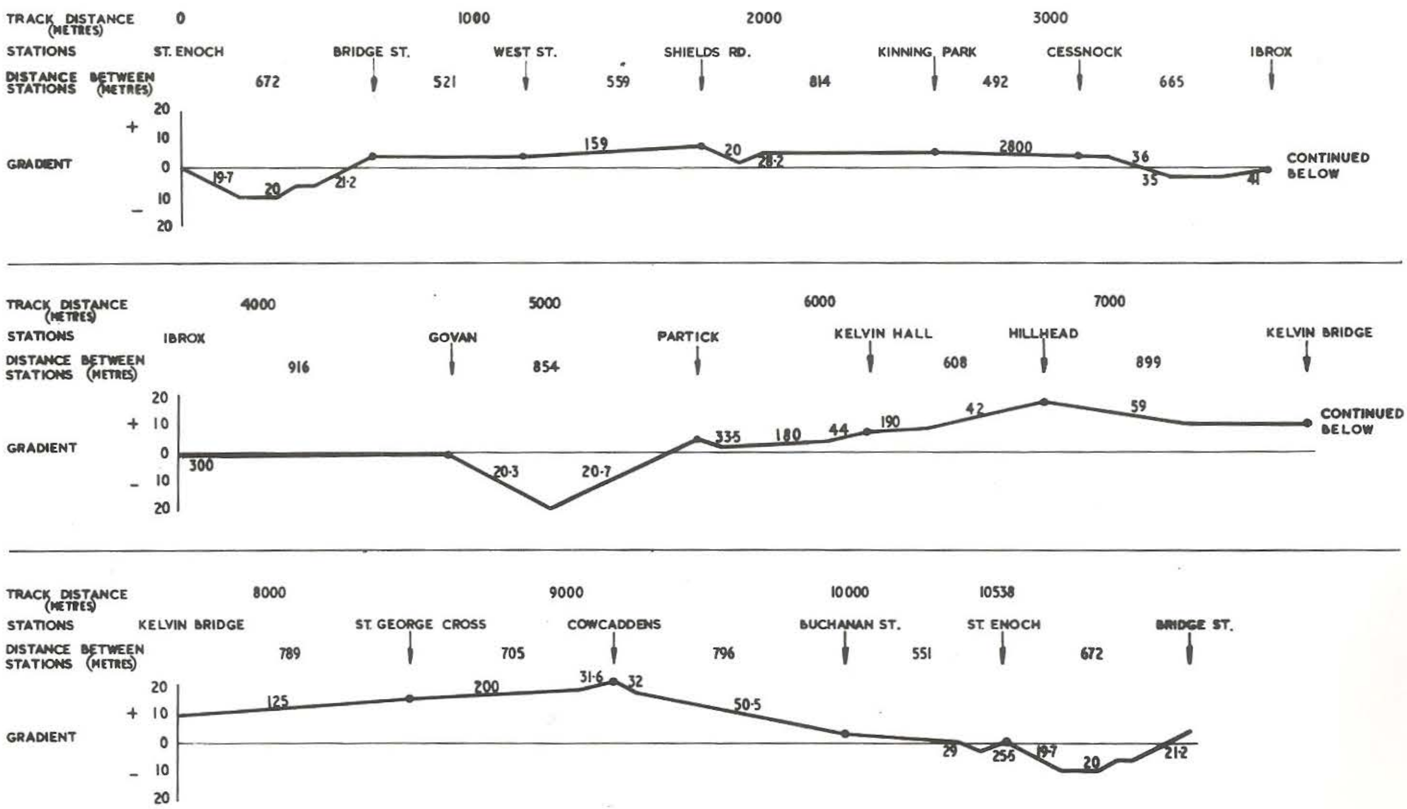
- the new cars were to be capable of operating singly, in pairs or in consists of three – the previous service was provided by a single motor car hauling a single trailer.
- as a result of the higher power to weight ratio a faster service could be provided – giving a complete circuit of the 10.5 km route in 24 minutes (including 2 minutes make-up time).
- automatic operation (which includes auto-docking) was introduced to permit one-man operation.
- the accuracy of auto-docking also made it practical to run 3-car trains even though many of the severely graded platforms could only just accommodate the length of such a train.

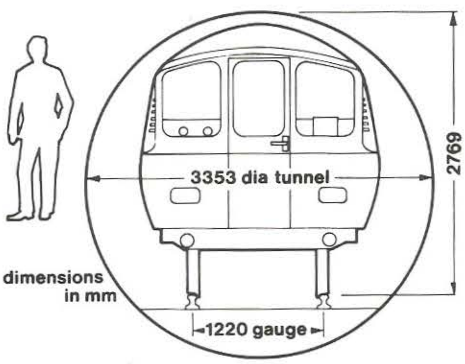
In addition the basic layout of the original system imposed a number of unique constraints:–

- the track gauge of 1220 mm (4 feet) precluded the use of standard gauge traction motors.
- the nominal tunnel diameter of 3353 mm (11 feet) would have required a car of unusually small cross-section but this had to be reduced even further because of doubts about the actual tunnel envelope resulting from misalignments during the original construction.

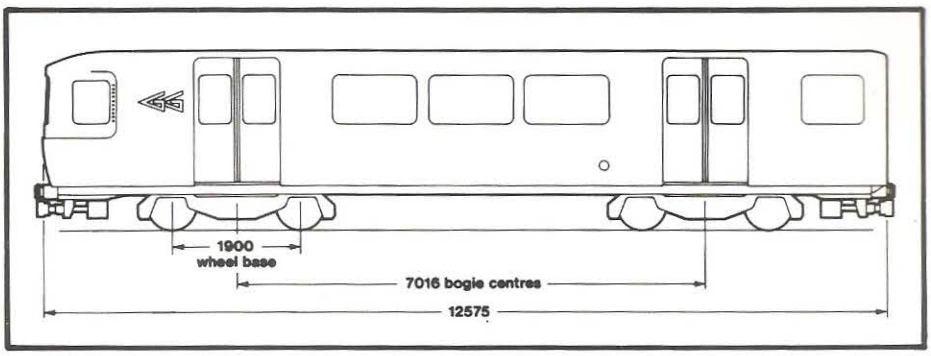
Cover illustration The map shows the overall rail network in the Trans-Clyde region with the central loop of the Glasgow Underground highlighted.

1 As can be seen from the route profile, many of the stations are constructed on the 'hump' principle.





2 The 3.35 m diameter tunnels are amongst the smallest in the world.



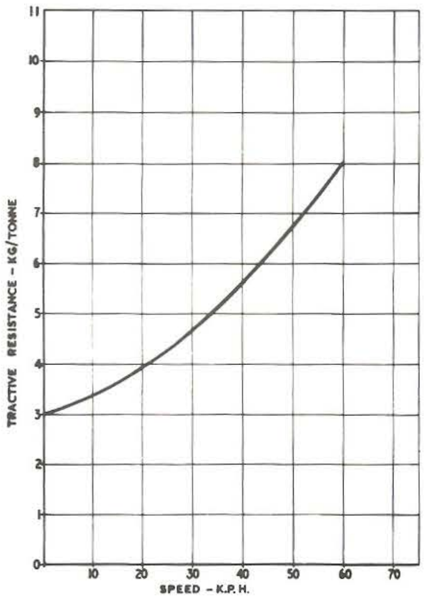
3 Car profile

Even the routine operating requirements of an underground railway presented a challenge such as the need to accommodate 90 passengers in a car whose outside dimensions were only 12.75 m x 2.34 m and for an empty car in an emergency to be capable of pushing a failed car out from the lowest point on the system under the River Clyde and up a 5.5% gradient for some 500m.

