Impacts of Automatic Train Operation on track & infrastructure

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INTRODUCTION

The world's first Automatic Train Operation (ATO) railway was the Victoria line when it opened in 1969 as part of London Underground (LUL) and following its subsequent upgrade in 2009 it is now capable of delivering a 36 train per hour service with headways of 100 seconds. Linking major terminal stations at Victoria, Euston and Kings Cross makes it one of the most critical points of failure within the overall integrated transport system, which is the responsibility of Transport for London (TfL).

Attempting to meet the demand for public transport has been the major challenge for TfL, and its forerunners, since the population of London began to increase again in the 1980s following its gradual decline since the Second World War. Chronic underinvestment in the system led to the failed Public Private Partnership (PPP) of the 2000s, which aimed to deliver the increases in reliability and capacity which were required to prevent the city grinding to a halt daily. The number of daily journeys across the network continued to climb steadily until March 2020.

Ridership across the tube was as low as 5% during the first Covid-19 lockdown, only ever rising to around 30% when restrictions were at their loosest during the summer of 2020, but hopefully as you read this in April 2021 there are signs of normality returning. The impacts of the global pandemic on ridership numbers will not become clear for months or even years, but as ever 'the prosperity of London and the health of its public transport system are inseparable'[1].

The challenges which ATO has brought to the maintenance of the Permanent Way, as well as all the other systems which make up the railway, are particularly acute on a system as old as LUL where many of the challenges are in-built. This article is written from the perspective of the Permanent Way engineer who is responsible for managing the interface between rolling stock, track and signals. The 'system of systems' which makes up an operational railway requires all engineers to take a holistic view; my experience means I do this even more than others. However, I am not an expert in signalling, automatic train control, traction or braking, merely an interested party!

THE CAPACITY CONUNDRUM

Increasing capacity on railways can be achieved in several different ways. Running bigger trains, such as double decker versions widely used on the continent, is an obvious first option but even on the mainline UK network the inherent gauge limitations of the infrastructure prohibit this, and this is an even more acute challenge for LUL. Since the construction of tunnels switched to the 'deep tube' method in the 1890s, rather than the 'cut and cover' method used for the first sections of the underground from 1863, which was enabled by the change from steam to electric trains, the maximum gauge of 'tube' trains has been severely limited (Figure 1).

Another option is to run longer trains with more carriages, however longer trains require longer platforms to allow that capacity to be effectively utilised, especially when dwell times are so short in order to keep throughput high. Extending platforms in deep tube stations is enormously expensive as it would require significant tunnelling to increase the size of the wider station boxes (Figure 2).

The final method that does not involve construction of new routes to increase capacity is to increase the maximum train speeds and hence reduce the journey time between stations, allowing more trains to be run. This is an option available to increase capacity on LUL, especially on the longer inter-station runs which are typically found the further from the centre of London, but is of limited value when inter-station runs are routinely as short as 500m, and 261m in the case of the shortest between Covent Garden and Leicester Square where it would be quicker to walk!

A much greater reduction in journey times for these shorter sections can be achieved by increasing the acceleration and braking rates, rather than by increasing the maximum achievable speed (MAS). The maximum achievable speed is inherently limited by the geometry of the tunnels, which prior to the construction of the Victoria line, were required to run parallel to the streets above them due to the cheaper land values, even once the deep tube tunnel construction method did not require the road to be dug up in order to build them. This has resulted in some unique geometries such as the Caxton curve located between Shepherds Bush and White City on the Central line where the radius is as tight as 70m.

Indeed, the iconic need to 'Mind the Gap' is a result of some of the extremely challenging curvatures through the platforms, such as Bank on the Central or Paddington on the Bakerloo (Figure 2), which result in some extremely non-compliant platform stepping distances. Approximately 36% of the entire track on LUL consists of curvatures tighter than 900m, 17% of it below 400m and this results in enormous challenges managing the wheel-rail interface, many of which are exacerbated by the implementation of ATO.

Therefore, the only method available to LUL to increase capacity has been to run more trains, closer together using a variety of different signalling systems under ATO. Most of the systems on LUL have achieved this by moving from fixed block to moving block systems. Fixed block systems maintain separation by limiting a train's authority to move based on the physical separation of trains using distance; moving block can change a train's authority to move based on its relative position to the train in front using the speeds from both. This allows trains to be run safely closer together as they are no longer having to assume the position of other trains relative to itself.

TONNAGES

The introduction of ATO across most lines has resulted in an increase in the number of trains per hour (TPH) significantly, if not across the whole line then through the busiest central sections. Figure 3 shows the changes in Million Gross Tonnes (MGT) from 2011 for 3 lines where ATO has been implemented: Victoria (Green Park to Victoria), Jubilee (Baker St to St Johns Wood) and Northern (Bank to London Bridge), and the final example where the current switch to ATO is being commissioned on the Sub Surface (Farringdon to Barbican). This shows an even greater increase than the deep tube lines despite the similar TPH because the S-Stock has an approximate axle load of 8.5 tonnes, compared to nearer 5 tonnes for tube gauge stocks.

