THE UNDERGROUND ELECTRIC TRAIN

by Piers Connor

34 – AUTOMATIC TRAINS ON THE UNDERGROUND

THE ATO EFFECT

Now that we've covered most of the important principles of conventional signalling on the Underground and the effects of signalling on capacity, it is perhaps time to see what influence automation has on throughput and capacity. There are a number of influences which can work to increase throughput with Automatic Train Operation (ATO) but the simplest, which I have mentioned before[1], is the removal of variability in train driving. If the driving is taken away from the driver, all the trains should behave in a similar way and train movement at least, will be predictable and reliable. To see what this does to throughput, we can use a simple adjustment to the operating margin and apply it to my spreadsheet model.

You may remember me mentioning before[2] that the margin used by the Underground in train planning for manually operated lines is 25 seconds. This is added to the signalling headway to allow for temporary speed restrictions, fluctuations in station loading, fluctuation in power supply, minor delays and variable driving techniques. As we saw last month, the Victoria Line originally had 120s headway with a margin of 18s, less than the standard 25s largely as a result of ATO removing the variable driving. If I apply an 18s margin to my model, it shows an immediate increase in throughput. On a line with a maximum speed of 35mph, this rises from 32.5 trains per hour (tph) to 34.7tph, a 2.2tph increase. Research carried out at various times on LU seems to confirm this is in the right ball park.

So ATO is worth going for, even if you just look at the additional capacity which it provides from the elimination of manual driving. There are other things it can do also, like improve safety and reliability and, if very modern technology is available and can be made to work, it might offer also the possibility of further capacity enhancements. Before we look at that though, it is essential to get to grips with how ATO works and how LU uses it.

WHAT IS ATO?

First, I need to sort out the irritating business of the initials used in connection with ATO. There are lots of acronyms used around the world in connection with automatic train operation and some of these use the same initials to mean different systems, some have different meanings in different countries and some are just plain mixed up. The following list gives a reasonable summary of the best known.

Name	Meaning
ATO	Automatic Train Operation. In this, both train driving and the train's response to the signalling systems are automated. The driver is limited to emergency manual driving on sight (usually limited to 10 or 15mph) but can drive manually at speed if the signalling safety element or ATP is still available.
ATP	Automatic Train Protection. This is the safety element for train operation where

[1] Article No.29 *Underground News* No.551, November 2007.
[2] Article No.32 *Underground News* No.554, February 2008.

	signalling aspects and speed restrictions are enforced automatically, regardless of whether the driver is responsible for driving the train or not. It is inherently part of ATO where this is provided.
ATC	Automatic Train Control. Originally used by the Great Western Railway to refer to what eventually became AWS[3] on the main line railways. Used in the US and other places to describe ATO with central control. In the UK we assume central control is inherently a part of ATO. Indeed, you wouldn't want ATO without it.
ATS	Automatic Train Supervision. US term used to mean central control of trains with ATO or ATP. A variation is when it is used to mean ATC. On the Underground, programme machines are a form of ATS.

As you can see there is lots of room for confusion and, as might happen with an empty space, the room is regularly filled with hot air. In my articles the expression "ATO" does what it says on the tin and includes ATP and ATC. Here we are concerned with ATO on the Underground in its various forms, both present and future. I will start with the first full ATO system installed anywhere in the world – the Victoria Line system.

THE ELEMENTS

By the late 1950s, all the elements for the automatic operation of a train service were in place. Trains had automatic acceleration, signalling was automatic and routes could be set up automatically with programme machines. Even maximum braking on trains was automated by the use of mercury retarder controllers[4]. All it needed was some means of gathering the elements, joining up all the dots and getting the whole lot to work together. The opportunity to do this came when authority to build the Victoria Line was given by the government in 1962 and London Underground was quick to take advantage of it.

Although money was far from no object in those days, there was enough to allow some research and development for automatic train operation, especially since the prospect of reducing the train crew from two to one was a desirable outcome in an era of rapidly worsening staff shortages. There was also the prospect of being the first fully automated railway in the world.

