LONDON UNDERGROUND SIGNALLING
A HISTORY
by Piers Connor
21. CAPACITY

IMPROVING THROUGHPUT

The gradual increases in traffic which followed the electrification of the District and the opening of the LER tube lines in 1905-07 began to show the importance of managing the effects of station stop times – otherwise known as dwell times – and of getting trains into and out of stations as quickly as possible in order to shift the crowds. This was particularly important on the District and Hampstead lines, both of which had multiple destinations requiring accurate timing of train presentation at junctions. Originally, dwell times were set at 10 seconds for most stations but soon, longer times had to be allowed for certain busy stations. Times were still often exceeded and some means was sought to reduce the effects of a long dwell on following trains. One of a number of responses was a look at signalling improvements.

There was a gradual approach. It began a few years after the 1905-07 period of electrification and tube line openings. Initially, a number of stations were provided with an additional home signal, between the original home and the station. The idea was that the additional signal, with its own track circuit, would allow a second train to follow the departing train as it left the station rather than wait until it had cleared the overlap of the starting signal. The outer home would clear as the rear of the departing train cleared the track circuit in the platform and the inner home cleared as the train cleared the starter overlap. Timing tests showed that this allowed a 10 second reduction in train clearance time or gave a 10 second longer dwell for the same headway. The tests were part of a series described by Harold Brown, Managing Director of Westinghouse Power Signals, in a paper presented to the Institution of Electrical Engineers on 1 May 1914[1].

Brown's paper offered the first documented instance of a technical and operational study into the performance of modern automatic signalling on a high-capacity railway and on how it could be used to maximise throughput. He began by explaining certain basic constraints and then went on to describe the details of how they got round to the idea of multi-home signalling.

CONSTRAINTS

Brown began by reminding his audience of certain constraints regarding the throughput of trains. He mentioned specifically:

- The maximum speed of the train. He fixed this at 25 mph for the Underground. Today, on the older tube tunnel sections, it is usually about 35 mph.
- The acceleration and braking performance of the train. He set them at 0.45 m/s^2 and 0.8 m/s^2 respectively. The acceleration is less than half what you would get today but the 0.8 braking rate is what a good driver can get. In ATO, it will be about 1.15 m/s^2 for both acceleration and braking.
- Train length: This was set at 300 feet or about 91 metres.
- The length of station stops. This was given as 10 seconds.
- The geographical layout of the line (curves, station spacing and terminal layouts) and,
- The limitations imposed by the signalling system.

In an initial example of a station stop, Brown showed that the driver of a train approaching a station at 25 mph would need to see that the home signal (Signal 1 in Figure 1) was clear some 655 feet (200m) before the end of the platform. This distance was the sum of the overlap of the home signal (400 feet, the standard LER tube line overlap) and the sighting and braking distance of the signal (255 feet). The green aspect of the home signal would appear as soon as the train in front (Train 1 in Figure 1) cleared the overlap of the starting signal (Signal 3). Note that the overlap of the starting signal is 300 feet, not 400 as for the home signal. This was because train speeds were lower at the starting signal, not more than 20 mph, even for non-stop trains. For stations where all trains stopped, the starter overlap was even shorter – 15 to 20 feet, which was, according to Brown, permitted by the Board of Trade inspectors.

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1 Brown, H.G., 1914. 'The signalling of a rapid-transit railway. A study of the relationship between signal locations and headway', *Journal. IEE*, *52*, p.233.