Any notion that LUL should still be considered as a light rail system has definitively been removed by the implementation of ATO. The method of accumulating tonnage may be very different to mixed traffic, or dedicated freight networks, but as the majority of the defects which are dealt with are based on an accumulation of fatigue then running lots of trains, even with relatively light axle loads, is a very effective way of reducing asset life. Track maintenance has become much more risk based in the last decade and many activities are defined in MGT intervals rather than time, which allows much more informed decision making when the impact of changes in the system are being assessed.

Track is not the only area which has had to move from time-based maintenance. Some fleets had biannual planned wheel turning prior to a wide-ranging study redefining these intervals based on the predominant failure modes[2]. On one line, as train frequencies were increased with the implementation of ATO to allow a 34tph service, two years was no longer the same in terms of wheel wear when individual train paths on a daily basis could be as different as 400 km. Asset management systems also had to be adapted to allow maintenance intervals to become mileage based, especially in the context of other systems on the train which do not necessarily degrade in a linear fashion like wheel wear.

The next generation of tube train which will be delivered under the Deep Tube Upgrade Programme (DTUP) should deliver significant improvements in the ability to steer through tight curves and reduce forces in the contact patch through fundamental changes to the bogie concept design. However, they will have an increased axle load which even prior to the introduction of ATO will have major impacts on the single biggest cause of rail breaks on LUL, fishplated bullhead joints[3] which equates to approximately 40% of the network. The lessons learnt from the Victoria and Northern line upgrades, where individual axle loads were not significantly increased, is that this inherently weaker rail section is completely unsuitable for running at 40MGT per annum. Therefore, changing the rail section through flat bottom conversions has been prioritised over full track reconstruction as its rate of delivery is much quicker and the costs much lower. This is not an ideal solution but will enable the biggest safety risk to be removed much quicker ahead of DTUP, as well as reducing the number of maintenance inspections.

THE ADHESION CHALLENGE

There have been enormous amounts of research into low adhesion at the WRI in the last few years and our understanding of this area has much improved. LUL has to manage adhesion at both the low (55% of the network is above ground) and high ends of the scale. Leaf fall plans for each line are implemented every Autumn which involve combinations of vegetation management, rail adhesion trains (RAT) and increased wheel turning capacities to cope with flats.

In most upgrade projects ATO has normally been implemented alongside a new train introduction, and this has almost always led to a change from DC to AC traction. This has normally come with much improved Wheel Slip Protection (WSP) systems which allow much better control of braking in low adhesion conditions. These systems have been very successful in reducing the amount of wheel flats suffered, although Autumn timetables are still implemented based on weather conditions which require reduced braking rates.

However, following the introduction of ATO on lines with modern AC traction systems and WSP, an entirely new rail defect emerged: the squat type defect. These started to appear on the Central, Northern and Jubilee lines in prodigious numbers from around 2010 and ultrasonically appear no different from mechanically induced conventional squats. Initial metallurgical analysis identified the presence of martensite above the cracks indicating thermal transformation of the steel[4] had taken place which would require temperatures in excess of 727°C. Further modelling of the traction package of a 92TS (Central) demonstrated that this was possible during low speed slip recovery in damp (as opposed to contaminated with leaves) conditions[5].

This explained why these defects are predominant around major junctions where under ATO train speeds are reduced, without necessarily coming to a stop, to regulate the service in the event of traffic disruptions yet are extremely rare in platforms, and only in open sections where nature creates far more low adhesion events than the occasional artificial ones created in the tunnels.

Figure 1: Deep tube concrete (left) and sub surface ballast (right) track-forms

Figure 2: Paddington Southbound platform on the Bakerloo line

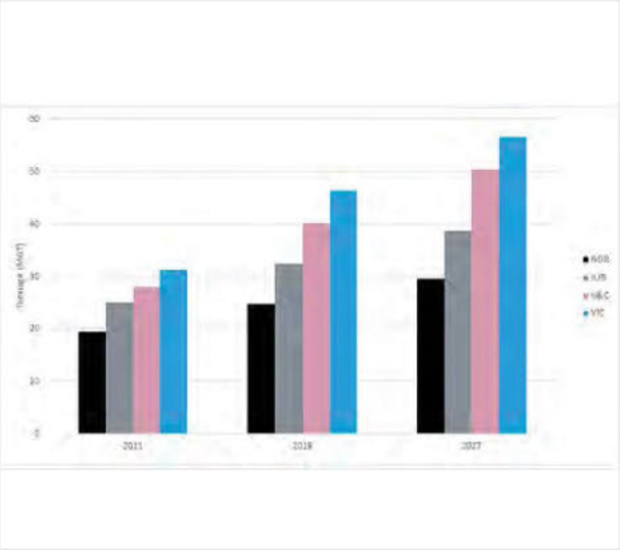

Figure 3: Tonnage forecasts (pre Covid-19)

Occurrences under 'damp' rather than 'contaminated' conditions also fits with much anecdotal evidence provided by train operators on manually driven lines that controlling accelerating and braking when rails are moist from dew or drizzle is far more difficult than in soaking wet saturated conditions. Defensive driving techniques in manual operation may be good at protecting assets but reductions in braking and acceleration rates result in lower tph, the conundrum which the whole industry has battled with for many years in the Autumn.