The concepts for ATO on the Underground were first agreed in 1959 and design work started in 1960. Physical experiments began on the Acton Town to South Ealing test track in December 1962 and this was followed by the modification of the test train – a District Line R Stock set – for passenger service in April 1963. A series of runs took place in automatic mode with a morning service train between Stamford Brook and Ravenscourt Park. Only the east end driving car was fitted with the equipment. It was switched into ATO mode at Stamford Brook and switched out at Ravenscourt Park. Some LT board members came down to have a look at it and decided that it offered sufficient confidence for the Board to authorise a full-scale trial. The Central Line's Woodford to Hainault shuttle service presented an ideal testing ground for this trial since it was a self-contained service and there were a number of 4-car units of 1960 Tube Stock available for conversion to ATO. The trials started there in April 1964 and their success led to the adoption of ATO for the new Victoria Line.

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3 AWS = Automatic Warning System, the main line railway system for telling drivers they are approaching a restrictive signal.

4 Retarders – see Article No.7, *Underground News* No.529, January 2006.

DESIGN PHILOSOPHY

We looked at some of the operating issues related to ATO a few months[5] ago but these were largely related to requirements arising from having only one person on the train. We didn't look at the technical requirements for ATO, nor how the train responded to them. Now we will.

The design philosophy for Victoria Line ATO was based on two requirements. The first was to get the train to respond to signals so that it operated safely, while the second was to get it to stop at the stations in the right place. This philosophy led to two separate control systems being developed, one becoming known as the Safety Box and the other as the Auto Driver Box (ADB). The Safety Box was developed by the signal engineer[6], who insisted that train safety was his responsibility and that the "oiks" from rolling stock engineering could not be trusted with it. He did agree eventually to leave them the ADB.

STATION STOPPING

In theory, the ADB is the simple part. As long as you know what deceleration curve the train should follow on its approach to the station down to the stopping point, you could guide it automatically to stop at the correct place. Drivers do it with a combination of their "Mark 1 eyeball[7]" and the seat of their trousers. Actually, the speed curve on the approach to a station is easily predictable. It should follow a gradually steepening curve from the maximum approach speed down to the stopping point, where the speed should be zero. If you provide a number of reference points along this curve and check that the train is doing the correct speed at each of these points, you should get a reasonably accurate stop.

The process requires an accurate measurement system to replace the skilled eye/hand co-ordination exercised by the driver and it needs an accurate brake adjustment system to match it. It hasn't been easy to get right and there have been some modifications to the Victoria Line ATO stopping system over the years in several attempts to do so. In the original design, which is still in place, although partially superseded, it is done by checking the train speed every 5mph or so as it braked to a stop. The checks are carried out by "command spots". A command spot isn't really a spot, rather a 10ft (3m) long circuit fed into one running rail which generates a special frequency corresponding to the required train speed. The command spots are positioned to match the ideal braking curve for a train stopping at the station. The diagram below (Fig. 1) shows how they are placed and how they affect the braking commands. Note that not all stations have the higher frequency spots as the entry speed at these locations doesn't require them.

5 Article No.20, *Underground News* No.542, February 2007.

6 The Chief Signal Engineer of London Transport Railways at this time was the legendary Robert Dell. He was both feared and respected right up to board level and the Victoria Line development work was carried out under his direct control. However, there was significant input from the rolling stock design division and it should not be assumed that this was simply a signalling project.

