Victoria Line – 50 Years Of Resilience (So Far)

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SUMMARY

At the peak of the Space Race in 1968, London Underground's new Victoria line symbolised the future of urban transportation, with a fleet of sleek, chrome trains and 'computers' driving each train from station to station smoothly, reliably, and safely. 50 years later, the Victoria Line remains a world leader in performance and reliability, with the highest service frequency of any line in London. The railway is a major transport artery, and its resilience to changes and external influences is critical to the smooth running of London.

In the early 21st Century London Underground, Siemens Mobility, and Bombardier worked together to upgrade the signalling and control systems while a new train fleet was introduced – all with minimal disruption to the travelling public. A staged migration took place, allowing old trains to use the old system and new trains to use new technology until the completion of fleet replacement.

Further investment has seen the performance of the system increase again with the VLU2 programme, allowing the current 36 trains per hour timetable to be introduced. Maintaining the high performance of the railway in the future will require further development of existing systems, and an ongoing commitment to obsolescence management to ensure that the Victoria Line is still resilient and World Class in 2068.

1 INTRODUCTION

London Underground's Victoria line is one of London's major arteries. With 21km of track, all in tunnel except the depot at Northumberland Park, the line runs across the central part of the capital. Over 200 million passengers use the line per year, passing through sixteen stations, all of which (except one) are interchanges to other Underground lines or the main line railway network. Recognising the importance of these vital interconnections, the original proposed names for the Victoria Line included the Viking line (Victoria to King's Cross) and the Walvic line (Walthamstow to Victoria), before the then London Transport board settled on the name of one its most heavily used stations, Victoria.

Originally constructed in the late 1960s to reduce congestion on other lines, and to improve journey times between those main line stations, the railway has seen considerable increase in ridership over the past 50 years. That change has resulted in extra pressure on an already well-used part of the London Underground network and forged a link between the smooth running of the Victoria line and the smooth running of much of Central London. Creating a resilient system has therefore been about a lot more than simply ensuring a positive passenger experience, as the availability of the line has wider socio-economic benefits.

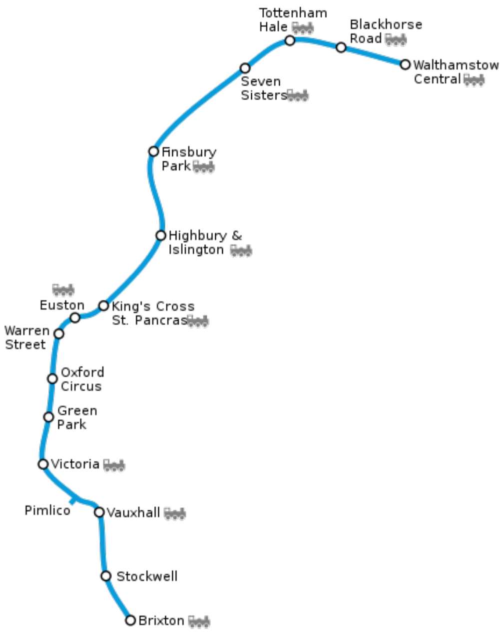

Figure 1 – Victoria line route

This paper considers four major phases of the railway's existence, lessons that have been learnt about resilience over that time, and looks at potential challenges that will be faced in the years to come.

2 VICTORIA LINE 1968

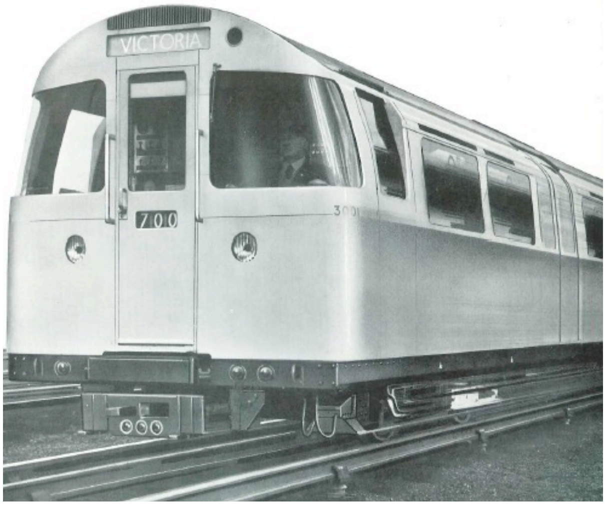

Figure 2 – Victoria Line 1968, sold as a paragon of modernity at a time of significant technology change.