The solution is to modify the WSP system to change the algorithms in managing low adhesion, and indeed we are currently awaiting software changes to S-Stock which will allow this, and the first unit of 92TS with a new traction package is ready for dynamic testing on the Central line in 2021. This unfortunately involves physical changes of the motors (which also suffer from major reliability issues) rather than software so will take a lot longer for the benefits to be realised.

The short-term solution combined changes to the standards based on monitoring several defects which were left in the track, as well as the implementation of a preventative grinding programme. The initial studies which were conducted demonstrated that the cracks below the martensite rarely propagated to any significant length or depth and were very low risk of leading to broken rails. Therefore, they can be categorised as 3M (no Emergency Actions and monitored in line with the normal ultrasonic testing frequencies). Should they start to propagate, they can be removed through a head wash weld repair process, or because they tend to occur in clusters then the longer timescales afforded to the maintainer can make it more economical to carry out re-railing to remove a number of defects.

Grinding was implemented as a preventative measure on the hypothesis that each individual activation of WSP was not necessarily resulting in a squat type defect every time but that repeated activations were forming a layer of martensite in the railhead, which being inherently more brittle was more likely to result in crack formation. Alternatively, the grinding is removing defects which are so shallow they have not even been detected ultrasonically (the grinding is never intended to remove defects which have already been identified).

This is the only kind of grinding on LUL which I categorise as preventative because the martensite layer is shallow enough that minimal material removal is required (target is 0.3mm). The limited gauge of deep tube tunnels means the grinders which LUL utilise have only 8 stones, requiring multiple passes of the same machine for significant material removal, and whilst the sections which are ground for squat type defects are in open sections, we use the same machines as the programme is not flexible enough to allow different machines in different locations.

The preventative grinding approach has been successful at reducing the number of squat type defects (normalised by line per open km of track) as can be seen in Figure 4 and is now proving even better value for money since closures have been granted for maintenance activities. Grinding in closures for squat type defects has reduced the costs to around £3/m from approximately £40/m in engineering hours; this is mainly due to many of the costs per shift being fixed whether the working window is 52 hours or 3 hours (which normally results in a maximum of 1 hour of actual 'spark time'). The Victoria and Waterloo and City lines do not suffer from thermally induced squats as the passenger running parts of the lines are all in tunnels.

Squat type defects are a result of low adhesion, however two of the other major rail defects suffered by LUL are affected by high adhesion between wheel and rail, and are exacerbated by ATO: rolling contact fatigue (RCF) and corrugation. The relationship between steel wheels and rails can be analysed in infinitesimal detail (necessarily so) and it is beyond the scope of this article to do so but some of the basic principles are required to understand why ATO has such an impact.

A way of thinking about adhesion between wheel and rail is to consider another contact patch which many of us are familiar with; that between your car tyres and the road. If you are sat in your stationary car on a dry tarmac road then you can put your foot on the accelerator as hard as you like and you will move away smoothly and accelerate. If you now place your car on an icy road and put your foot hard on the accelerator, then you are likely to start the wheels spinning and you will not be able to move.

However, it is possible to drive on ice, but you need to very gently apply the accelerator because the lower friction between the surfaces means there is less adhesion available to support demand from the wheels to accelerate. It is possible to drive at the same speed on the dry and icy roads, up to a point where all the adhesion has been used up, but to do so in the icy situation more of the contact patch will be slipping than in the dry situation.

In railway wheel-rail interface terms we describe this as the creep-creepage relationship where some of the contact patch remains in stick, and some of it is in slip as illustrated conceptually by Figure 5.

The maximum amount of creep (T) that can be supported at the interface is related to the normal load of the wheelsets (N) multiplied by the friction between the two: $T = \mu N$

A simple rearrangement of this formula gives the traction ratio (T/N) where the maximum amount of creep force that can be supported is limited by the friction between the two surfaces, with the amount of creepage between them increasing to accommodate this, often referred to as creep saturation.