7 An expression borrowed from the aircraft industry, where pilots still often prefer it to instrument flying.

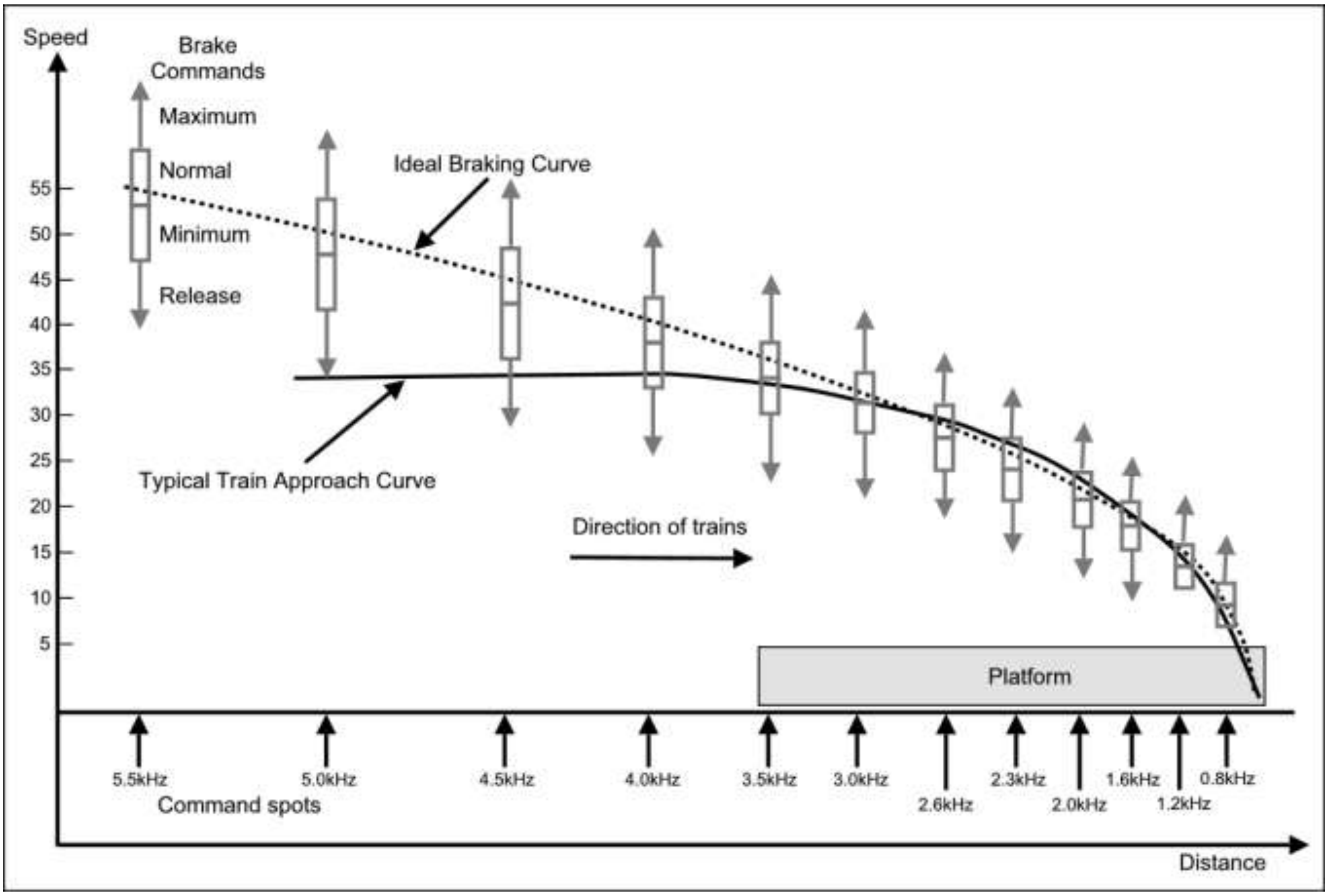

Fig. 1: Schematic showing the basic design of station brake command spots and train braking curves as used on the Victoria Line ATO system. The curves show the ideal train braking curve (dotted) and a typical braking curve for a train approaching at 35mph. The commands are "Maximum", "Normal", "Minimum" and "Release". When it passes the 4.0kHz spot, braking commences because the train speed falls within the Minimum brake command band. Each spot causes a check on the train speed and a corresponding brake command. Normal is the optimum brake rate. If the train speed drifts away from Normal, then Minimum, Maximum or release will be called for as necessary.

Each command spot generates a frequency proportional to the required speed at that point. 100Hz[8] represents 1 mph beginning with 5.5kHz at 55mph[9] and ending at 0.8kHz for 8mph. As the train passes over the command spot, a pair of detector coils on the leading bogie of the train picks up the frequency, which is read by the Auto Driver Box and compared with a speed equivalent frequency generated on board the train. The train-mounted frequency generator is fitted to the end of one of the traction motors on the leading car.

The braking control system is arranged as shown in the next diagram (Fig. 2 below). When the train passes over a braking spot, the train speed is compared with the signal from the command spot picked up by the coils on the train. If the train speed is too fast, a brake command is passed to the brake valves. The command is

8 Hz = Hertz or, as they used to be known, cycles per second. They are named after Heinrich Hertz who proved the existence of electromagnetic waves in 1887.