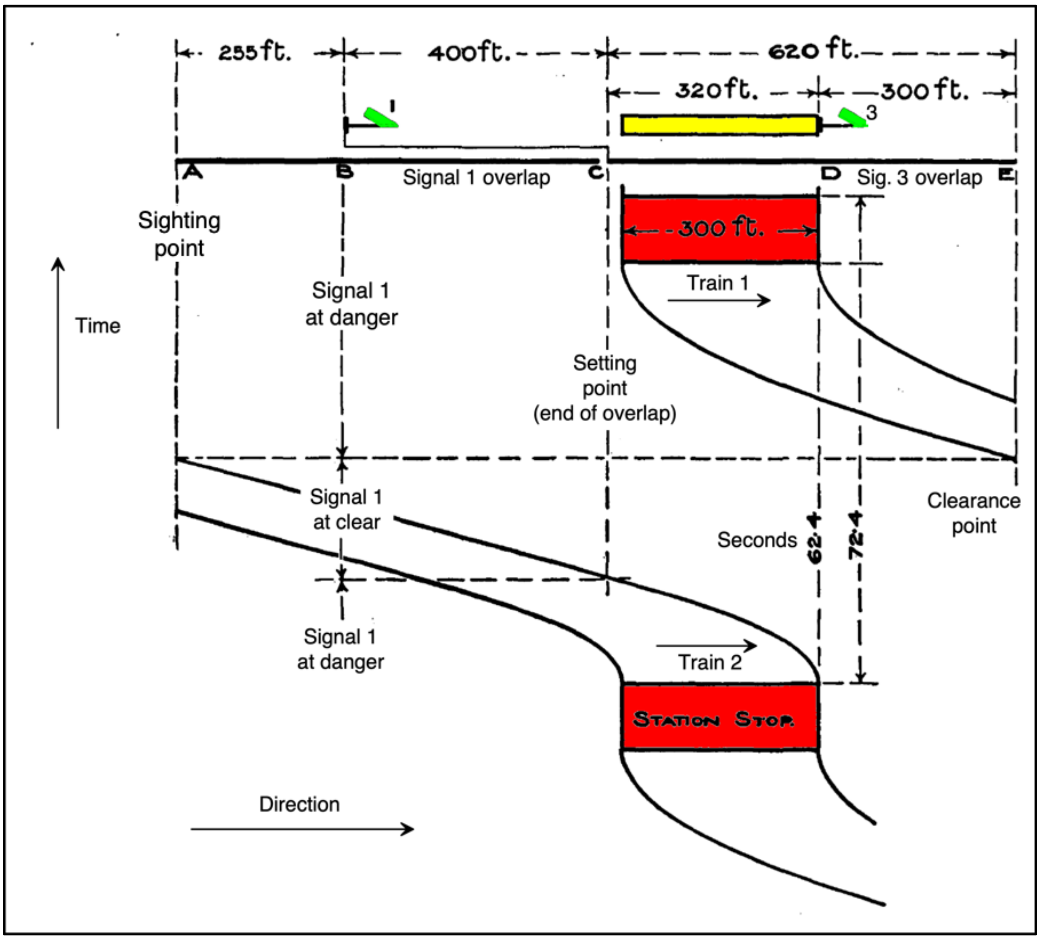

Figure 1: A diagram of the clearance times of a train leaving a platform (in yellow). The curves depict the front and rear of the moving train. The red blocks depict the train stop position and times. Signal 1 will remain at danger until the rear of Train 1 clears point (E) at the end of the overlap of Signal 3. Because of this, Train 2 stops in the platform 62.4 seconds after Train 1 and departs 72.4 seconds after Train 1. The headway is the time it takes for the front of a train to run from the sighting point of Signal 1 to when the rear clears the overlap of Signal 2, plus the dwell time (10s). Brown's diagram was later developed and widely used to show train headways up to the time of the Bakerloo Line resignalling in 1987-1991. Diagram modified by P. Connor from the IEE paper.

Brown showed that for a train to complete the station approach, stop and then accelerate away to clear the starter overlap and allow the home signal to show 'clear' to the next train, took a total of 62.4 seconds. If a 10 second station dwell time was added, the time increased to 72.4 seconds. This was the minimum headway possible but it was only possible if the rear of the first train cleared the starter overlap at the instant the driver of the second train first saw the clear aspect of the home signal. A simple assessment of the laws of probability will show that this sort of timing is impossible and that some extra time must be allowed for fluctuations. A margin of up to 30% had to be added for variations both in station design and location and in train driving performance and this, added to the minimum headway, became known later as the 'operating headway'. It was the basis upon which a timetable could be prepared. The theoretical minimum headway Brown described became known as the 'technical headway'. These terms are common today.