The Victoria line was seen as a technical miracle of its age – an era of rapid advances in space travel and during the development phase of the remarkable Concorde aircraft. Sleek new trains driving themselves through central London attracted a lot of attention. Whilst the underlying technology of the signalling system was, in fact, not particularly modern, the use of electronics in safety-critical applications as well as a remote control centre were certainly new.

The system concepts had been proven in the early 1960s on the Hainault loop of the Central line. The visionary leader of the whole scheme, London Transport's Chief Engineer Robert Dell, had developed a close relationship with his rolling stock and signalling suppliers, and taken an incremental approach to proving that his automated railway, the first in the world, would work from day one.

The opening of the line saw the first trip by a reigning monarch on the London Underground as Queen Elizabeth met railway dignitaries and visited the pristine stations and trains.

The creation of the line caused considerable chaos to road traffic in London. Major disruptions occurred at locations such as Oxford Circus where a steel 'umbrella' was constructed over the station box whilst fairly 'man-draulic' construction techniques were used to dig out the station areas, frequently working around existing infrastructure for the interconnecting lines and other services.

Upon completion of the full railway network in 1969, London benefited from the first new-built railway in decades, gaining a major artery to interconnect major transport systems with its first automatically driven trains.

The architecture of the original system was based upon electropneumatic interlockings ('V' frames). The line was track circuited throughout, with track codes being injected to give ATP information to the trains. These track codes were generated by pendulum-driven generators and electronic devices for higher frequencies. Timetable operation was provided via the 1950s-generation programme machines, operating in a manner similar to a pianola, with a roll of punched plastic being driven past a set of contacts. The timetable was coded into that roll, and the routes were set as the various holes were 'seen' passing the contacts.

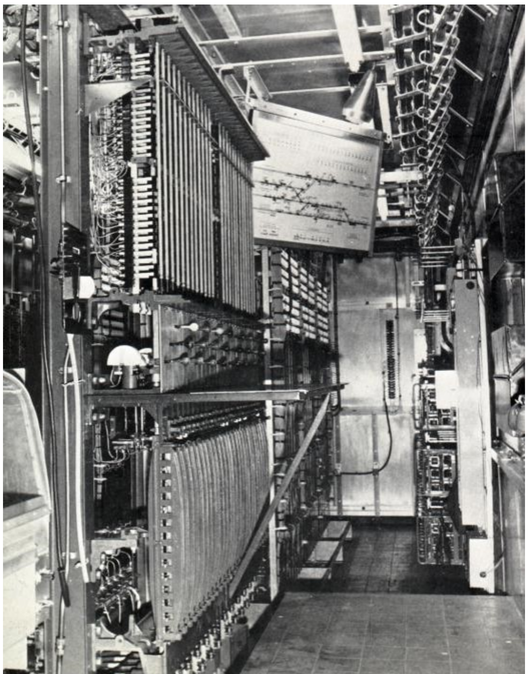

Figure 3 – A interlocking machine room showing the electropneumatic interlocking and local control. The programme machine is to the left.

Central control was provided from Coburg Street in central London, where a large panel-based system was installed in an appropriately futuristic looking facility.

There were three main systems on the train. Mounted under a passenger seat, the safety box received track codes and compared current speed with permitted speeds. If current speed was lower than permitted, the brakes were held off. Also under a passenger seat, the autodriver received frequency tones from loops mounted trackside, combined this with speed data from tachogenerators, and used transistorised circuits to apply acceleration, deceleration, and coasting. Thirdly the 'Identra' train identification system was mounted in the cab roof, communicating train identity with trackside equipment.

3 VICTORIA LINE 2003

By the turn of the 21st Century, the line had been running for 32 years. The same rolling stock, ATP, control centre and signalling systems were still in use, although the autodriver boxes (the ATO electronics) had been replaced twice. Maintaining reliable service was becoming a challenge for all the classic reasons related to maintaining technology over a long period of time.

The underlying signalling system benefited from using electro-pneumatic interlockings – basically mechanical interlockings operated using compressed air – which generally were not subject to failure provided they were routinely maintained. The electronics were another story however, particularly due to the amount of bespoke technology used and its increasing age. The issue was not restricted to the availability of the individual system elements, but also to the availability of individual components which had been made specifically for the project decades earlier.