9 Victoria Line trains never normally reach that speed as the on-board control system restricts them to 47.5mph.

passed through one of three mercury retardation controllers – Minimum, Normal and Maximum. Each retarder is set at its required angle to monitor the braking rate of the train. The Maximum retarder is set at the steepest angle and the Minimum at the flattest. The default is the Normal retarder. Maximum brake is invoked by the ADB if the train speed is higher than the normal setting and Minimum brake is invoked if the speed is less than the pre-set normal rate. If the train speed is too low, the brakes will release until the speed is checked at the next spot. The train speed is checked at each spot until, at the last spot, a holding brake of 14psi air pressure in the brake cylinders is selected to bring the train to a stand and hold it until it's ready to leave. This is called "low minimum" and is activated by a pressure switch to maintain the set pressure.

The same principle is used for a signal stop command. On the approach to a stop signal, a 20kHz command spot is provided. This is automatically switched on by the stop signal. The command is detected by the pick-up coils and passes through a 20kHz filter on the train (Fig. 2) which sends out a "Normal" brake command so that the train slows down using the service brake to stop at the signal. Generally, the trains manage to stop within about 50ft of the signal but allowance is made for them to stop up to 150ft short. We will deal with signal stops in more detail next month.

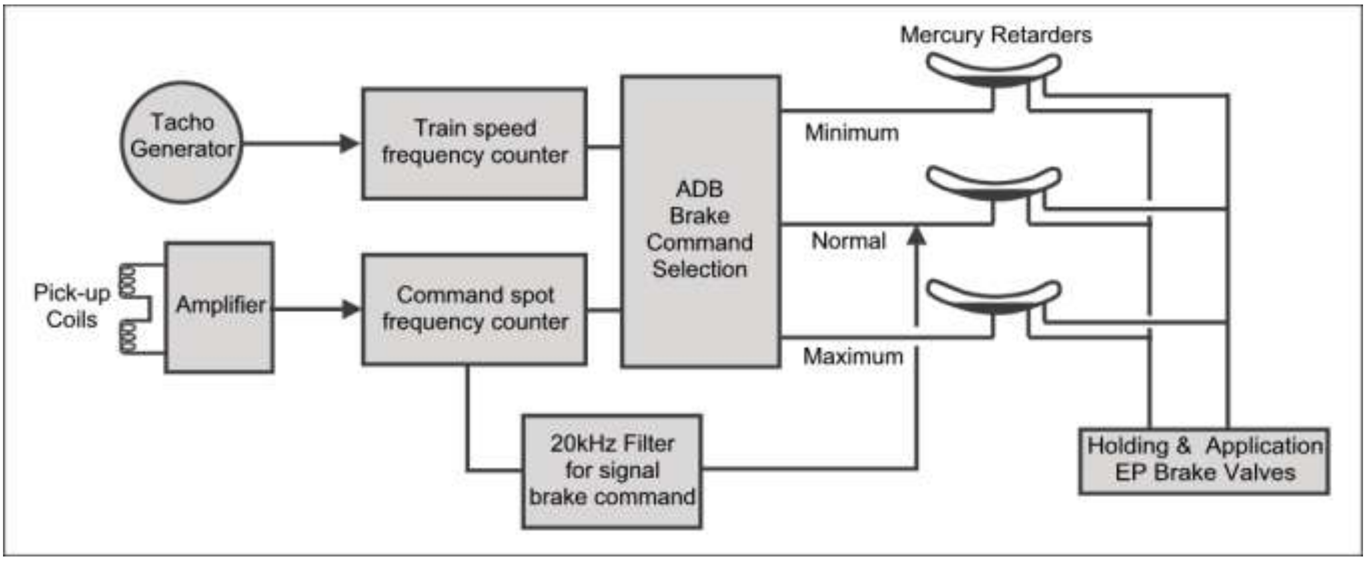

Fig. 2: Schematic of the brake control used on the original Victoria Line ATO system for station stopping. The train speed is provided as a frequency by the tacho generator. This is counted and sent to the ADB where it is compared with the command spot frequency sensed by the pick-up coils mounted on the front bogie of the train. Depending on the results of the comparison, a "Minimum", "Normal" or "Maximum" brake request is called for by the ADB and sent via the appropriate retarder to the brake valves. There is also a filter for the 20kHz brake command which initiates a "Normal" brake command if switched on by a stop signal ahead.