INITIAL AND CUMULATIVE DELAYS

Brown next introduced the concept of initial and cumulative delays. He described how an initial delay of 11 seconds to a train taking too long at a station went on to allow the delays to each of the following trains to accumulate. This was due to the next train being forced to slow down for the red home signal. Brown demonstrated that the act of slowing the train almost to a stop, then restarting it when the signal cleared and getting into the platform, added 19.45 seconds to the train's scheduled time. This time is made up of the 11 seconds original delay plus 8.45 seconds added for the signal check. On top of this, provided all the following trains maintained their allotted 10 second dwell, each one would be delayed by 8.45 seconds. From this, it can be seen that the 10th train would be 9 times 8.45s plus 11 seconds late departing the station. This made the 10th train 87.05 seconds late. If you totted this up at the end of a 3-hour peak, you're looking at the service running over 17 minutes late.

Brown reckoned that, with a single home signal, the minimum practical operating headway would be 120 seconds, i.e., two minutes or 30 trains per hour. If we add a 30% margin to his original 72.4s headway, we increase it to 94s. This would allow a longer dwell time of up to 26s, much more realistic. Today, maximum peak hour dwell is supposed to be 40s but we have much better acceleration and braking rates.

In the pre-First World War days on the Underground, the volume of passengers was not nearly as high as it became during and after the 1914-18 war but the seriousness of the delay patterns already being seen was enough to encourage the Underground to look at ways of relieving the problem. One solution was to reduce the delay caused by the signal check to a following train when a train ahead exceeded its dwell time. To do this, additional home signals were installed (Figure 2). They became known as multi-home signals.

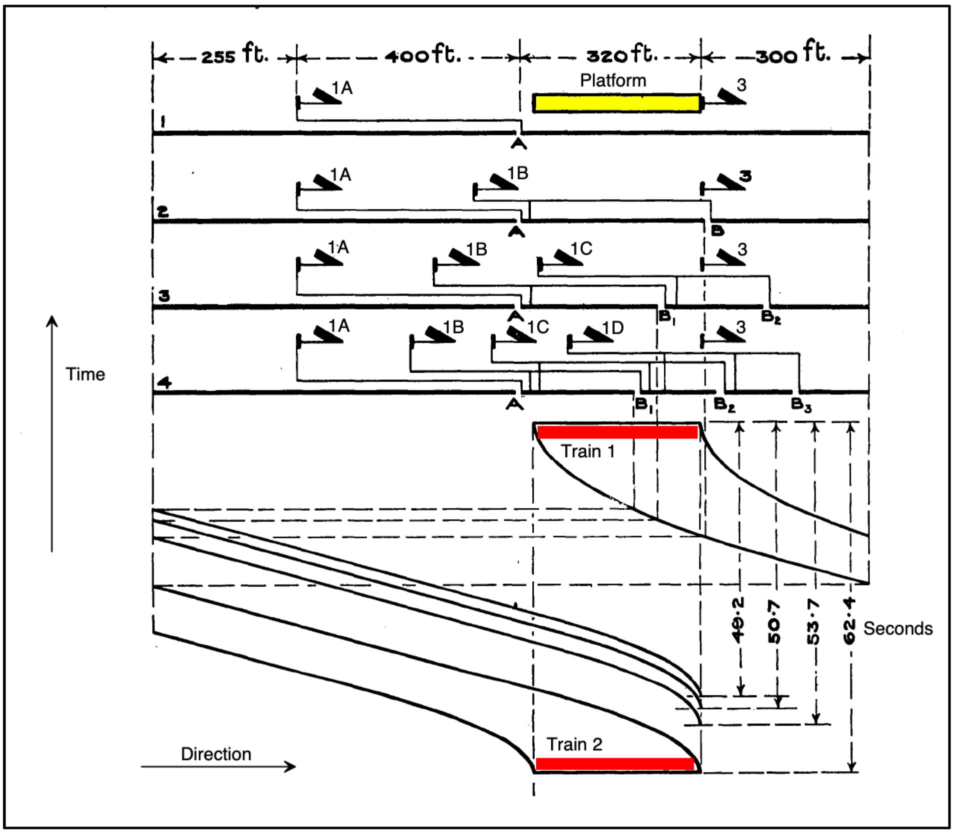

Figure 2: Brown's diagram showing how the headway is reduced by the installation of additional home signals placed within existing station limits. Line 1 shows the original plan for a single home signal (1A). Line 2 shows an additional home signal (1B). Signal 1A will clear as the train clears point B next to the starting signal and providing a 320 ft overlap. This reduces the headway from 62.4s to 53.7s. With two additional signals, this goes down to 50.7s and with 3 added (four homes in total), it becomes 49.2s. The clearance point for each signal is calculated so that they all clear in sequence as the preceding train clears the platform and starting signal overlap. Drawing modified by P. Connor from the original print of the IEE copy.