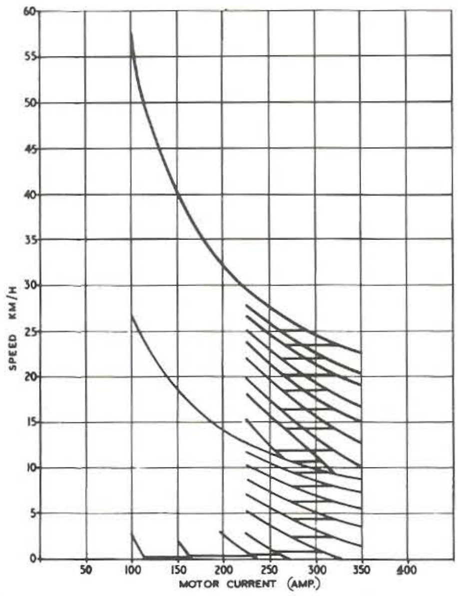
The combination of a very small diameter tunnel, the rather narrow track gauge and curves of 50 m radius at the turn-out have resulted in a very small coach and the requirement that the coaches be capable of single unit operation (each requiring a full set of equipment) posed an extremely difficult problem of fitting everything in.

Data

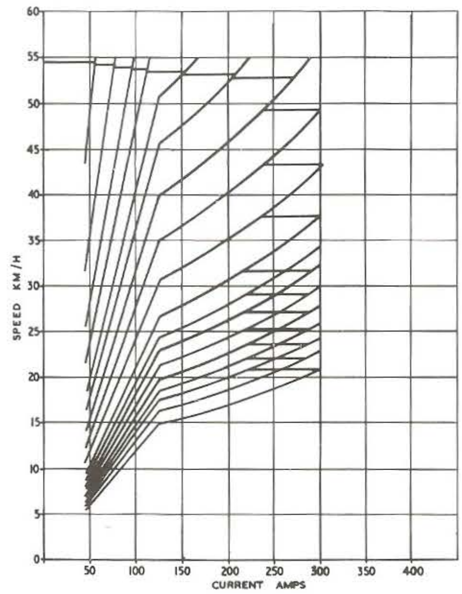
Nominal system voltage	600V dc
Current collection	3rd rail with return through running rail.
Tare weight	19,400 kg
Gross weight	25,250 kg
Number of axles	4
Number of axles motored	4
Train make-up	1, 2 or 3 coaches
Average acceleration in tunnel	1.05 m/s^2
Average brake in tunnel	0.83 m/s^2
Maximum speed	54 km/h (15 m/s)
Stopping accuracy in stations	± 1 m



4 Tractive resistance in tunnel – 2 car set



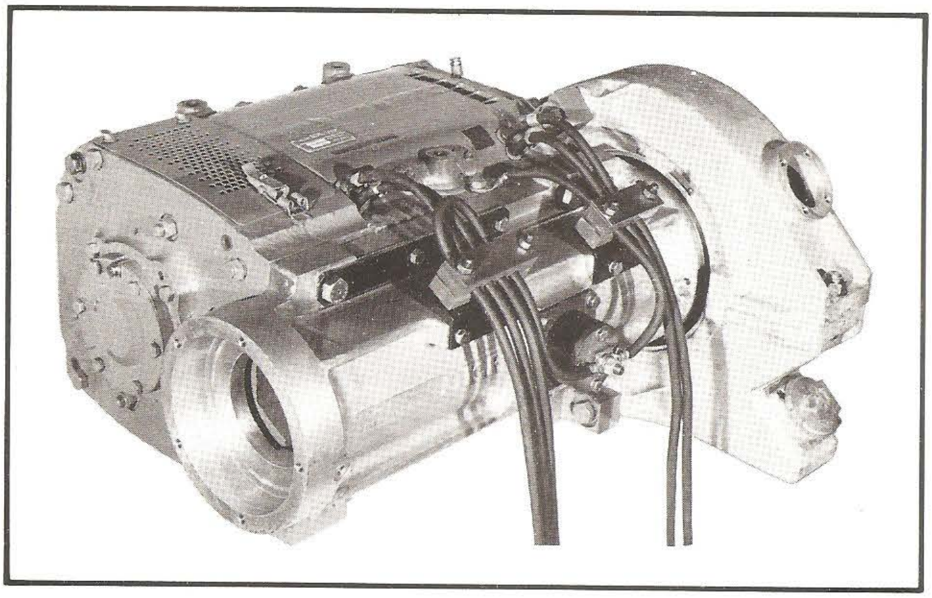
5 Performance – motoring



6 Performance – braking

7 The main Broomloam Depot, which is above ground

G312AZ traction motor



8 The 'U-tube' roller suspension and the cast aluminium gearcase are clearly shown in this photograph.

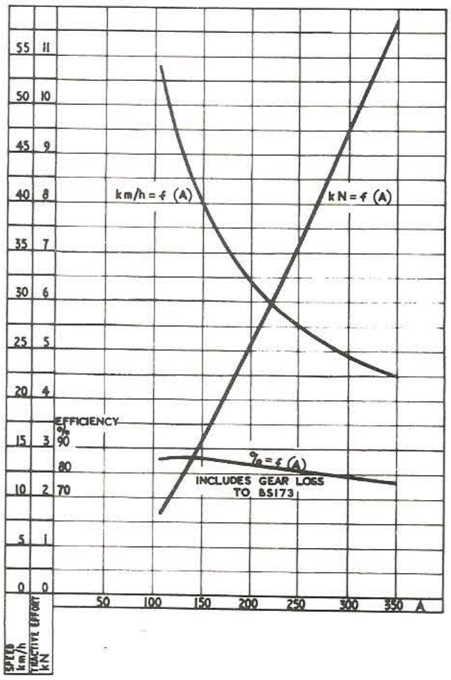
The 1220mm track gauge and small clearance under the car required a new traction motor to be designed to meet the performance requirements. In designing the G312AZ motor the aim was to produce a motor with high reliability and low weight with moderate noise levels and moderate temperature rises. The 312AZ motor is a 300 volt series-wound, self-ventilated motor mounted on a roller bearing suspension sleeve and resilient rubber nose suspension unit. It has class 'F' insulated fields and class 'H' insulated armature.

The magnet frame is fabricated from steel with a cast steel commutator chamber spigoted, dowelled and bolted on. The end shields are cast aluminium to save weight. The series field coils are vacuum impregnated with varnish after forming. The compole coils are bonded together by pre-treated inter turn insulation and are pressed and baked before application of the epoxy bonded mica ground insulation. The completed coils are bonded to laminated poles with epoxy resin.