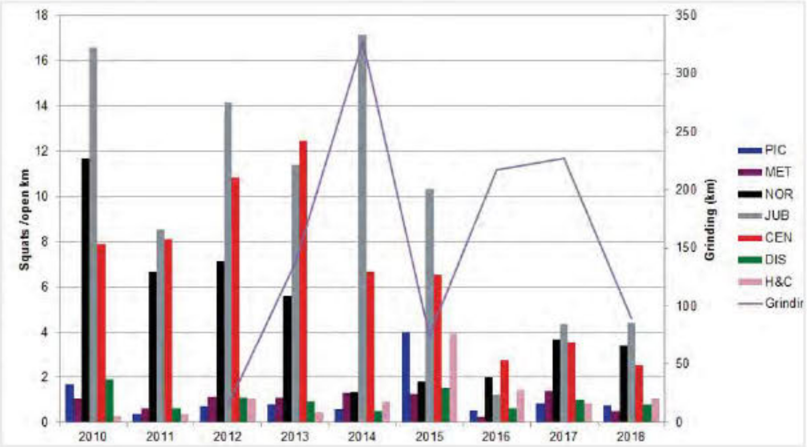

Figure 4: Squats per open km and grinding volumes per annum

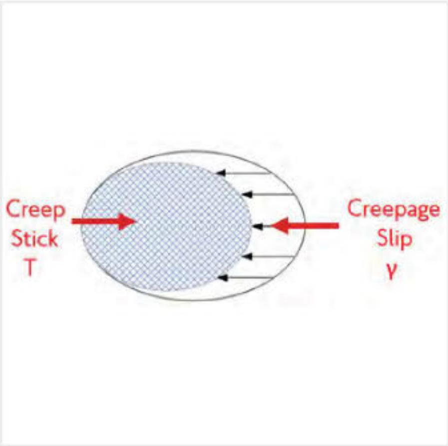

Figure 5: Relationship between creep and creepage

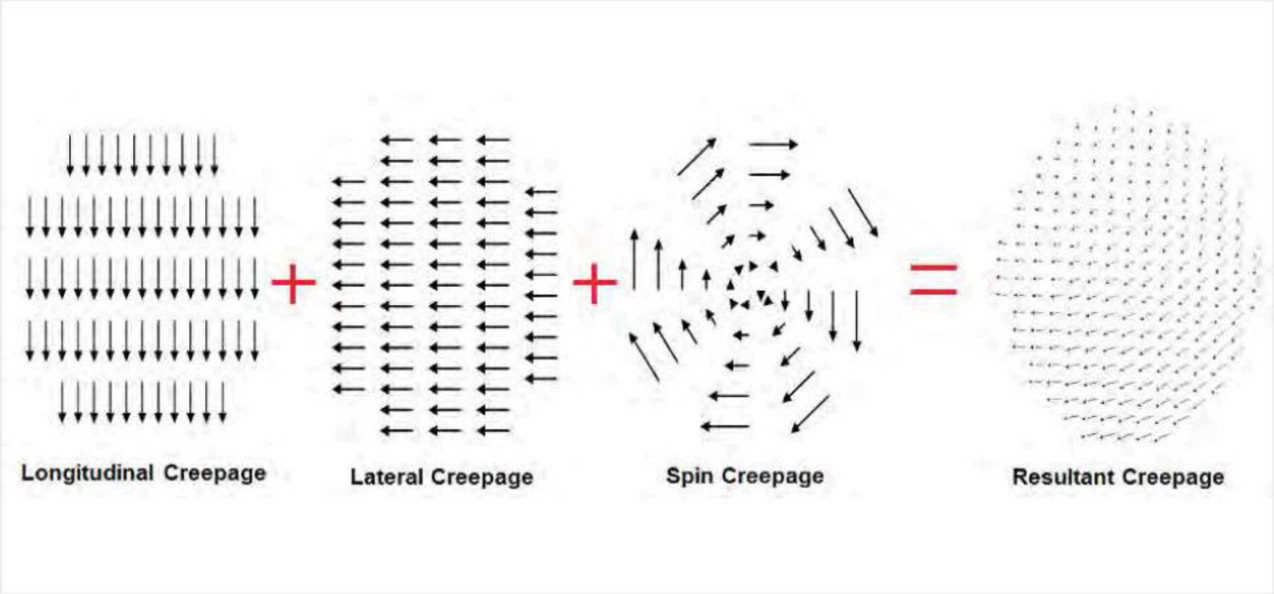

Figure 6: Resultant creepage in curving

Figure 7: Short wavelength corrugation on LUL

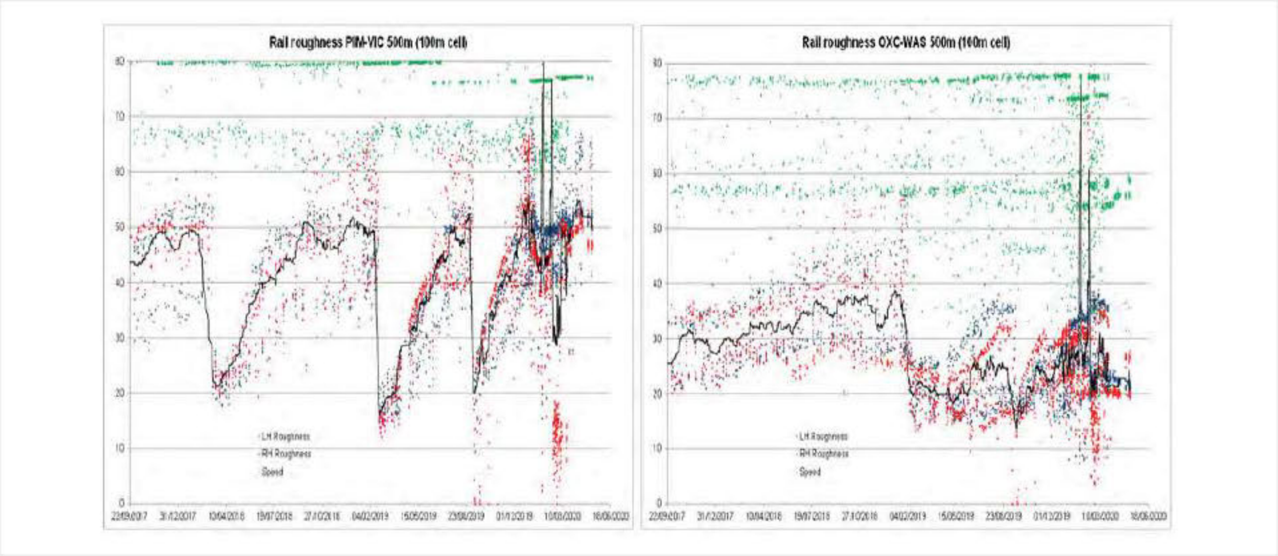

Figure 8: Rail roughness growth Pimlico to Victoria (left) and Oxford Circus to Warren St (right)

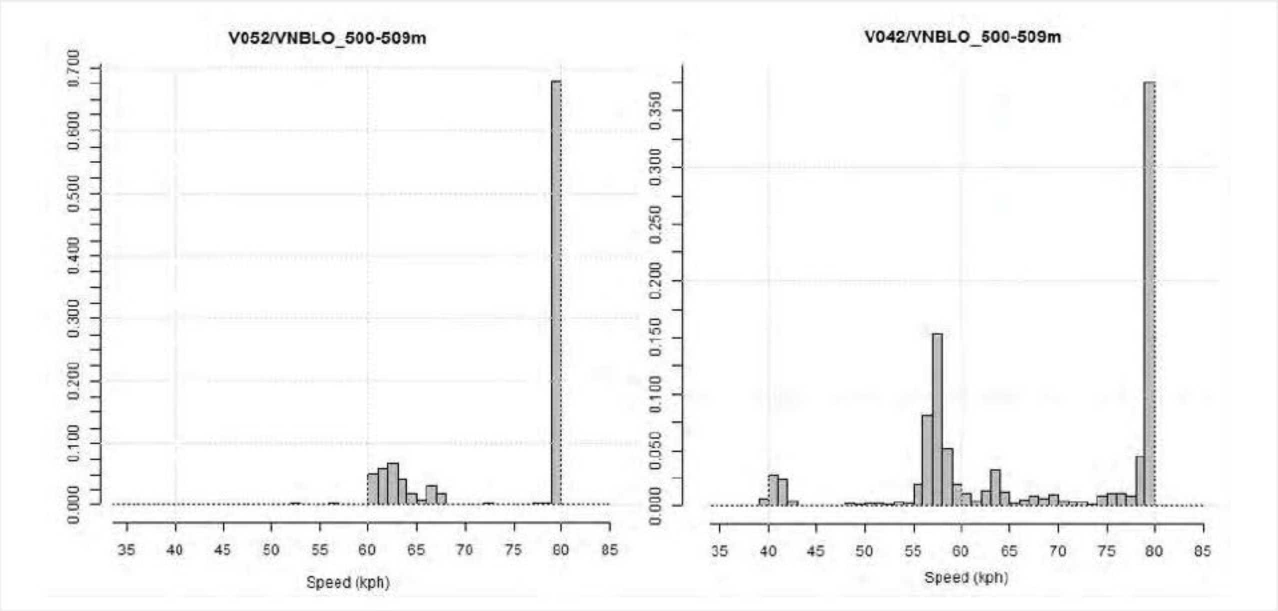

Figure 9: Speed distributions Pimlico to Victoria (left) and Oxford Circus to Warren St (right)

The tighter the curve, the more lateral creepage the wheels and rails have to accommodate increasing the demand for the available adhesion. If this is combined with increased tractive demand from power being applied at the wheelsets then more of the available adhesion is consumed, in even more simplistic terms 'traction destroys curving'.

Creep saturation may also be thought of as the point at which wheelsets are no longer able to steer around curves without the flange of the wheel contacting the gauge corner of the rail. There are numerous factors which affect this including the primary yaw stiffness of the bogie, the wheel and rail profiles and the cant deficiency to name a few which would need a whole other article to cover in enough detail.

I have previously described much of our work into our understanding of RCF on LUL in this Journal[3], and further work is currently ongoing within an RSSB funded cross-industry study. One of the initial hypotheses is to explore the effects of applied traction on the overall T_γ, the product of the creep force (T) and the creepage (γ) which is one of the underlying inputs used in the Whole Life Rail Model[6].