Brown describes in detail the methods of calculation for the location of each signal and he also explained that the optimum solution for each site was best obtained by carrying out observations in real time and then testing with trains. He showed how, correctly positioned, the additional signals could reduce the headway or allow additional dwell time for the same headway as the original. Either way, there was a benefit. Brown did note that the most cost-effective solution was normally a 3-home signal arrangement, as the 4th signal only saved 1.5 seconds extra and thus wasn't really worth the extra expense. In later years, when longer trains were introduced, the 4th signal was provided for some busy stations.

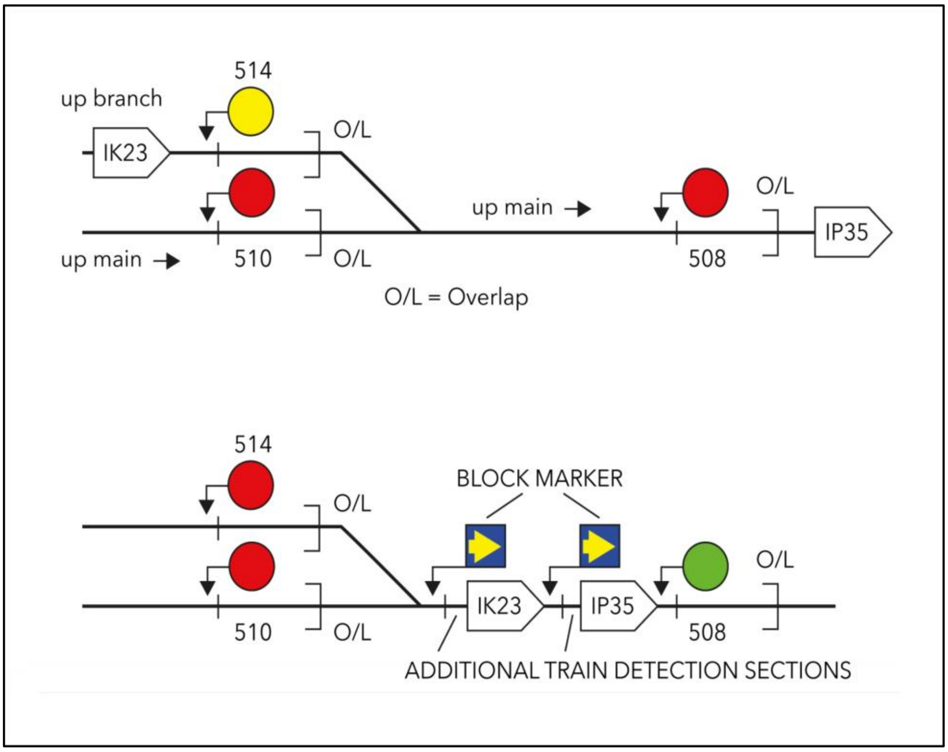

Figure 3: Multi-home signalling finally reached the main line in 2017 over 100 years after it was first adopted on the Underground. This diagram shows the original signal layout (upper diagram) and the later (lower diagram) multi-home arrangements on the approach to St. Pancras Thameslink station. The additional train detection sections and home signals (labelled Block Markers) installed with the European Train Control System (ETCS) allow trains to approach the station at much closer intervals than was possible with the old system. It is said that the new arrangement here and at other locations on the core section of the railway allow an increase in throughput of up to four trains per hour. Diagram from Rail Engineer, March 2018.