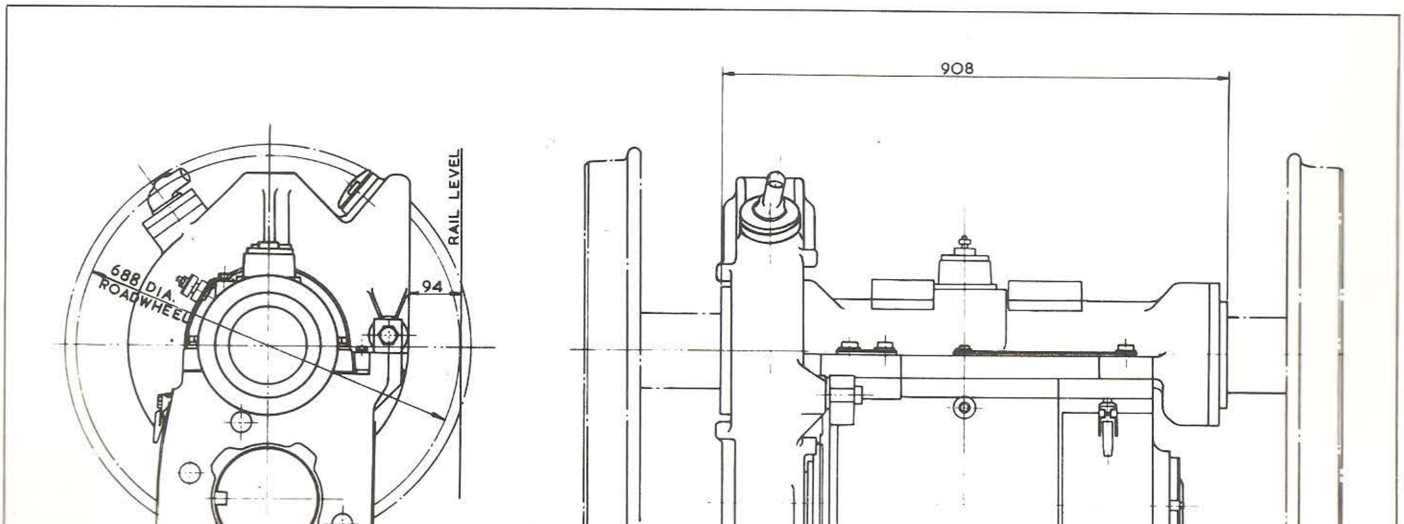
The armature core is built directly onto the shaft but can be removed from it if necessary. The winding is insulated to class 'H' with glass braid with flexible silicone varnish, and mica glass is used for the slot and end winding insulation. The whole armature is vacuuum impregnated with high temperature resistant polyester based varnish.

A V-ring commutator with micanite segments and epoxy glass V-ring is used, the connections to the armature conductors being made by the TIG welding process.

Single reduction helical gears are used to keep the noise level down and these are enclosed in a cast aluminium gearcase.



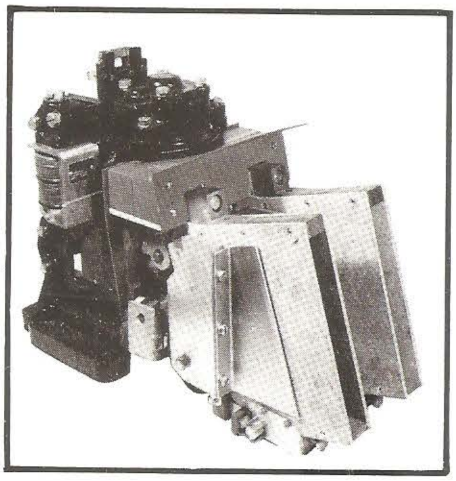
9 *Right* Characteristics of the G312 traction motor
10 *Below* The general arrangement drawing shows the small dimensions of the traction motor which is clearly suitable for much narrower gauge applications.

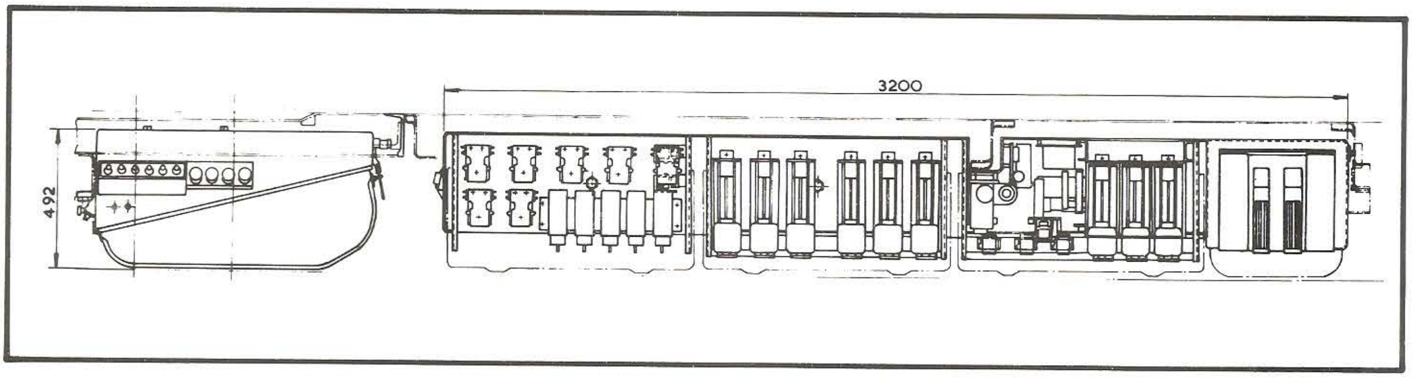


Conventional control equipment

11 *Right* Double pole line contactors – this design is also widely used on London Transport tube trains where low overall height is vital.
12 *Below* The low height of the equipment case is shown in this cross-section view.

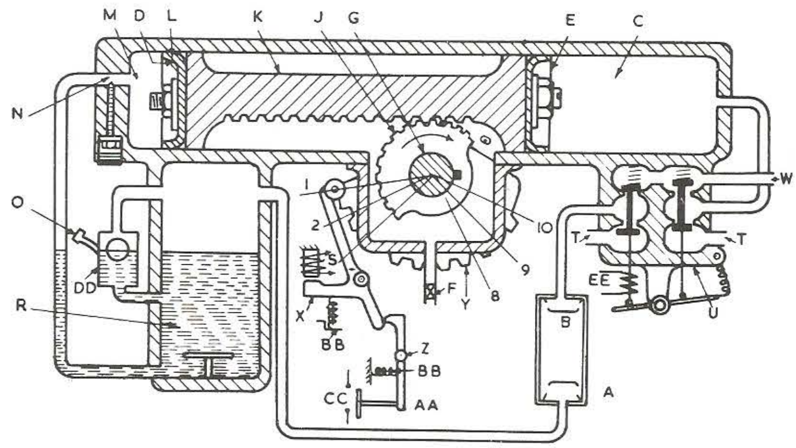
This is based on the equipment supplied by GEC Traction to London Transport for their 'Tube' railway, which has been developed to give a very high degree of reliability over many years and many billion car miles of operation. The main part of the equipment is mounted in a single steel case with glass fibre covers, beneath the underframe between the bogies, with the notching and braking resistors alongside. There are two camshafts driven by air/oil engines, one for series notching and one for parallel notching. They are used for both motoring and braking and they are controlled by a static notching relay with signals from dc current transformers in both branches of the motor circuits. This is a departure from the practice on London Transport equipment where an electro-magnetic relay is used, the reason for the change being the necessity for continuously variable control of the electric braking in order to obtain the required smoothness and accuracy of stopping.