CORRUGATION

The impact of ATO is even more acute on another major rail defect which occurs on LUL; that of rail corrugation which has been the focus of much work since the introduction of Night Tube in 2016 when residential and commercial noise complaints increased in response to the longer running hours. Rail corrugation is a constant frequency phenomenon which requires a wavelength fixing mechanism from the dynamic behaviour of the vehicle/track system[7]. Excitation of this frequency results in vertical movement of elements of this system and a rippled effect on the vertical longitudinal profile of the rail (Figure 7). All types of corrugation which LUL suffers from are driven by wear when the limits of adhesion are approached[8].

However, so far, we have only considered the relationship between creep-creepage in the longitudinal direction but as soon as we start attempting to curve there is also demand on the contact patch to support lateral creepage, as well as a much smaller spin element due to the relative rotation of the surfaces (Figure 6).

The majority of ground-borne noise complaints related to rail corrugation were initially found to be related to a particular type of deep tube track-form which was installed across LUL from the mid-1990s. This consists of an NTF415 concrete sleeper with built-in baseplates cast directly into a concrete track slab, giving major advantages because this arrangement takes up very little of the vertical clearance available in the tunnels. The consequence of this is that there is very little resilience built into the system, other than the small rail pad which can be fitted between the rail and direct cast baseplate.

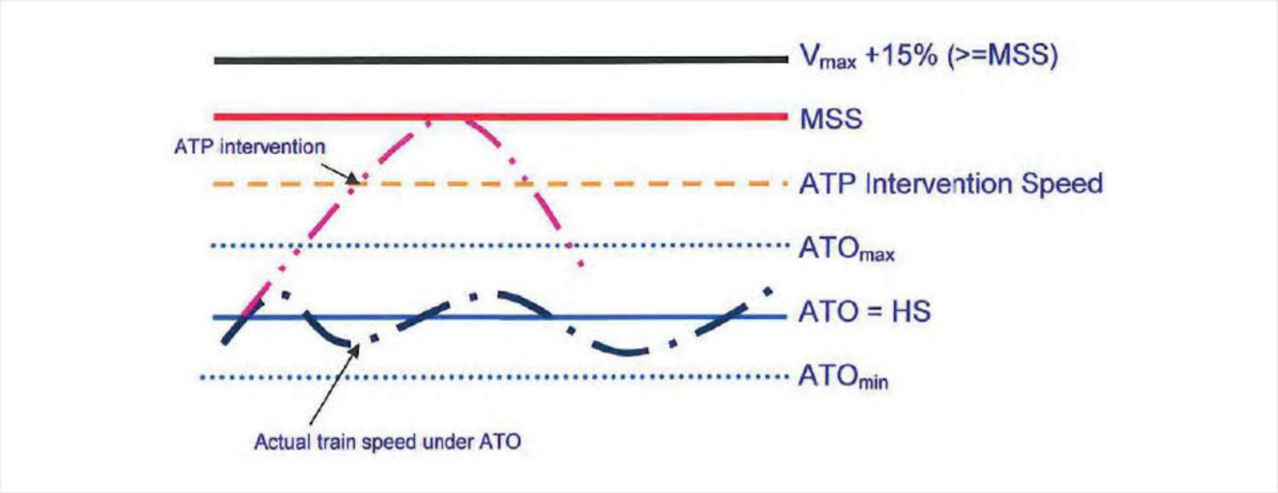

Figure 10: Conceptual relationships for ATO on Central Line

Figure 11: Stock rail fitted enDAQ Sensor

The initial response to many of these noise complaints was to install a retrofit version of the Pandrol Vanguard system, which suspends the rail from the baseplates in a rubber mounting, and results in a very vertically soft track which does not transmit the rail vibration from corrugation into the ground. The original configuration (left) and retrofit Vanguard (right) can be seen in Figure 7. However, this was installed without understanding the root cause of the corrugation and whilst it was successful in reducing ground-borne vibration, since the corrugation was still being developed it resulted in this vibration becoming airborne noise in tunnels.

The constant frequency of corrugation means that the wavelength developed on the rails (λ), when combined with the train speed (v) allows the frequency (Hz) to be derived:

$$f = \frac{v}{\lambda}$$

The frequency enables the root cause of the corrugation to be identified and across LUL this appears to fall into one of three categories: pinned-pinned, track-form specific and rutting[8]. Unfortunately, Pandrol Vanguard was developed to reduce the vertical track stiffness associated with a different form of corrugation, that of P2 Resonance[8] which is mostly related to the unsprung mass of the wheelset and has a frequency range of 50-100Hz (some of which does exist on LUL), whereas the predominant types in the NTF415 sites are pinned-pinned (450-1220Hz), and trackform specific (300-500Hz)[9].

There are two very distinct impacts from ATO on corrugation: the repeatability of train speeds that comes from automation and the way that the signalling system maintains that speed. When considering that it is a constant frequency phenomenon, and one of the major inputs into corrugation development is the speed (v) of the train to develop a wavelength (λ), then the more consistent this is the quicker the growth rate of corrugation will be.