The multi-home arrangement soon became established and was so successful that it survives to the present day. Now, even the main line railway in Britain has started using it (Figure 3). On the Underground, the system was updated over the years with specifically calculated overlaps for each station but, as a driver, I noticed that some locations were better done than others. If the signals were correctly positioned, they would clear one after another in even time as you approached behind the departing train. If they weren't placed in quite the right locations, they would clear too quickly, or too slowly compared with the speed of your train. To some extent, the types of trains had an effect. Following a Q Stock on the District was always a slow process since their acceleration was poor compared with the R Stock, which took off a lot more quickly.

SPEED CONTROL APPEARS

Brown went on to introduce the idea of speed control signalling. In 1914, this was new for Britain but it was already in use in the US. It was reported in the New York Times for 23 December 1908 that a new system of speed controlled, multi-home signalling had been installed at 96th Street station on the Interborough subway in the city.

The system was arranged so that the train approaching an occupied platform was allowed to approach closer than normal to the train in front provided it was proved that its speed was reduced to match the reduced length of the overlap. To force the driver to reduce the train's speed to the required level, the outer home signal was held at red until the train reached a certain point where its speed would be low enough to be able to stop at the signal or that, if tripped, it would stop before hitting train in front. At that point, the signal would clear to allow the train to roll forward towards the next signal, where the same process took place but at a lower speed.

I have not been able to find any more details of how the original installation worked but, soon afterwards, descriptions of a 'time element relay' appeared in the technical press. This relay was used to hold the signal at red for a specific time after the track circuit on the approach to it was activated by the train. The relay could provide a delay of up to 30 seconds but they were generally set at much lower intervals. When the Underground began to use them, they were set at either 4.5 or 15 seconds.

In the US, there were at least two suppliers; our old friends, Union Switch & Signal and the General Railway Signal Company of Rochester, New York. Broad descriptions of both of them appear in early 20th Century trade literature[2]. They were rapidly adopted at busy stations on New York subway routes from 1908 onwards and they were also used for limiting train speeds to 15 mph on the downward gradients at the ends of the Manhattan and Williamsburg bridges. They were common around the system by 1914 and they were still in place on these bridges when I did train testing trips over them in 1983.

Having described it, Brown then said he didn't like speed control. He complained that it "*had the drawback that the deceleration of the train is checked only at certain points. It is possible to enter a section at a speed below normal and then to accelerate, passing the next signal after it had cleared and then being tripped by the following signal, by that time having attained a higher speed than was anticipated at that point. An arrangement of sections and section times which would satisfactorily overcome this would partially defeat its own purpose".* Over 30 years later, as we will see, Brown was to be proved right.

He went on to say that he didn't think speed control was worthwhile, even for steep inclines, (like those fitted on the New York bridges over the East River) or junctions. He wasn't to know that 25 years later they would appear in London and, after World War Two, sophisticated systems would be installed on the Piccadilly and District lines. Perhaps his resistance was why it took so long for London to accept them.

SPEED CONTROL IN LONDON

Although a form of speed control using approach control on a track circuit had been introduced at Watford South Junction in 1925, as I described in Article 18, it does not seem to have been used elsewhere on the Metropolitan or the Underground until another version of it appeared in 1939, when a new speed limit control was brought into use on the Northern Line extension to East Finchley.

The former Hampstead Line branch to Highgate was extended to East Finchley on 3 July 1939. It was decided that the observance of the 30 mph speed restriction on the curve at the bottom of the long 1 in

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[2] Railway Age Gazette, 23 March 1916, p.659 and '*Railway Signalling*', and Everett Edgar King, McGraw Hill, New York, 1921, p.236 et seq.

50 down gradient on the southbound road from Highgate to Archway needed to be enforced, more for safety reasons but also for comfort.

The arrangement was described in 1944 by Robert Dell, the Underground's Signal Engineer[3]. He showed that it was done using two speed-controlled signals, with a 40 mph speed limit on the approach to the first and a 30 mph on the approach to the second. The signals were held at red until the speed of the train was deemed to be under the required limit. The signals were each controlled by a time element relay with a 4.5 second delay, which was triggered by the occupancy of an approach track circuit (Figure 4). The length of the track circuit was calculated to match the required speed. Another, single speed-controlled signal set for 30 mph, was also installed on the southbound between East Finchley and Highgate at the end of the 1 in 61 using a single 198-foot timing section[4].