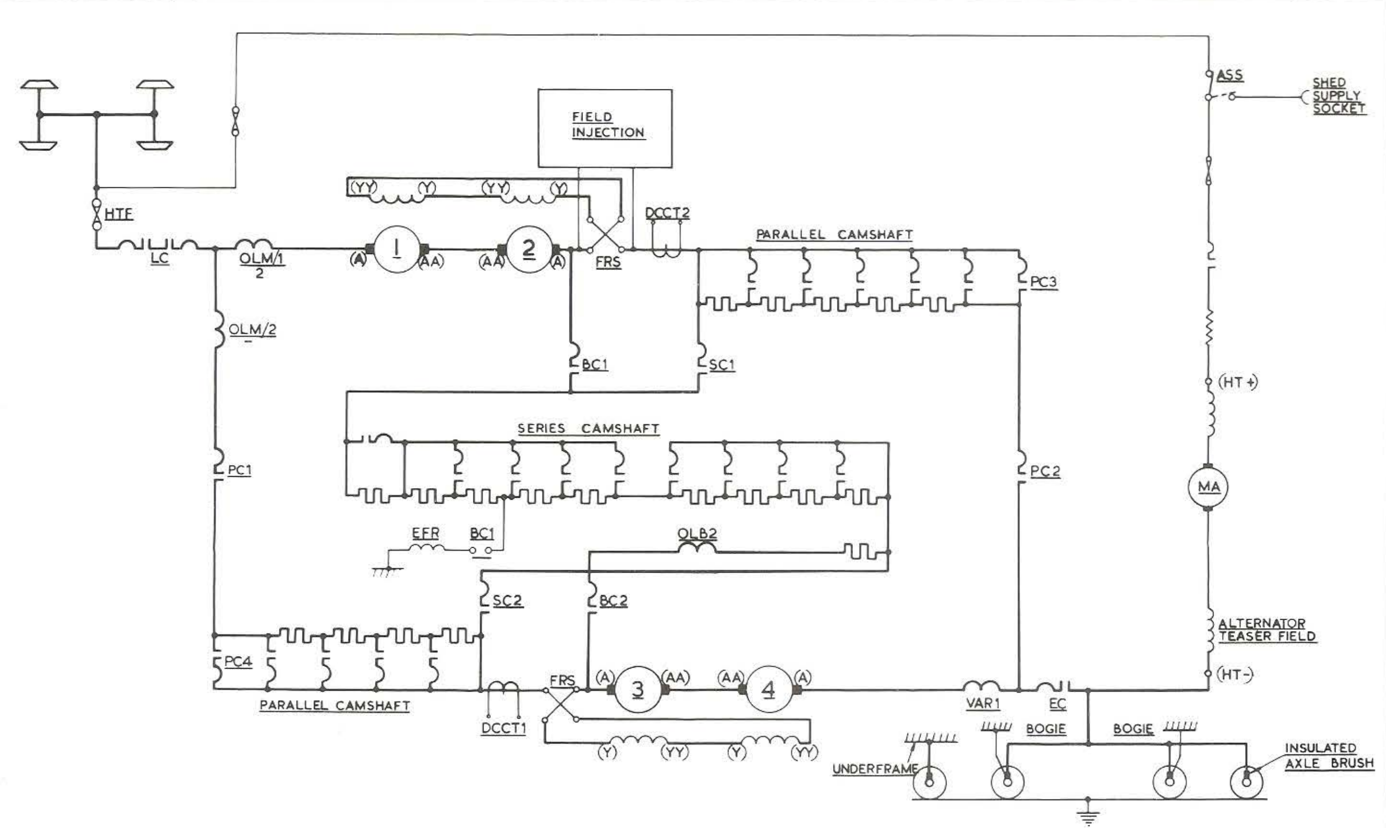


13 Rotary camshaft notching-up unit schematic showing air-operated piston/rack-and-pinion group LKEE-JG controlled by magnetic valve U and solenoid EE.

Operation: With the magnet valves 'U' de-energised, compressed air is admitted from 'W' via the right-hand valve to the air cylinder 'C', thus holding the camshaft in the OFF position. When 'U' is energised the left-hand valve moves to close the exhaust port 'T' and to admit air via the expansion chamber 'A' to the oil reservoir 'R'. Simultaneously, the right-hand valve opens the air cylinder to exhaust. The piston then moves towards the right, rotating the camshaft clockwise through pinion 'J'. As the camshaft moves from position '1' to '2' the PC internotch device closes, thus energising the stop coil 'S'. In parallel with this internotch contact is the output contact of the notching relay. If this is closed the stop coil remains energised and the camshaft stops in the next notch position. If it is open the stop coil is de-energised when the internotch opens and allows the camshaft to run through. If the notching relay contact remains open the camshaft will rotate from position '1' to position '0' in 1½ to 2 seconds. The rate can be adjusted by the needle valve 'N' in the inlet of the oil cylinder 'M'.



A Expansion chamber
B Baffle
C Cylinder
D Expander
E Piston packing (air)
F Drain cock
G Cam shaft
J Pinion
K Air engine piston
L Piston packing (oil)
M Cylinder (oil end)
N Timing adjustment (needle valve)
O Oil filter plug
R Oil reservoir
S Stop coil
T Exhaust
U Magnet valve
W To air reservoir
X Stop magnet (spring biased to closed position)
Y Starwheel
Z Fulcrum
AA Inter interlock lever
BB Spring
CC Inter-interlock. Indicator
DD Windonut type oil-level
EE Magnet valve coil

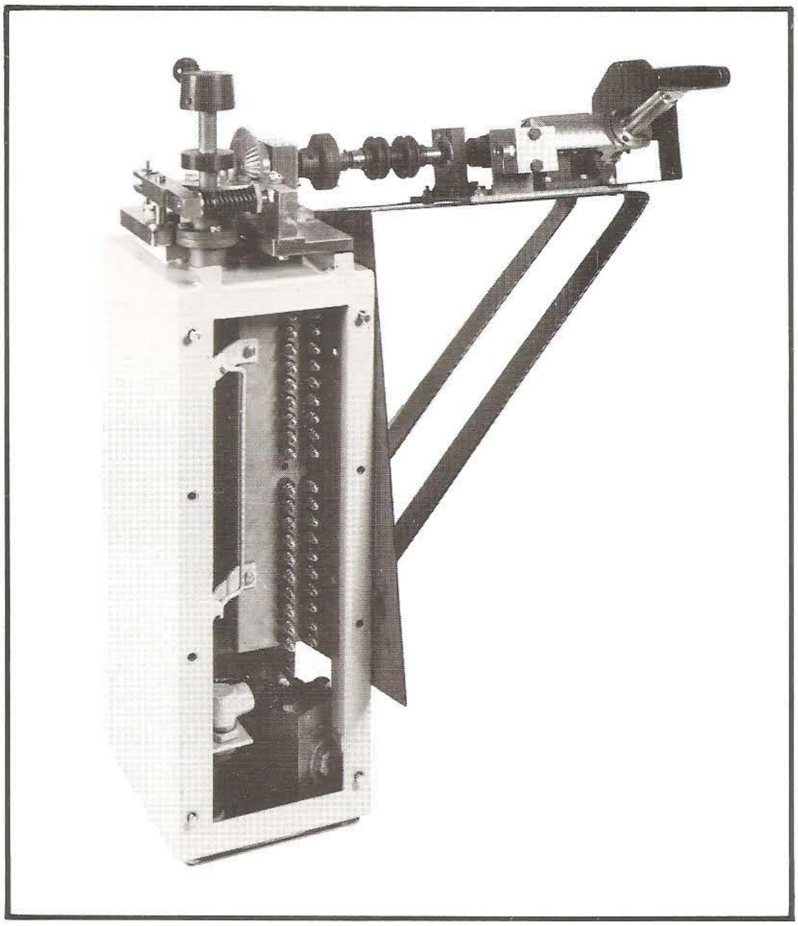


ASS	Auxiliary H.T. selector switch	FRS	Forward/revese switch	OLM	Motoring overload relay
BC1-2	Brake contactors	HTAF	H.T. auxiliaries fuse	PC1-2	Parallel/braking contactors
DCCT1-2	D.C. current transformers	HTF	H.T. fuse	PC3-4	Parallel contactors
EC	Earth contactor	LC	Line contactor	SC1-2	Series contactors
EFR	Earth fault relay	OLB	Braking overload relay	VAR	Volt amp relay