The resilience of the system was largely down to the skills of the dedicated team that knew the underlying systems intimately and could work out how best to coax the system to keep working. This was a particular issue on the train carried 'safety box' which could not be upgraded without considerable engineering effort. The autodriver box benefited from its non-vital nature and was in fact replaced twice during the lifetime of that 1960s generation system, in order to reduce dependency on obsolete components and to make use of modern computing technology as far as possible.

The trains too were becoming amongst the oldest on the Underground, again benefiting from their relatively simple mechanical and electrical architecture but needing great care and skill to keep them operating as required.

The costs involved in upgrading significant elements of the Underground were immense, and traditional procurement methods were considered unlikely to deliver the investment required in the timescales identified. The government of the day therefore chose to use a Public Private Partnership (PPP) mechanism to inject private finance into the upgrade of the entire network.

The PPP model involved splitting the entire Underground into three sections and seeking companies or consortiums to lease them and provide a service back to London Underground. The Victoria line was part of the BCV grouping of lines (Bakerloo, Central and Victoria), for which the successful bidder was a consortium called Metronet. Metronet's business case was based upon receiving increased 'service charge' payments as a result of improving key performance indicators for the lines. Victoria line was the first planned for upgrade, and Metronet committed to deliver a fleet of 47 new trains from Bombardier, and a completely new Distance to Go – Radio (DTG-R) command, control and signalling system from Westinghouse Rail Systems (now Siemens Mobility).

Resilience was one of the performance indicators measured by the PPP delivery model, so from the get-go Metronet's partners and contractors had clear requirements to work to in terms of disruption to service during the upgrade, system reliability, availability, and flexibility.

4 VICTORIA LINE 2012

2012 saw the completion of the upgrade of the line. The major challenge throughout the scheme had been related to London's dependence upon the Victoria line, and the role it played in interconnecting the various main line and metro lines. Quite simply the line could not shut during the upgrade, despite trains, traction system, stations, and the signalling system all being replaced or heavily altered.

Faced with the decision between making the old trains work with a new signalling system, new trains talk to the old signalling system or finding some form of overlay that would allow mixed operation, Metronet opted for the latter choice. The approach was therefore to leave the 1960s signalling and control systems untouched, but to introduce the new system and find a means of interconnection which left the original electro-pneumatic interlockings as the ultimate arbiter of safety during the performance enhancement phase.

Lack of space was a major challenge to the upgrade. By keeping the railway running with the old signalling operational the existing equipment rooms were obviously full of equipment. The cost of creating new rooms would have been high, so instead the approach was to use any existing spaces, regardless of shape. In order to mitigate the risks associated with this, a full replica of a typical equipment room was built at the contractor's factory in

Chippenham. Lessons learnt from this proved invaluable throughout the lifecycle of the project, and indeed the facility is still maintained and frequently used in order to service the after-market support contracts between Siemens Mobility and London Underground.

Contacts were taken from the 1960s interlocking and used by the Trackguard Westrace interlockings of the new system, initially just to provide information to the trackside ATP system. This in turn was passed over the radio to new trains on the network.

With this installation complete, new trains were made available to the testing programme. This involved running tests with firstly one of the new rolling stock in engineering hours, then a mixture of old and new trains, then more old trains and the new trains, leading up to the introduction of the new trains into passenger service. During fleet introduction the balance between old and new trains changed until ultimately the last old train left service and the Victoria line was entirely operated by new Bombardier '09 stock. Extensive testing had already taken place at the train manufacturer's factory in Derby, at the facilities of the software developer, and on the various test rigs at Chippenham. Thorough off-site testing and simulation of the signalling system is a major contributor to the overall resilience of the system. On-site testing was then a matter of incremental testing to gain confidence that each level of functionality and interface was safely and reliably attained. Throughout development of the software for the system, a specialist contractor with extensive experience in the creation and testing of aviation and defence software – BAE Systems – was engaged to create specialist code. The approach to testing was to create accurate representations of the systems in service and to literally test them to destruction, not only testing that they functioned as required, but also didn't function as they shouldn't

The architecture of the system made use of appropriate levels of redundancy throughout. On the train, three line-replaceable units of ATP were used on a 2-out-of-3 basis, with the mobile radio unit also duplicated. The interlockings were operated in a 'hot standby' configuration with two identical, constantly communicating sets of equipment in place, and the trackside ATP system used 2-out-of-3 hardware. Whilst much of the vital and train-carried equipment was proprietary, allowing development of a SIL4 safety case and ensuring all failure modes were clearly understood, extensive use of commercial off the shelf hardware was used for network components, diverse monitoring of performance, and the control centre systems.