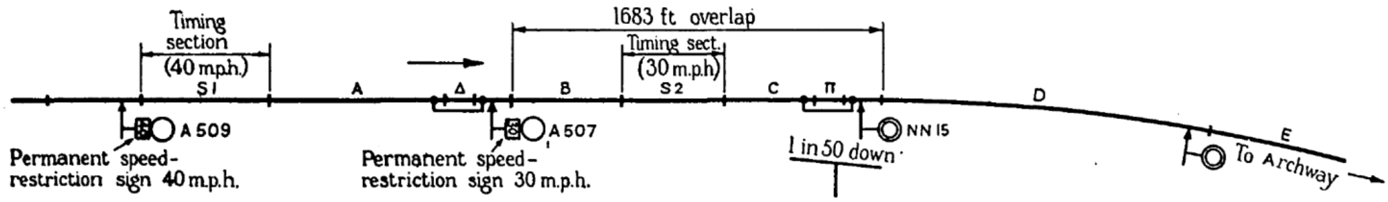

Figure 4: Speed control comes to London in 1939. This diagram of the southbound road between Highgate and Archway on the Northern Line at the time shows the location of the timing sections controlling signals A507 (40 mph) and NN15 (30 mph). The 40 mph sign was placed at the signal in rear (A509) and immediately afterwards the track circuit S1 activated the time element relay. If the train occupied Track S1 for 4.5 seconds before reaching Track A, Signal A507 would clear. If it reached Track A too early, the signal would remain at danger and the driver is forced to stop at it. If this happened, a short rail circuit adjacent to the signal was activated to allow the signal to clear after the came to a stand. This was to become known as a 'delta track'. A similar arrangement was provided for Signal NN15. The timing sections were designed for the particular speed required so Track S1 was 266 feet long and Track S2 was 198 feet. Drawing from Dell, 1944.

If the train ran through the timing track at too high a speed, the signal remained at red. Once the train had proved it had arrived at the signal, it would clear but only after the train had drawn up close. This was achieved by a special short (11 foot 6 inch) track circuit placed just in rear of the signal. When the train arrived on it, the signal would clear. This track circuit was known as a 'delta track'. It was to become a device used widely around the Underground, primarily to confirm train location.

There is evidence that Delta tracks were used earlier than their appearance on the Northern Line in 1939. Exactly when isn't clear and the only evidence I can find is in the resignalling carried out on the Northern City Line at Moorgate in 1937. This was in conjunction with the calling-on signals installed there[5]. The train had to occupy the Delta track before the calling on signal could be lowered. Prior to this, approach track circuit occupancy or tripcock treadles provided the release for the control on the signal.

CENTRAL LINE RESIGNALLING

Despite the availability of time element relays and the knowledge that subways in the US were using quite sophisticated forms of multi-home speed control, they were still being resisted in London in 1940 when the Central Line was being resignalled between Wood Lane and Bank following the platform lengthening works to allow 8-car trains to be run. The new signalling was commissioned between July and October 1940. The standard three multi-home signals were put in at most stations but there were four at busy sites like Oxford Circus and Tottenham Court Road or where train speeds were limited on the exit from the platform, like Shepherd's Bush westbound or where a siding or crossover was in place

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[3] Dell, R., 1944. 'Developments in railway signalling on London Transport'. *Journal of the Institution of Electrical Engineers – Part II: Power Engineering*, *91*(23), pp.400-415.

[4] I have not found any record that time element relays were used before this installation but Tom Crame notes that evidence would suggest they were in use prior to the 1939 Northern Line installation though not in signal control functions – Notice to (Chief Signal Engineer's) Drawing Office staff 42/1937 refers.