14 *Above* Power schematic.
15 *Below left* Notching sequence chart

APPARATUS		NOTCH No	SS STEP	PS STEP	LC, EC	SC1, SC2	PC1, PC2	PC3, PC4	BC1, BC2	SERIES CAMSHAFT SS 1	2	3	4	5	6	7	8	9	PARALLEL CAMSHAFT PS 1	2	3	4	5	6	7	8	9
MOTORING	OFF	0	1	1					●																		
MOTORING	SHUNT	1	1	1	●	●																					
MOTORING	SERIES	2	2	1	●	●				●																	
MOTORING	SERIES	3	3	1	●	●				●	●																
MOTORING	SERIES	4	4	1	●	●				●	●	●															
MOTORING	SERIES	5	5	1	●	●				●	●	●	●														
MOTORING	SERIES	6	6	1	●	●				●		●	●	●													
MOTORING	SERIES	7	7	1	●	●				●			●	●	●												
MOTORING	SERIES	8	8	1	●	●				●				●	●	●											
MOTORING	SERIES	9	9	1	●	●				●					●	●	●										
MOTORING	SERIES	10	10	1	●	●				●						●	●	●									
MOTORING	TRANSITION	10	10	1	●	●	●			●						●	●	●									
MOTORING	PARALLEL	11	11	1	●		●																				
MOTORING	PARALLEL	12	1	2	●		●												●								
MOTORING	PARALLEL	13	1	3	●		●												●	●							
MOTORING	PARALLEL	14	1	4	●		●												●	●	●						
MOTORING	PARALLEL	15	1	5	●		●												●	●	●	●					
MOTORING	PARALLEL	16	1	6	●		●												●		●	●	●				
MOTORING	PARALLEL	17	1	7	●		●												●			●	●	●			
MOTORING	PARALLEL	18	1	8	●		●												●				●	●	●		
MOTORING	PARALLEL	19	1	9	●		●												●					●	●	●	
MOTORING	PARALLEL	20	1	10	●		●	●											●						●	●	●
COASTING			1	1					●																		
BRAKING		1	1	1			●		●																		
BRAKING		2	2	1			●		●	●																	
BRAKING		3	3	1			●		●	●	●																
BRAKING		4	4	1			●		●	●	●	●															
BRAKING		5	5	1			●		●	●	●	●	●														
BRAKING		6	6	1			●		●	●		●	●	●													
BRAKING		7	7	1			●		●	●			●	●	●												
BRAKING		8	8	1			●		●	●				●	●	●											
BRAKING		9	9	1			●		●	●					●	●	●										
BRAKING		10	10	1			●		●	●						●	●	●									
BRAKING		11	10	2			●		●	●						●	●	●	●								
BRAKING		12	10	3			●		●	●						●	●	●	●	●							
BRAKING		13	10	4			●		●	●						●	●	●	●	●	●						
BRAKING		14	10	5			●		●	●						●	●	●	●	●	●	●					
BRAKING		15	10	6			●		●	●						●	●	●	●		●	●	●				
BRAKING		16	10	7			●		●	●						●	●	●	●			●	●	●			
BRAKING		17	10	8			●		●	●						●	●	●	●				●	●	●		
BRAKING		18	10	9			●		●	●						●	●	●	●					●	●	●	
BRAKING		19	10	10			●		●	●						●	●	●	●						●	●	●
APPARATUS		NOTCH No	SS STEP	PS STEP	LC, EC	SC1, SC2	PC1, PC2	PC3, PC4	BC1, BC2	SERIES CAMSHAFT SS 1	2	3	4	5	6	7	8	9	PARALLEL CAMSHAFT PS 1	2	3	4	5	6	7	8	9

16 Cut-away view of master controller



In motoring the setting of the static notching relay is modified by a pressure transducer actuated by load weighing cells between the bogies and the underframe. This increases the accelerating current for loaded cars and ensures the same accceleration of the train for all load conditions.

In braking the setting is controlled by a signal from the EP brake system, itself compensated for load weighing, which regulates the demand for electric brake.

In motoring the traction motors are connected conventionally four in series controlled by the series camshaft and two parallel strings of two in series controlled by the parallel camshaft. Field weakening is not required to produce the desired performance. Both the *group* contactors and the *line* contactors are standard GEC Traction electro-pneumatic contactors, as are the *brake* contactors. The standard cross-field braking circuit is used with field injection to ensure a rapid build up of electric brake.

The resistors are GEC type PKT heavy duty units made of non corrodible chrome aluminium steel alloy strip wound edgewise on porcelain formers, they are mounted in a frame underneath the coach alongside the main equipment case and are naturally cooled. For this particular job they are very generously rated and in service show no sign of overheating even when using a manual notching driving technique to push a dead loaded coach up the worst gradient.

The driver's controller and desk presented considerable problems in layout because of the very restricted space, the need for a central door in the front of the car, and a right-hand operated controller in the left hand driving position. This resulted in a T-bar combined power/brake handle for right handed operation driving a horizontal shaft across the top of the drivers desk which in turn drives the vertical camshaft of the controller and the automatic air brake valve in the left hand side of the desk through bevel gears. A potentiometer is mounted at the bottom of the controller camshaft for the control of the EP brake when driving in manual mode. The master switch is mounted on the left hand side of the desk alongside controller camshaft.
The positions on the master switch are *'Reverse' 'Neutral' 'Forward' 'Auto'* and *'Off'* and on the power handle *'Emergency' 'Full Service' 'Initial'* (all brake positions) *'Coast' 'Shunt' 'Series'* and *'Parallel'*.

An indicator panel with dim/bright indicator lamps is mounted in front of the driver. As well as fault indications this shows the condition of the equipment when the train is being driven in *'Auto'*.

17 One of the new trains in a typical station

Auxiliaries

The motor alternator is a standard GEC Traction MA3007AW as used on London Transport which provides power through a transformer, at 115V 850Hz for fluorescent lighting and through rectifiers at 110V dc for the compressor and at 53V dc for control and battery charge.

The alternating current is produced by an inductor type alternator driven by 600 volt dc motor. This type of alternator consists of a solid rotor, a homopolar field and a stator winding, and hence there are no slip rings or rotating parts to require maintenance. The complete motor alternator set is totally enclosed.

With the permanent series resistor in circuit, the motor is designed to withstand the voltage disturbances frequently encountered on traction systems. It can also be short circuited without flash over when running at normal speed and voltage and can be started from rest, direct on line without damage.

The alternator supplies a constant voltage to the low tension circuits via the transformer, rectifier and regulator equipment. The alternator voltage is maintained constant by a static regulator which controls the separately excited motor field current. If the alternator voltage should rise slightly above the required value due, for example, to supply voltage change and a corresponding increase in motor speed, the regulator increases the motor field current which reduces the speed and corrects the error. Conversely, if the alternator voltage should fall below the required level, the motor field current will be reduced to increase the speed and restore the generator voltage. The alternator set is also level compounded which compensates for both load and line voltage variations and the speed is therefore maintained; it is resiliently mounted below the coach.