A complete replica of the automatic train supervision system was created and connected to detailed simulations of the railway service. This allowed development of the system – and extensive testing – to be carried out off-site, vastly reducing the risks when introduction in London. During the early phases of product introduction this replica was used for factory acceptance testing and staff training, allowing a wide variety of scenarios to be run and optimal responses identified. The approach taken with the control centre solution was to 'over and back' test. The new control centre was installed in a different physical location to the original ATS, and a system of connecting either old or new systems to the railway was applied. Control could then be passed 'over' to the new system, or 'back' to the old system, thus allowing service to be maintained throughout this phase of work.

At the point when all new trains had been delivered, the 1960s system was no longer required, and for the first time during the upgrade the line was shut for a series of nine weekends, during which the old signalling was decommissioned. The Westrace interlockings were reprogrammed to take full logical control of the railway (a role previously carried out by the 1960s system) and connected to all trackside objects. This phase – asset replacement – saw the completion of the upgrade and the point at which the full benefit of the increased performance of the new trains and the capability of the signalling and control system could be realised.

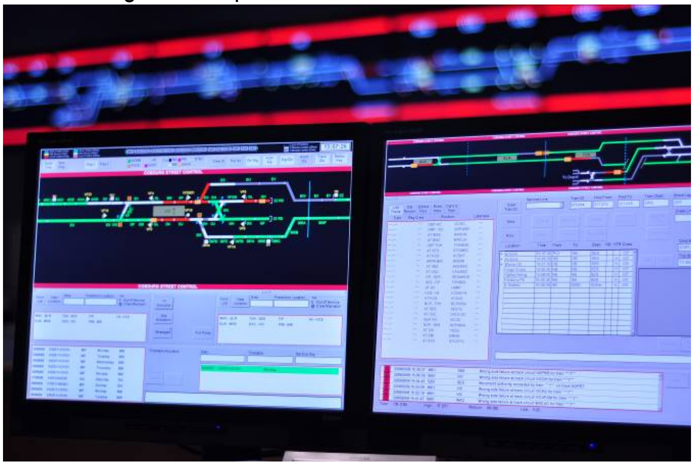

Figure 4 – Resilience was built in through the use of complex integration rigs for testing, training and long-term support purposes.

The final commissioning took place in 2012, and reliability growth on the line was significant. That year brought the ultimate test of resilience as London hosted the Olympic games. Following the successful completion of the capital projects associated with the event, London was committed to delivering a world-class service throughout the summer. London Underground worked closely with its suppliers to ensure that the skills and equipment necessary to keep the network operating optimally were available.

At this stage the programme had successfully delivered faster, more reliable, and more comfortable journeys for passengers with capacity increased from 28 trains per hour to 33 trains per hour in peak periods. [1]

5 VICTORIA LINE 2017

By 2017, the Victoria line upgrade was regarded as a success. Capacity had increased, the new trains were popular with the travelling public, and publicly published statistics showed that it was performing well in terms of availability and reliability. London Underground had invested in a condition monitoring system for the train detection system used throughout the line which had a positive impact on availability, and the control centre systems were working.

The increased demand for service on the Victoria Line resulted in the instigation of the Victoria Line Upgrade 2 (VLU2) project in 2012. This five-year programme took a multi-disciplinary approach to increasing supply to match this demand, with work being carried out on signalling and control systems, rolling stock, cooling, and infrastructure. Work was finished after a 57-hour blockade in April 2017, with the infrastructure in place to allow the introduction of a 36 trains per hour timetable. This achievement is about much more than just having an engineering solution that supports run-times and headways to move the numbers of trains through the system, it is also about managing and moving passengers around. Today's Victoria line continues to provide this 36tph service through peak periods.

A major element necessary to provide this timetable is the automatic train regulation in the control centre. This is an automated system that continuously assesses the performance of the railway and makes small adjustments to timetable (down to 1s increments) to recover the timetable as quickly as possible. This system is a clear example of resilience through automation, as it routinely manages the service through the day-to-day life of a complex, heavily used railway where station dwell time is a major driver of overall system performance.