PROBLEMS AND MODIFICATIONS

During the years after the opening of the Victoria Line, a number of weaknesses in the ATO system gradually became apparent. To begin with, station stopping wasn't always too accurate. It took a long time to get the station stop spots optimally located because train performance varied widely depending on load and location. The retarders are not refined enough to cope under all possible circumstances. Finsbury Park was particularly difficult because of the hump in the platform profile.

Mention of Finsbury Park reminds me that an interesting comparison between manual driving and ATO is possible there because the Piccadilly and Victoria lines run side by side and trains approach the platforms at a similar speed. If a train on each line approaches from the south at the same time, it is possible to compare the stopping sequence. In the days just after the opening of the Victoria Line, it was a point of honour for some Piccadilly crews to make sure to bring their train to a stop, open the doors, complete platform duties, close the doors and get their train moving before the Victoria Line train had managed to decide where to stop. I think we were aided by the ATO difficulties with the hump profile.[10]

The service braking system on the Victoria Line has always been problematic. The 1967 Tube Stock has a combination of dynamic and electro-pneumatic air braking with the Westinghouse automatic air brake as the back-up. The dynamic braking is a crude (by today's standards) rheostatic system relying on a notching relay to control the rate of deceleration and which fades at about 20mph. After that, the retarder controlled e.p. brake takes over. The dynamic brake only operates on the 50% of the train's axles which are motored, the trailer cars using air braking controlled by the retarders. The retarders don't control the dynamic brake.

The dynamic brake also has a round-the-train inhibit circuit which switches it off the whole train if just one car fails to raise enough dynamic effort. If this occurs, the air brake has to replace it quickly on all axles and, unfortunately, it doesn't do this fast enough. This sometimes leads to overruns. However, drivers have got used the trains' quirky performance over the years and can usually spot when a train isn't braking enough so they stop the train by quickly applying the emergency brake. Thanks to their vigilance, overrunning the platform doesn't happen too often.

The stopping accuracy problem got worse when the CCTV monitors were modernised and placed on the platform edge. Previously, monitors were mounted on the platform wall about 3m high so they could be observed over the heads of passengers. There was one picture, transmitted from a camera located at the rear of the platform. The camera was provided like that to give the driver the guard's view of the train. As the best stopping accuracy they could get for the system was ±6 feet, the monitors were placed in the best position for visibility over this range. These monitor were replaced some years ago and the new monitor location on the platform edge requires a stopping accuracy of about ±500mm to get a reasonable view. Since the train can rarely do this on its own, the driver has to intervene, using the Westinghouse emergency air brake. This is the main reason for the very rough stops on the Victoria Line.

There are also problems with "underrunning" or stopping short. This is where the train tries to stop too early, leaving some doors at the rear facing the tunnel wall. If the driver sees this is happening, he has to quickly switch the train out of automatic operation and select manual driving. This is more difficult, particularly as he is doing it "on the fly" and he has to release and re-apply the e.p. brake in a very short time. Again drivers have become very adept at this. They regard it as a matter of honour not to get caught out by the mischievous behaviour of trains (some of which have a particularly bad reputation) and, for a long time, management positively encouraged them to intervene when necessary.

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[10] The Central Line's ATO system provides a hugely improved station stopping performance.

MODIFICATIONS TO STATION STOPPING

By the mid 1980s the auto driver boxes (ADBs) were 20 years old and they were becoming unreliable. With parts for them getting more difficult to obtain, it was decided to replace them with a modern electronic, microprocessor-based version. New boxes called RADBs (Replacement ADBs) were installed on the 1967 Tube Stock fleet in 1988-89 and the opportunity was taken to provide a number of enhancements. The most significant of these was a major modification to the station stopping system called “Distance To Go” or DTG.

DTG is an attempt to improve the accuracy of the final stop at each station by providing a stopping profile of each station in the RADB memory. This geographical profile is imposed over the original command spot control system, which then became known as the “Standby Mode”. When a train approaches a station, the first command spot initiates the original Standby Mode braking and the train decelerates under retarder control. When it reaches the 3kHz command spot (30mph), the DTG mode is automatically initiated.

Once DTG is initiated, the train brakes itself to a stop using the station profile stored in its memory for that particular station. As a back-up, the DTG braking is shadowed by the Standby system so that, if the train fails to brake properly, the Standby Mode takes over. The train will then brake under the original system.