A centrifugal double sided type fan on the motor end of the shaft blows cooling air over the machine frame, it also circulates the air within the machine but a running seal with centrifugal thrower of the fan periphery prevents the external air from being drawn into it. The motor armature and alternator rotor are both mounted on a common shaft. Class F insulation systems are used throughout including epoxy bonded poles and coils in the alternator field. Resistance to creepage on the four brush arms on the motor is provided by PTFE sleeves. The motor armature core, main poles and alternator stator are of laminated construction but the motor compoles are solid.

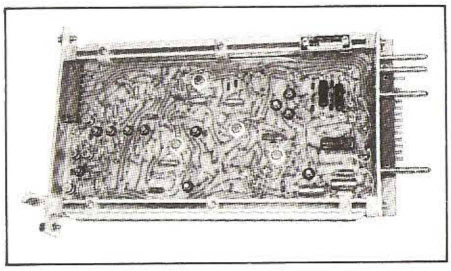
Electronic equipment

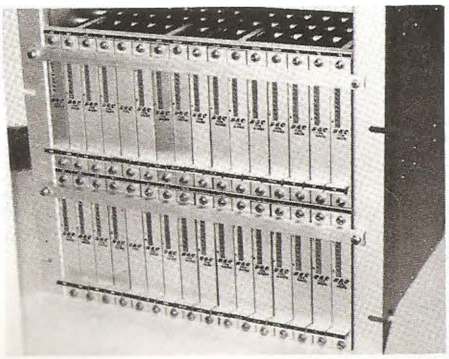
The electronic control system is constructed on a modular plug in basis. Each individual electronic circuit is built on a single glass fibre printed circuit card which is itself mounted on a protective metal chassis to form a plug in module. The construction of a typical module is shown in Fig. 18, and Fig. 19 shows the two tier rack into which the modules are plugged.

All the circuitry, including plugs and sockets, is mounted on the printed board with outgoing connections made at the rear of the car by means of a multi-way plug with gold plated pins. A similar but smaller socket is mounted at the front of the car to allow access to monitoring points when the module is plugged into its mounting rack. No adjustable controls are fitted to the module, the calibration and all settings being made by fixed resistors soldered to turret pins. Polarising pins are fitted on the rear of each module to mate with appropriate holes in the mounting rack to ensure that they cannot be plugged into the wrong position.

Components are specially selected and are operated at currents and voltage below their rated capacity. The equipment is designed for a minimum of 20 years life and special attention has been paid to the mechanical design to ensure that no deterioration will result from vibration and shock.

Practical experience has shown that variable potentiometers can give trouble and they are not on the equipment except for wheel wear compensation for the speedometer only (wheel wear compensation for the automatic train control is automatic). Modern electronic devices do not drift with age and once a module has been accurately calibrated during manufacture and test there is no need for further adjustment during its life.





Compressor

Because of the requirement that each car can be operated as a single unit there is a Westinghouse E13P compressor mounted on the underframe of every car. It delivers 221 litre/minute (free air) at 7 kg/cm^2, for the operation of the brakes, door gear and pneumatically operated auxiliary and control equipment. The capacity is sufficient for the operation of two cars off one compressor in an emergency.

The compressor is driven by a GEC type 738 motor running at 110V dc off the rectified supply of the motor-alternator set transformer.

Load weighing

Variations in load are measured by Davis & Metcalfe load sensing cells fitted in the suspension between the bogies and the underframe. The output of these is a variable air pressure which in one case is used to vary the pressure of the brakes in proportion to the passenger loading and in the second case, via a pressure transducer, varies the setting of the static notching relay during acceleration.

Brake system

The brake system is supplied by Davies & Metcalfe and comprises an electro pneumatic service brake with back-up by an automatic air brake.

When the train is being driven in the manual mode and a brake application is made the electro pneumatic brake operates in accordance with the position of the power/brake control handle. The power/brake control handle also sets the regulating valve of the automatic air brake to an equivalent air brake application, but this application is inhibited by a change-over valve which is energised by the electro pneumatic system. If the electro pneumatic system is cut-out for any reason the change-over valve is de-energised allowing the direct air brake to be applied in accordance with the regulating valve.

18 Typical printed circuit board
19 Layout of a 2 tier rack into which pcb modules are plugged.

Electro pneumatic brake

The brakes are controlled by the Davies & Metcalfe EBC5EP brake control unit. This unit varies the brake cylinder pressure smoothly from 0 to 100% in accordance with the brake demand. The brake demand comes from either the driver's power brake controller or the automatic train control equipment on the leading coach, and is sent down the train by a single train wire to the individual EP units on each coach. If this signal were a simple voltage proportional to the brake demand there would be various losses down the train wire particularly the jumper plug pins, therefore a pulse width modulated (PWM) analogue system is used. On the leading car an encoder generates a fixed frequency, variable width square wave with the mark/space ratio proportional to the brake demand. This is then sent down the train wire and the decoder at each EP unit works on the mark/space ratio ignoring the magnitude of the signal thus eliminating any attentuation effects of the train wire. A load weighing pressure transducer adjusts the brake demand on each car in accordance with the passenger load and the demand is fed into a comparator which measures the difference between the brake demand and the actual brake (air plus dynamic) applied and energises the brake EP control vales to increase or decrease the air brake as necessary.

When air brake is demanded by the EP system, a signal is also sent to the dynamic brake which if available builds up whilst the air brake reduces. Dynamic brake is not allowed to build faster than the air brake fades in order to prevent over-braking. Dynamic brake on these coaches can provide up to 60% of the maximum brake available but generally maximum brake is not required so that in practice the dynamic brake caters for about 75% of normal braking requirements.

Automatic control

When operating in passenger carrying service these trains are operated in the fully automatic mode. It is only necessary for the driver to press two push buttons and the train will start, accelerate, obey all speed limits, stop at intermediate signals on red, re-start automatically when the signals clear and stop at the next station well within the specified tolerance of ± 1 metre of the stopping position. In practice it is found that the majority of stops from all trains at any station are within ± 0.3 metre of the specified point. From the passengers point of view the stop is as hard as can be achieved without discomfort and there are no jerks even when finally reaching standstill. The condition in which the ATO is operating is indicated by a series of lamps on the driver's display panel.

Signals for actuating various operations such as braking, various speed restrictions, permission to start, etc. are passed to the train by track beacons. These are positioned in the centre of the track and are examined by an interrogator the aerial of which is mounted on the bogie. Some of these beacons are for one condition only such as the *Stop* beacons at stations and the speed restrictions, and others are switchable, operated by the central signal control, such as the *Start Permit* and the intermediate signal *Stop* beacons. Temporary beacons can also be placed in the track if required.