One of the assumptions of the implementation of ATO is that every train will accelerate and brake in the same place, leading to very localised degradation of track assets. However, on the Victoria line this has been shown to not necessarily always be true. Two trains on the Victoria line are fitted with the Automated Track Monitoring System (ATMS), which allows constant monitoring of various track geometry outputs, such as speed and rail roughness, and information from this system has revealed why two very similar sites on the Victoria line show such different growth rates.

The two sites in question both consist of c.500m radius curves with a speed limit of 80kph, an annual 40MGT and consist of Pandrol Vanguard retrofit on NTF415 sleepers. They have both been identified as suffering from pinned-pinned corrugation by the wavelength of 50mm equating to a frequency of 441Hz, the sleeper spacing being approximately 1m in both sites. However, as can be seen in Figure 8, corrugation growth rates are vastly different; the blue and red dots indicate roughness on the left and right rails, with the black line a rolling average (there were some issues with the ATMS equipment towards the end of the period analysed). The grinding interventions (three times at the first site Pimlico to Victoria and once at Oxford Circus to Warren St) also clearly shows how effective it is at reducing rail roughness.

The green dots also seen in Figure 8 give the speed of the train when the measurements were taken, and this was further analysed across the two ATMS units for a period of 2 months to give a speed distribution. The results from this for each of the sites can be seen in Figure 9, which shows the distribution of speeds at 500m where for the quickest corrugation growth site nearly 70% of trains reach 80kph, whereas in the lower growth site this is only around 35% of trains (the y-scale is unfortunately different due to the graphs being automatically generated).

The second issue which exacerbates corrugation growth in ATO systems is the way in which the system controls the speed of trains. As previously described the more demand there is in the contact patch for the available adhesion, laterally through curving or longitudinally in traction or braking, then the more likely that creep saturation will be achieved leading to corrugation.

Therefore, in areas where we are accelerating or braking (utilising rheostatic rather than any friction braking) and we are attempting to curve, then the more likely we are to develop corrugation. In LUL we are far more susceptible to this due to having numerous curved platforms and approaches, and short interstation sections where tractive effort will always be high. However, in some ATO systems the way that constant speed is achieved is by the train either accelerating or braking, as there is no 'coasting' element built

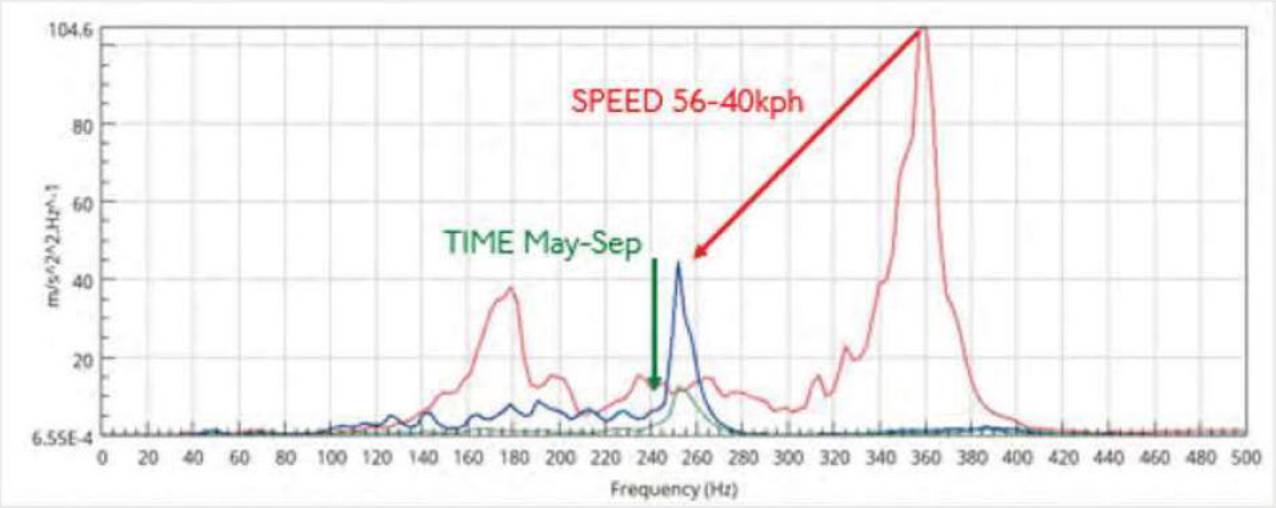

Figure 12: Impact on frequency of speed and time

in as conceptually shown in Figure 10 by the black line to achieve the Headway Speed (HS). Therefore, even in areas where constant speed is achieved, we can still be making even more demands on the adhesion available to achieve it.

Corrugation has also been the root cause of several issues for signalling components mounted on the track. One such issue was on a set of points on the Jubilee line extension which has historic issues with developing corrugation and where several failures occurred on KLM clips associated with the points resulting in costly delays. Initial monitoring was carried out using an enDAQ sensor (Figure 11) which is a tri-axial accelerometer which can be simply attached to the rails, or point operating equipment, and records a number of train passes to identify the Power Spectral Density (PSD) of the vibration. This is a method used to identify the relative power of the signal (in this case the acceleration of the vibration) against the frequency (rather than time) which enabled us to establish if the corrugation was causing the damage.