6 VICTORIA LINE IN THE FUTURE

What the future brings, and how the resilience of this small but significant line will be maintained, is to some extent a matter for crystal ball gazing. However, there are a number of common challenges facing railways worldwide.

6.1 Cyber-security

First amongst these challenges is the recognition that the new technology potentially brings new threat vectors. Whilst the command, control, and signalling system used by the Victoria line today is a closed network, it is a complex one. Ensuring that future upgrades and obsolescence fixes are not only safe but also secure will remain a major area for analysis. In theory, the fact that passenger running takes place entirely within tunnels may offer some protection, but the full extent of cyber-security challenges today and in the future is important to the continued resilience of the line.

Whilst railways like the Victoria line are currently controlled by equipment fitted close to the track, and by a dedicated control centre close to the railway, the underlying system does not rely on this. Network connection of trackside object to centralised processing logic and control systems is perfectly feasible with the technology already in use on the line, and indeed this approach has been taken on other railways where these systems have been used. As functionality is moved onto the cloud, even a private cloud (i.e. a dedicated server, or instance on a server) will continue to raise challenges in the context of cyber security.

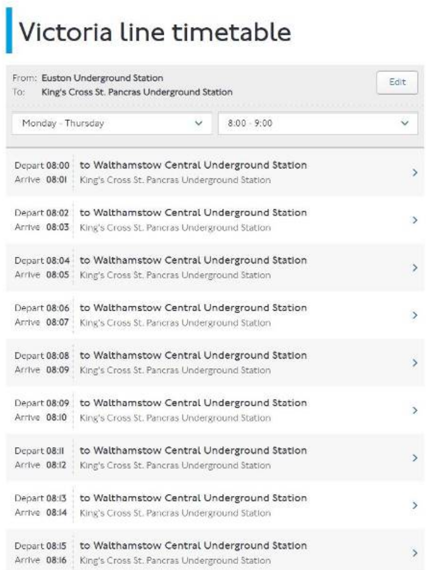

Figure 5 – An extract from the published timetable for the central section of Victoria line, downloaded in March 2019.

6.2 Obsolescence

The 1960s generation of technology used by the original Victoria line was very much a bespoke solution for an industry-leading application of electronics. To the modern electronics engineer, many of the original systems seem ludicrously simple, whilst others seem to rely on magic to have ever worked. What is certain is that the original system relied on a large number of unique components – tuned pendulums, specially manufactured transistors, magnetic amplifiers and so on – that simply became outdated as the electronics revolution of the 70s and 80s took hold. Obsolescence was a major challenge.

The 2012 generation of technology uses a different mixture of proprietary and off the shelf hardware. Whilst the SIL4 elements such as interlockings and train control sub-systems are indeed specifically designed for their applications, they primarily use industry standard components used by other industries around the world. Much of the information technology related hardware, for example train supervision system servers, uses commercial off the shelf parts. Whilst this brings the advantage of a much larger user-base and a larger pool of spares, it does also bring the complications associated with tracking changes in behaviour as operating systems are updated or obsolete parts replaced with alternatives.

If the new systems are to last as long as their predecessors, resilience of the systems will depend on a clear understanding and analysis of design decisions made to overcome obsolescence. The impact of subsystems on the greater, increasingly complex, system of systems will remain a major challenge. Experience suggests that it is often more straightforward to manage obsolescence of proprietary parts in safety-related and safety-critical hardware.

A secondary, but major, issue concerning obsolescence relates to people. One of the major challenges of keeping the 1960s Victoria line system running was finding the people with the skills and knowledge to maintain electronics of that generation. Today's maintenance approach tends to focus on the simple replacement of line replaceable units, but as spares holdings dwindle and replacement parts take longer to source, it is down to the technicians on the front line to provide resilient infrastructure. How that is manged in the future will be a fascinating challenge. The internet makes information available and allows sharing of experience, but skilled and experienced people still have a major part to play for the foreseeable future.

6.3 Changes in Demand

Demand for services on the Underground has seen a strong upward trend for some time, albeit with minor dips in recent years. The expectation is that as London grows there will be a continuing demand for journeys on the Victoria line, although the rate of change may drop slightly as new patterns of working start to take hold. This leads to a difficult position in the future – is it possible to increase supply further to meet demand, or will there be an increasing gap?