In order that the correct station braking profile is selected, the first command spot which triggers the Standby Mode also "recognises" the station being approached. This is done by measuring the distance from the last station (where the start buttons were pressed). Where this distance may be similar at more than one station, the corresponding distance to the next command spot is also used and so on until the RADB is satisfied that it recognises the station being approached. Where this recognition process fails, the train will complete the whole station stop in Standby Mode.

As we have seen above, the coarseness of the rheostatic brake control means that during the last 50 feet or so of a station stop it is virtually impossible to release the brakes and successfully re-apply them without overrunning the stop mark. Because of this, a special point is provided on the DTG profile (called the MINDIST point) where the selection of release is inhibited. One could speculate that this may cause some instances of stopping short.

SPEED MEASUREMENT

So that the auto driver box knows what speed the train is actually doing, an axle end frequency generator (a “tacho” in engineering speak) is fitted to the “C” axle on the motor cars. As I mentioned above, the frequency of its output pulses are proportional to the train speed, using the same scale as the command spots. However the accuracy of this frequency/speed relationship is affected by the diameter of the wheels on that axle. Wheels get worn and their diameter is therefore not constant. Under the original scheme, wheel calibration was manual, only had two steps and had to be done in the depot by a fitter. So that the RADB can get improved station stopping accuracy, it has been arranged so that the train’s existing wheel diameter can be measured and a wheel calibration factor (WCF) determined.

The wheel calibration factor is obtained each time a train leaves the depot by means of three 5.0 kHz command spots placed just inside the tunnel portal on the approach to Seven Sisters station. These command spots are accurately located at 500 foot intervals. Calibration normally occurs between the first and second command spots but a third is provided in case one fails to activate the check.

DATA LOGGING

One of the enhancements of the RADB was the inclusion of ATO system data logging facilities. Information related to the operation or malfunction of the RADB and the ATO System is captured whenever the train is running in automatic operation. One may safely assume from this that any instances where the driver uses manual driving are recorded. Of course, the log also records faults, overruns etc., so unlike the original system, there is some record of intermittent defects. This is a real boon. Many is the time a driver reports a defect and, when the "call point" technician turns up to fix it, it's gone and you can't get it to repeat. Still, the technicians are usually very understanding about such things since they've met them many times before.

NADB

Since the introduction of the RADB, almost another 20 years has passed and it's become necessary to renew the ADB again. The trains will have to last another 6 years or so and the RADBs are getting on a bit. They also suffer from some problems, particularly control at the lower end of the station stopping profile, plus the usual difficulties of getting spares for ageing equipment. So now, another ADB has appeared – a sort of replacement ADB. Not wanting to call it that, they decided to call it the New Auto Driver Box or NADB. One feature of this box is the hope that it will be able to provide a gentle final stop as opposed to the rough stops currently experienced on the line. Another is that the stopping profile will be more accurate, getting down to ±1m. Also, the braking rate will be generally higher. This is, in part, a contributor to a reduced journey time requirement, although regular travellers would hardly notice the few seconds saved.

A special feature of the NADB is that the mercury retarder operated braking control is by-passed by using a "Hall Effect"[11] internal electronic accelerometer. The NADB also has improved data logging facilities and will be able to retain up to 15 days data logged during operations. So far, at least 10 trains have been fitted with it but there have been some teething troubles and the remainder of the fleet has yet to be done.

TRAIN COMMAND SYSTEM

What we have seen so far was originally described in early papers referring to Victoria Line ATO as the "train command system". It included the station stop commands, the 20kHz signal stop command and an additional 15kHz command. This last one was for coasting. If a train passed over a 15kHz spot, the motors were switched off and the train would coast to the next station stop or signal stop command. The coast command spots were controlled from the control room at Cobourg Street. Originally there was one switch for each direction of running but in the last couple of years some in selected locations have been disconnected as part of a small "interim upgrade" for the line.

Having seen the "train command system" or the ADB and its successors, the next thing to consider is the Victoria Line solution for signalling under automatic train

[11] A device using a small moving plate between two magnets which changes the voltage in an electric circuit according to the movement. Wouldn't you know, the effect was first discovered by a very clever man named Hall.

operation or, what we would now refer to as ATP. This involves some old LU principles being adapted for the “new” line, as the Victoria Line was in the 1960s. This will be our subject for next month.

To be continued …….