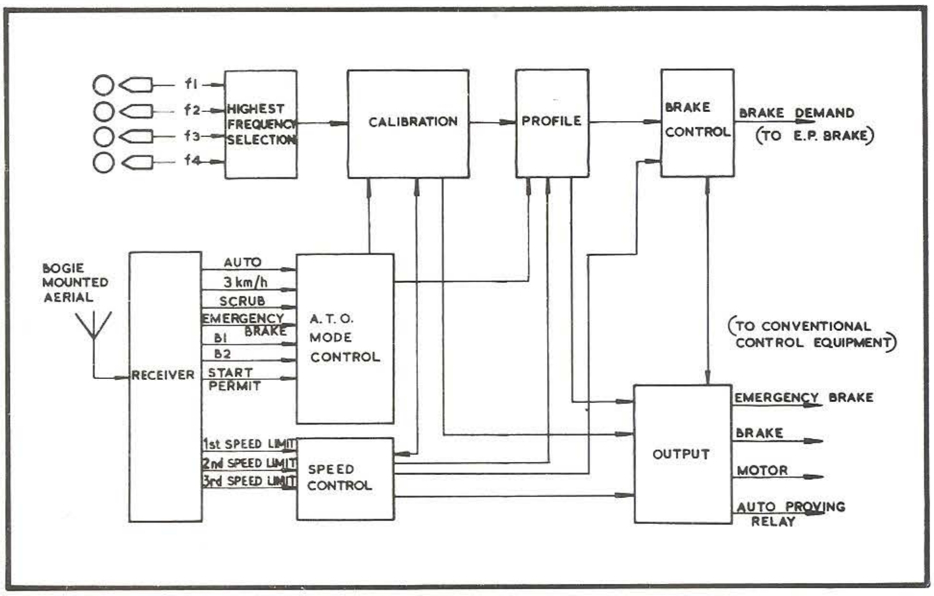
Output of the interrogator is by a series of relay contacts which switch the commands on the auto controller.

Speed control

The maximum speed of the system is 54km/h and there are also two short sections where there are 18 km/h and 35 km/h restrictions in both directions where the tunnel was slightly mis-aligned when originally dug in 1894.

Normally when the speed limit is reached power would be reduced or if the train were on a down gradient, a brake application of sufficient magnitude to hold the train at the correct speed would be made. In this application, however, because of the short distance between the stations, it was decided to keep the speed control to a simple *power on, power off, brake* system. When accelerating up to a speed-limit, power is shut off when the speed-limit is reached and the train is allowed to coast. If the speed rises to 0.5m/s above the speed limit a partial brake application is made and if the speed falls to 0.5m/s below the speed restriction, power is re-applied. In practice, because of the severe gradients and the restricted power of the cars the speed control is not continually switching on and off.

20 Automatic control block diagram



Starting

In the depot the driver will operate the train in manual control. When driving into the first station he stops the train in the correct position which leaves the interrogater aerial positioned over the *'start'* beacon. When the system ahead is clear the signal turns to green and at the same time the start beacon gives a *Start Permit* signal to the interrogater which brightens the *Start Permit* lamp in the driver's display panel and sets the auto control ready to start. The driver then presses the two *Start* buttons and the automatic control energises the appropriate train wires to close the motor contactors and the train accelerates in the normal manner with the camshafts controlled by the static notching relay.

Speed measurements

Speed is measured by inductive probes mounted on all four traction motor gearboxes which sense the passage of the main gearwheel teeth. The four frequency signals thus generated are compared and the highest frequency selected. This is to allow for wheel slide in braking, possible uneven sized wheels or possible damage to a gearbox probe. For automatic control, of the accuracy required in this case, it is necessary to have an accurate measure of speed and where speed is measured as in this case by wheel rev/min correction must be made for wheel wear. A manual adjustment as part of routine maintenance was considered but rejected as undesirable and an automatic correction system was devised.

The number of pulses from the gearbox probe are counted over a fixed distance of 112.5 metre between the two *Brake* beacons on the approach to each station. This is then checked against an information store to generate a multiplying factor to correct the speed signal. Thus the system is continually corrected for wheel wear.

Stopping

In designing the automatic stopping system a number of factors had to be considered:–

1 final stopping point within ± 1 metre.

2 it was necessary to have the highest possible rate of braking in order to keep the nominal running time down to within 22 minutes for the complete circuit.

3 wheelslide had to be avoided as this would reduce accuracy and in the limit if all four axles slid during braking the speed signal would be incorrect.

4 gradients at various stations vary from 4% upgrade to 2.5% downgrade.

5 sufficient brake to be left applied when train came to a standstill, so that it would not roll on a gradient.

6 smooth braking that would not throw passengers off balance, with no oscillation between over and under braking.

The system devised takes into account all these considerations and produces a remarkably smooth and accurate stop.

A braking profile of speed against distance with a deceleration of $1 m/s^2$ is stored in a digital memory device (Fig 21 below). On approaching a station a first beacon B1 positioned 150m from the final stopping point triggers off this memory giving a value of speed for every 160mm travelled. At 37.5m from the final stopping point a second beacon B2 switches to give a speed for every 40mm. The actual speed of the train as measured by the gearbox probes is then compared with this stored brake profile and the stopping is controlled accordingly. With a deceleration of $1 m/s^2$ the initial speed on the stored brake profile 150m from the final stop is 17.32m/s which is well above the maximum speed of the train of 15m/s and ensures that on passing B1 beacon the train speed is below the stored profile speed.

If the difference between the stored profile speed and the actual speed value is less than 5m/s, power is switched off. If the difference between the stored profile speed and the actual speed is greater than 5m/s power is maintained until such time as this difference falls to 5m/s at which point power is switched off. This means that if the train approaches the station at a low speed due to gradient or perhaps speed restrictions, power is held on until the last instant thus preventing the train from braking too soon and having a long creeping approach to the stopping point. For instance with an approach speed of 10m/s power is switched off 112.5m from the final stop point but with an approach speed of 6m/s power is switched off only 60.5m from the final stop.

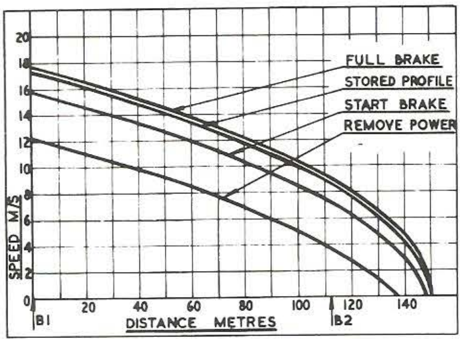
As soon as power has been switched off the control circuits reset ready for braking.

When the actual speed approaches to within 1.5m/s of the stored profile speed, ie the speed error falls to 1.5m/s, braking commences and as the speed error falls the brake demand increases linearly until, with the speed at zero, 83% brake is demanded from the EP brake. Then as the speed error goes negative the brake demand rises to 100%, this is clearly shown in curve Fig 22. Finally, when the *actual* speed falls to 1m/s, the EP brake demand switches to a fixed 30% of maximum brake. This brings the train to a smooth halt and remains on to hold the train on a grade, if necessary, until such time as the signal turns green and the driver starts his train again, or, if the train has halted at an intermediate signal, a restart signal is given to the interrogator. Fig 23 illustrates this brake routine for different approach speeds.

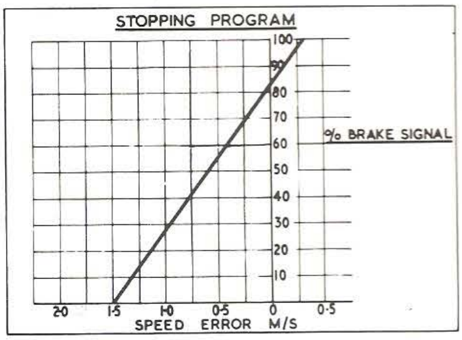
Before the trains were required for service, considerable testing was done on a straight length of test track with a continuous grade of 0.5% where the basic control parameters were adjusted and the operation of the ATO control proved. Then, as various sections of the tunnel became available, the system was proved for operating conditions gradually building up over 3 months to driver training on a *ghost* service. During this period further adjustments were made and the equipment settled down with the result that the system opened to traffic in April 1980 without any troubles.