The initial monitoring carried out in February 2020 identified that the frequency of vibration with the greatest power at the stock rail was 355Hz. The speed through this particular trailing set of points is 56kph, which equates to a wavelength of 44mm which tied up pretty accurately with measurements taken on site during maintenance. As they say in politics 'don't waste a good crisis' and given the ridership at this point was so low, operations were consulted as to whether putting a speed restriction on would be acceptable. A 40kph speed restriction across the points was agreed (approximately a seven second increase in journey time) and implemented with the intention of trying to wear out the corrugation which had developed, a result which had previously been achieved using this method on the Victoria line[10].

Figure 12 shows that the speed restriction had an immediate impact, in both reducing the power of vibration being experienced (y-axis) and a change in the frequency (x-axis) from 56kph (red) to 40kph (blue) as the speed restriction was applied between these two sets of measurements on the same day in May 2020. The speed restriction then remained in place until the next set of measurments in September 2020 (green) which shows the reduction in power, but the frequency remains constant.

The initial change in frequency is achieved by the new train speed running over already corrugated rails (40kph @ 44mm = 253Hz), the reduction in the power of the vibration was achieved over time due to the constant frequency nature of corrugation. The root cause of the corrugation, in this case most likely a trackform specific issue due to the lateral track stiffness, remains the same at 355Hz but now we are running at 40kph the wavelength it is trying to generate is 31mm and hence it starts to wear out the 44mm.

The results from September 2020 indicate that we may have nearly worn out the 44mm wavelength, but we are now expecting to see the 355Hz increasing as the 31mm is being generated.

The next phase will be to remove the speed restriction and return to 56kph, and once again change the wavelength which is being generated. We have effectively tried to recreate some of the variability of manual driving, into an ATO system, but if the number of passengers starts to return in 2021 then it is unlikely that implementing speed restrictions will be tolerated.

CONCLUSIONS

The impacts of ATO on track and infrastructure on LUL have been significant, from a new type of rail defect which had to be understood and managed, the overall increases in tonnage which reduce asset life, and the repeatability of train speeds on a constant frequency driven defect. The improvement to the overall condition of the track assets on LUL through renewals has both solved and created problems, some of which have been exacerbated by the implementation of ATO.

The removal of jointed bullhead track has enormously reduced the number of broken rails by increasing the time available between detection and failure, however this has essentially been achieved by increasing the stiffness of track both laterally and vertically, through both the rail section and underlying componentry. Modern tube track aims to balance the increased stiffness by building resilience into the baseplates, which should reduce some of the impacts vertically but laterally this is more difficult to achieve the tighter the curvature.

Whilst the majority of corrugation on LUL which falls into the pinned-pinned or track-form frequency ranges affects curves in the 400-600m radius, once 200m is approached then rutting corrugation develops (50-150Hz)[9] as can be seen in Figure 13, and at sub-100m radius curves corrugation becomes less of an issue but often results in low rail wheel squeal, causing airborne noise issues.

The most demonstrably successful solution to both these issues is managing the adhesion at the top of rail through friction modifiers to prevent stick-slip[7, 11] which has been used with some success on LUL but is more limited by the ability to deliver the material to the interface and distribute it through the curves. However, more recent work has started to look at the role of stiffness in the generation of wheel-squeal[12] and the experience on LUL certainly supports this, as sites which have historically never suffered from wheel-squeal in bullhead, almost inevitably do in flat bottom 100m radius curves.

Figure 10 demonstrates another area in which much better understanding of the relationship between ATO and ATP (Automatic Train Protection) will allow track design to be better optimised for whole life cost. During the Northern line upgrade new track installations were designed using the principle that the ATP intervention speed would result in a maximum of 8kph over the HS, yet there was no statistical analysis carried out which would give a risk of this occurring, indeed the examples in Figure 9 show that the actual speeds through a section may even be lower in some cases.

Whilst the speed limits are mostly driven by the curving rules governed by the Permanent Way engineer through cant, cant deficiency and potentially more importantly the rates of change of these elements, when ATO is implemented, the computer rather than the human controls the likelihood of over speed events occurring.

The Maximum Safe Speed (MSS) which is used to govern the relationships between these systems is set much lower than that at which an overturn derailment becomes a risk, and whilst the risk of other types of derailment needs to be considered in deriving limits, the risks involved can be controlled. This is the approach that was used by LUL to determine where check rails need to be installed[13] and will be applied in rewriting these rules to be based on relative, rather than absolute risk.

The tools we have at our disposal to both monitor and model the effects of low and high adhesion are a world away from when the world's first automatic railway opened in 1969, and we also have the benefit of hindsight which allows us to be in a much better position to receive the next generation of ATO systems within the many limitations of the infrastructure bestowed upon us by also being the world's first underground railway.

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Figure 13: Rutting corrugation on modern track-form