[5] These calling-on signals were unusual in being a single lens type which showed a small green light when the driver was required to draw forward in the platform to couple up.

like Marble Arch. Bank had five home signals on the westbound but the last one was actually in the platform and was simply a trainstop with no lights. There was no room for a proper signal so the driver had to watch to see the trainstop go down as the previous train cleared the overlap track 160 feet beyond the starter. Oxford Circus also had a 'blind trainstop', as these were called, in both platforms. Train crews soon began to refer to them as 'policemen'. Blind trainstops had appeared the year before on the Bakerloo when it was resignalled for the extension of services to Stanmore in 1939, again after platform lengthening. I've not found any evidence to show that they were used prior to this time but …

A new idea was introduced at Holborn. The outer home signals in both directions were approach-controlled using delta tracks. These were positioned 20 feet in rear of the signal so that, when the front of the train reached that point, the signal cleared, even if the train in front was still in the platform. The idea was that, since the driver had slowed the train, the next signal would be approached at the lower speed and still have a safe braking distance if the train got tripped. This was supposed to keep it within the safe distance allowed by the remaining overlap of 145 feet. The speed of the train at the delta track would have to be down to about 5 mph in case it had to stop at the signal. There was no time delay.

A delta track for the outer home was also installed at Chancery Lane eastbound. In both locations, the purpose of the arrangement was to get the rear of the train clear of the overlap of the starting signal of the station in rear. Bearing in mind that drivers would soon learn to anticipate the outer home clearance, this arrangement was a hostage to fortune. It would end up being proved almost 40 years later.

One driver, approaching Holborn westbound on 9 July 1980, knew the setup and assumed that the train ahead would leave as he approached. It had always done so before so why not this time. He approached at normal line speed. As he entered the delta track, the first signal cleared. He expected the next one to clear as the train in front left the platform but it didn't and he got tripped at close to full speed. The overlap on this second signal was not designed for a full speed trip and the train ran through to the rear of the one in the platform and collided with it at about 12mph. It turned out that the train in the platform was delayed while the crew were attending to a sticky door. Luckily, no one was killed but a valuable lesson was learned. If you devise a system which relies on the integrity of a wide variety of users, eventually one of them will find a way to abuse it. As a result, approach control of this type on the other Central Line signals was quickly removed[6].

POP-UP SIGNALS

In September 1941, a year after the Central Line resignalling, a modification was introduced on some of the central area signals. In several locations between Shepherd's Bush and St. Paul's, selected automatic signals were modified to become 'approach lit'. Taking the arrangement at Oxford Circus as an example (Figure 5), when a train occupied the platform, the three home signals in rear would be protecting it but the red aspects would be suppressed, even though the trainstops were in the raised position. This meant that the signals would be invisible to an approaching train until it reached a certain point. At this point, the red lamps of the signals would switch on and the driver would slow down the train as required. These signals quickly became known as 'pop-up signals'.

Originally, 11 signals on the eastbound and 10 on the westbound were treated in this way. Later, more were installed near Bethnal Green and Mile End and in the Redbridge and Gants Hill areas when the eastern extensions were opened in 1946-47. In the original installation, all the home signals at Oxford Circus and Tottenham Court Road (both roads) and Bond Street (westbound) were done, together with the outer and intermediate homes at Bond Street eastbound. Some intermediate signals were also done, along with the outer home repeater at St. Paul's westbound. All the signals involved were chosen because they were visible from a long way in rear. A classic example is the view from Tottenham Court Road (westbound) towards Oxford Circus. Even as a passenger standing on the platform at Oxford Circus, you can look back and see the headlights of the train at Tottenham Court Road. Although later, selected signals in other locations were treated this way, the Central Line was unique in using them in such numbers. This was because the line was largely straight. The rationale behind the scheme was described by Robert Dell in his paper to the IEE in 1944[7].

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6 King, Major A.G.B. (1983), Report on the Collision that occurred on 9 July 1980 at Holborn Station. H.M. Stationery Office.

7 Dell ibid.

Dell thought that to get the maximum throughput of trains, drivers needed to follow just two instructions – go as fast as possible on seeing a green signal, and, on seeing a red signal, stop at it as quickly as possible. This philosophy still holds good today, whether or not it's followed or even allowed. On the Central Line, the generally straight geography of the route across central London meant that, unlike other tube lines, red signals could be seen from a long way back and the temptation for drivers was always to avoid stopping in the tunnel by approaching red lights slowly. The trouble was that this regularly held up following trains. Dell commented that often the signal would clear before the train got close to it, so that, if the driver hadn't slowed up, the signal would still have cleared long before he reached it.