The current 36tph timetable, and the ability of the railway to support a few more trains every hour in order to allow recovery to incidents, is generally seen as getting close to what is physically possible in terms of moving trains around a network. The point of the railway is not, however, to move trains around a network, but to move people around a city. Achieving a 36tph timetable is increasingly dependent upon dwell time, not platform reoccupation time. Even the most minor of incidents, perhaps a bag or umbrella getting caught in a set of doors, can have sufficient impact to affect the delivery of timetable. Technologies such as automatic train regulation, the slight adjustments made to timetable to recover service quickly, make a significant difference in this field and certainly enable that level of service, but again there comes a point where there's little more that can be done. Increased automation may improve the precision of starting the despatch process, but it can't make people stand clear of closing doors. It seems unlikely that we will teach future generations of travellers to have better travel etiquette, but we can at least provide them with more information that helps them make decisions about their journey. That may be something as simple as sending messages to mobile phone apps to advise of service disruption, or it may be more advanced such as advising the level of crowding in individual coaches of specific trains. This area of psychology vs technology is a major future challenge and opportunity.

A further, closely related, issue is that of making urban transport systems accessible to those with disabilities, visible or hidden. It is hard enough for fit and agile passengers to move on and off a crowded train, but for those who may be mobility impaired, partially sighted, or indeed those who have a range of mental issues that can make movement through crowded areas a significant challenge, transport via this means can seem unattainable. If it is unlikely that we can ever move enough trains around or change demand patterns in such a way that train crowding is permanently eased, then this will potentially create a long-term challenge to the railway industry.

6.4 Passenger Expectations

For the two or more generations that have lived with hugely reliable technology as a fact of life, being told that their train is not running due to signalling issues or problems with trains can be completely impossible to understand. For the majority of the travelling public, trains are simple systems which obey 'traffic lights'. Perhaps the majority are unaware of the level of automation that supports their journey, and certainly a significant majority are unaware of the complexity of the safety-critical systems that assure their safety.

As an industry we have perhaps become a victim of our own success in this field. On railways such as the Victoria line, it is recognised that passenger behaviour does change as the system becomes more reliable. Although it is sometimes hard to believe, evidence shows that travellers on the Victoria line are more likely to stand back from a crowded train, rather than trying to push their way on, because they know that the next one is no more than 100s away. When the system ceases to work as expected, especially in our industry where failing to a safe state will often result in stopping trains, confidence in the service is quickly lost.

It is also interesting to recognise that the trains on the Victoria line are running so close together, with more trains than platforms, that stopping in tunnels and waiting for the train ahead to depart is a daily occurrence for many passengers. What is a nuisance for a few seconds can become uncomfortable very quickly if any longer delays are experienced.

This is not a simple problem to solve as slowing a train down so that it keeps moving slowly rather than waits at a block marker to move into the next platform as it becomes available will have knock-on effects on following trains. As the automatic train supervision technology that has been developed for use on metro railways gets rolled out on to main lines as Traffic Management, the complexity increases exponentially. This is certainly an area where machine learning, artificial intelligence, and a range of other computing-based approaches will come to the fore.

7 CONCLUSION

The Victoria line holds a special place in many Londoners' hearts, allowing them to travel swiftly and comfortably across the West End, to work, to go shopping, and to visit theatres. However, it is also a significant part of critical national infrastructure – when it stops, London notices. The road network cannot take the strain of the increased demand for buses, and there are limited time-efficient alternatives on the Underground network. The resilience of the Victoria Line is therefore important to the smooth running of large parts of London, and for over 50 years the skills of the staff at London Underground and its contractors has provided this.

After the considerable disruption during the line's construction, the Victoria Line was quickly taken for granted as being a fast and efficient link across town, and between other modes of transport. When it was upgraded in the early 21st Century, the teams carrying out this work managed to deliver an upgrade without more than a few weekends' closure. The line worked flawlessly throughout the 2012 London Olympics, and saw ridership growth that required further investment to increase throughput to the highest levels currently seen on the network.

Maintaining those highest levels of capacity, reliability, and availability, thereby ensuring the continuing resilience of this densely used metro service, will remain a challenge for many years to come. Supplying sufficient services to meet changing demand will remain a significant issue, and future generations of command, control, and signal engineers will need to achieve what today seems limited by the laws of physics and passenger behaviour.

What is certain is that the Victoria line has delivered 50 years of resilience, so far.

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