During the period of testing on the test track and in the tunnel a number of major points became obvious.

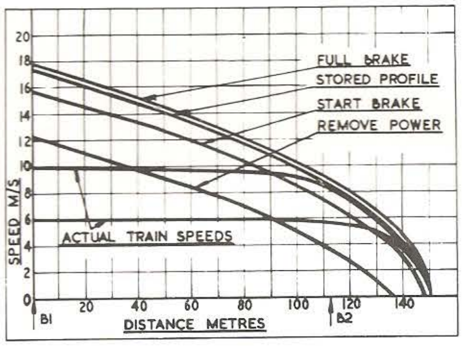
1 response to the EP brake system must be very fast. Davies and Metcalfe had



21 Position of beacons and the stored braking profiles.



22 How braking effort varies with 'error' speed.



23 Braking routines for different approach speeds.

included an *inshot* device which cut the delay of the initial rise in brake cylinder pressure after the initial brake demand. It was found necessary to reduce this time to 0.2 seconds. Response times of the order of 0.5 seconds or more resulted in an overshoot of the brake demand followed by an overshoot of the brake effort setting up a relatively slow oscillation of the brake effort giving about 3 peaks during a stop from 15 m/s. Though this oscillation could be clearly seen on ultra violet recorder traces that were taken, it could not be felt physically on the car during braking, but the peak brake effort could cause wheelslide.

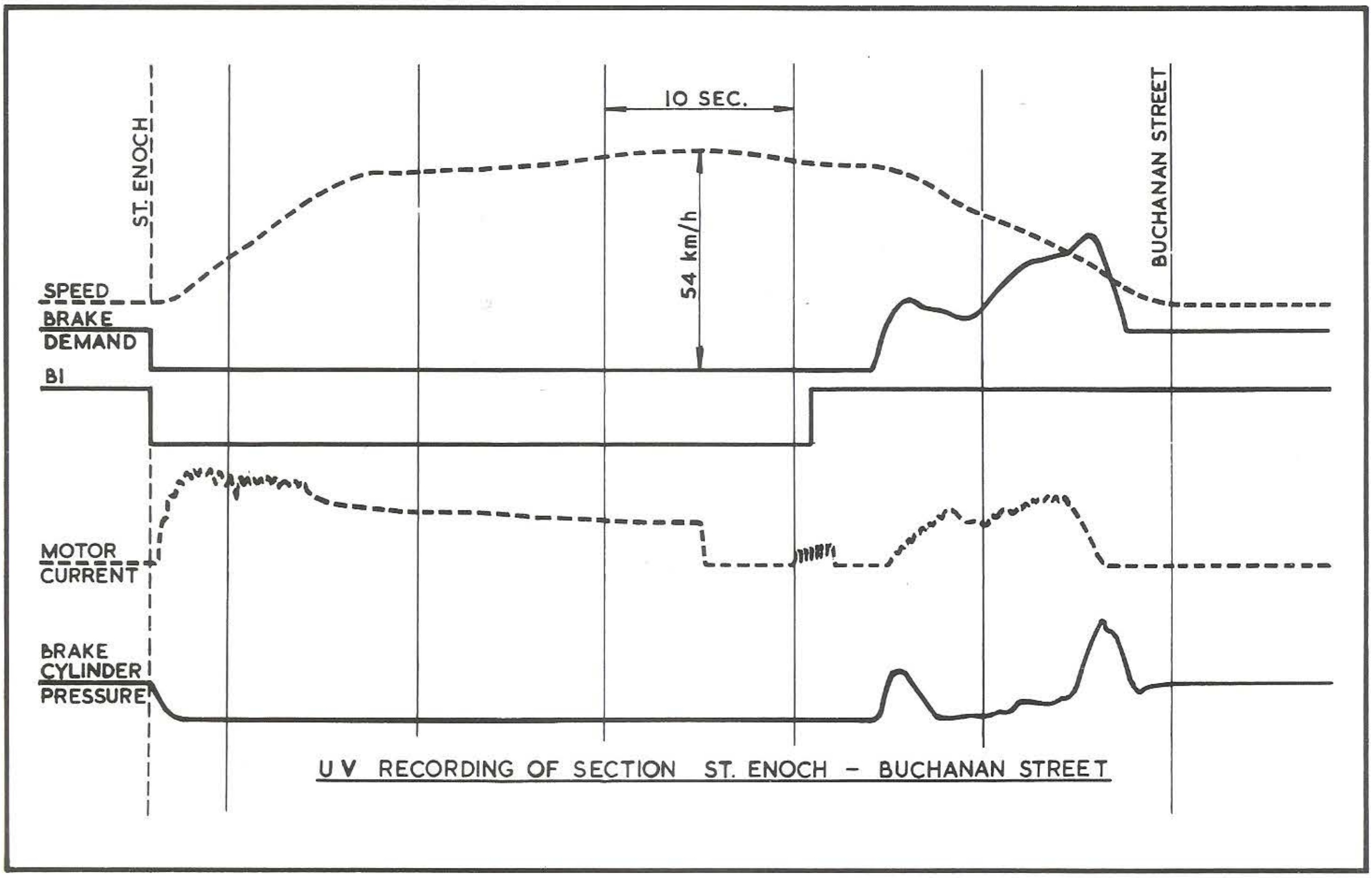
2 Adhesion Levels: Initially the stored brake profile was programmed at 1.6 m/s^2 and on the newly laid test track ATO controlled braking was achieved with virtually no wheelslide. When operations were transferred to the tunnel, however, it was found necessary to reduce the stored brake profile to 1 m/s^2 in order to avoid major wheelslide. Surprisingly, small amounts of wheelslide on one or two axles only, do not affect the accuracy of stopping as the response of the equipment is fast enough to be able to correct for this, but the reduction of the stored brake profile to 1 m/s^2 virtually eliminated all wheelslide.

3 Variations in brake shoe friction are to a large extent compensated for by averaging eight wheels of a single car and by correction of over or under braking by measurement of speed error and finally, by use of electric brake as much as possible as this has a much closer tolerance than brake shoe friction. But even when the electric brake is cut-out the ATO stopping system retains its accuracy.

4 The degree of accuracy of this method of control is remarkably high. For any one car stopping at one particular station the repeatability is within a few centimetres. For one car stopping at any station the accuracy is nearly the same. For all cars stopping at all stations the accuracy is well within ±1 metre and is normally within ± 0.3 metre.

During the official proving trials a number of circuits of the track were made in both directions with 2 and 3 car trains loaded and unloaded, the results showing a remarkable consistency. The maximum variation in the time round the circuit was only 10 seconds. It was also demonstrated during these trials that electric brake could be cut-out or cut-in half way through a stop routine without affecting the performance.

24 U/v recordings taken during service trials and showing actual braking forces (both electrical and pneumatic) as compared with the braking demands.



Safety

Fail safe arrangements have been designed into the system so that in the event of a fault an emergency brake application is made, but on the Glasgow system the final safety arrangement is the tripcock at each signal, as in all deep level tube railways in the UK.

Future developments

The system as designed is perfect for a small circular route such as Glasgow but is also capable of considerable development for the full automation of larger systems. The principal of pre-programming on board for various operations and comparing actual performance with this can be extended to cover complete routes and various overriding safety controls built in.

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