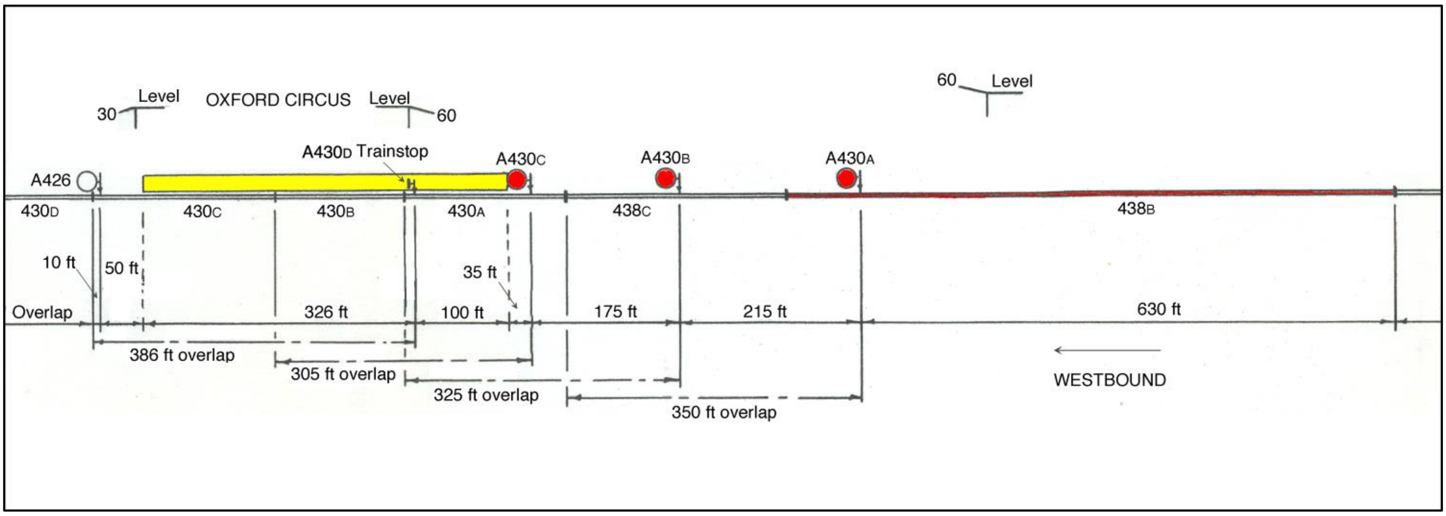

Figure 5: A diagram of the signalling installed on the westbound Central Line at Oxford Circus in 1940. The standard setup of three home signals is shown together with their overlap distances. Also shown is the equivalent 4th signal, the blind trainstop in the platform (A430^D). If a train was standing in the platform, all three signals would be set to show a red aspect but it would be suppressed until a following train entered track 438^B when they would 'pop up'. At that moment, Signal A430^A would be 630 feet in front of the driver. At 30 mph, this gave the driver 14 seconds to react and brake to stop at the signal if necessary. This was plenty of time. The hope was that, before the train stopped, the train in the platform would be on the move and A430^A would clear and allow the train behind to roll into the platform as the remaining signals cleared. Note the 1 in 60 gradient up into the platform and the 1 in 30 out to assist braking and acceleration. The 1 in 60 extends into the platform for 100 feet because the platforms were extended to take 8-car trains. Drawing from Supplement to Traffic Circular 27/40 modified by P. Connor.

Drivers getting familiar with the operation soon found that it allowed enough time to see and react to the popping up signal but, as they say, familiarity bred contempt and drivers knew that a train was in front and tended to drive more slowly anyway, partially defeating the object. Nevertheless, Dell's scheme must have been considered a reasonable success and it remained in place until the line was converted to ATO in the mid-1990s.

Other locations had 'pop-up' signals, as between Aldgate East and Tower Hill westbound and the wrong road starter at Northwood. Very few remain today but there were examples at Morden, St. John's Wood – Baker Street (Jubilee) and two at Baker Street (Met.) until recently. The only one remaining on a 'main line' now is A386 on the Heathrow loop, where it is on a long straight section. Most of the Baker Street examples were due to the potential for read-through confusion.

To be continued …