



New Tube for London

Feasibility Report

October 2014



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Introduction

London is growing rapidly. By 2031, there will be an extra 1.8m people living and working in the Capital – that’s an extra Tube train of people every three days. As a result, demand for Transport for London (TfL) services – Underground, Overground, Docklands Light Railway and Trams – is growing too. In 2013-14, London Underground alone carried over 1.25 billion customers.

Our vision is to be world class despite the challenge of delivering improved services to an ever-growing population.

We have recently started to experience the benefits of the renewal and modernisation of many of our lines in the level of service and comfort we offer.

Our approach is defined by four priorities. These are: safety and reliability, maximising capacity from the existing network, growing the network and meeting the growing expectations of our customers by providing excellent customer service.

Our aim is to achieve a steady state of renewal where modernisation is a continual process, built into our everyday operations. This will minimise disruption and will also provide best value for London and the UK, as well as creating certainty for our supply chain and consequently greater value for money.

In order to achieve this aim, we must first finish the network modernisation we’ve started.

Around two-thirds of our lines are being or have already been modernised. We are delivering world class service frequencies on the Victoria and Jubilee lines as a result of this investment, with work underway to achieve even higher frequencies.

This year, the Northern line upgrade will deliver a 20 per cent increase in capacity and works continue to modernise the Circle, District, Hammersmith & City and Metropolitan lines.

The introduction of Crossrail services in 2018 will also contribute

to the growth of our network, increasing rail-based capacity in London by 10 per cent.

By the 2020s, the Bakerloo, Central, Piccadilly and Waterloo & City lines will be operating the oldest trains and signalling on the Tube. We are therefore developing a programme for a comprehensive modernisation of these 'deep Tube' lines. For the first time, we are procuring a single train fleet and signalling system. We expect the Piccadilly line to be first, with modern, air-cooled trains entering service in the early 2020s and the full modernisation

complete by 2025. The remaining lines will follow in a sequence which will maximise the benefit from our investment.

This comprehensive modernisation programme for the deep Tube lines is referred to as the New Tube for London (NTfL) programme.

A feasibility study has been conducted to examine the technical challenges of delivering this programme and this report documents the study's results.

Context

Strategy

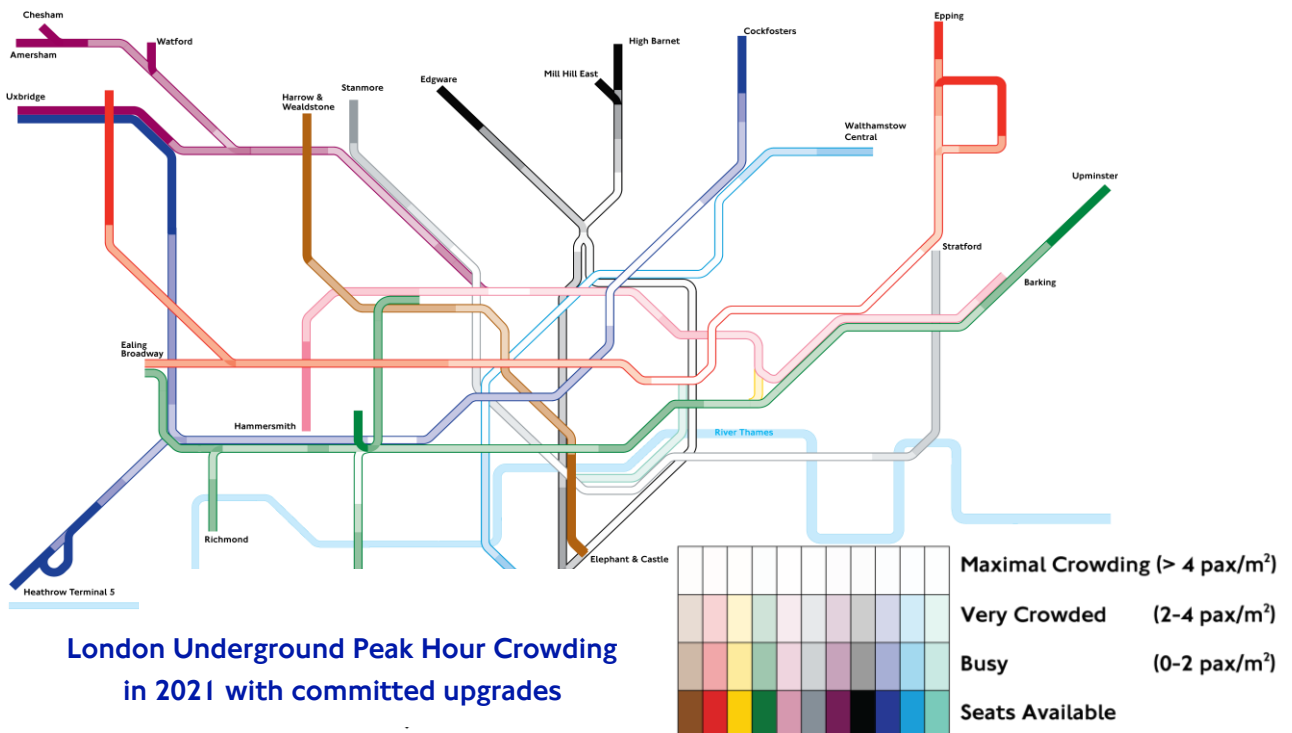
TfL’s major programme of investment to upgrade its existing lines and stations, and implement new or extended rail services aims to contribute to the Mayor’s Transport Strategy by meeting the goals of:

- Supporting economic development and population growth
- Enhancing the quality of life for Londoners
- Improving transport opportunities for Londoners
- Improving the safety and security of Londoners

In meeting these goals and ensuring the transport needs of London are met, TfL Rail & Underground has established four key priorities for its business, as follows:

TfL Rail & Underground Priorities
Improve reliability and safety
Improve customer service
Increase capacity from current network
Increase capacity by growing the network

The NTfL programme provides the opportunity to advance three of these key TfL Rail & Underground priorities on the deep Tube lines: improving reliability and safety; improving customer service; and increasing capacity from the current network.



Context

System Constraints

The Edwardian-era tunnel infrastructure presents a formidable challenge to the modernisation of the deep-level Tube lines.

As a system, these lines were not designed to dissipate increasing levels of heat from traction energy, leading to a steady rise in tunnel and station temperatures since the lines opened in the early 1900s.

Pioneering Technology - The advent of the new tunnelling shield method and electric traction enabled the construction of the world's first operational electric railway in 1890 with the opening of the City & South London Railway between Stockwell and the City. This was followed in 1898 by the Waterloo & City railway and in 1900 the Central London Railway.



Private Enterprise - By 1907 the network of the deep tube lines in central London had been firmly established by private entrepreneurs and financiers – notably Charles Tyson Yerkes. The Underground Electric Railways of London group

comprised the Baker St & Waterloo, the Piccadilly & Brompton and the Hampstead Tube line.

Legacy Constraints - Today's fixed infrastructure constraints on the deep tube lines originate from their construction, including: 3.5m diameter bored circular tunnels, cast iron tunnel linings and the line topography. The tight curvature of lines in the central London area reflects the arrangement of the street plan above ground.



Additionally, the fixed platform lengths, their depth below ground and sub-optimal ventilation systems are all legacies of the original design. The insulated four-rail direct current traction supply still in use today was first introduced with the early deep tube lines.

The deep-level tubes present physical constraints which severely limit the potential for capacity enhancement. These require bespoke and unique applications for key assets such as rolling stock.

Context

Asset Renewal

Rolling Stock: Legacy trains

The Bakerloo line trains are now over 40 years old and although refurbished in the 1990s are beyond their design life and require urgent replacement. Targeted investment is required to maintain the condition and performance of the 36-train 1972 Tube Stock fleet until its renewal in the 2020s.



The 86 Piccadilly line trains have benefitted from an extensive refurbishment in the late 1990s. This 1973 Tube Stock is beyond its design life – with reliability ever-more difficult to maintain – and in urgent need of



replacement.

The 90 trains of Central line and Waterloo & City line 1992 Tube Stock are equipped with the first generation of solid state direct current thyristor control traction

equipment. Although relatively modern and well within their design life, work is required in the medium term to ensure the continued reliability of the traction control equipment and maintain fleet serviceability until renewal in the late 2020s.



Legacy Signalling & Control Systems

The Bakerloo and Piccadilly lines are equipped with electro-mechanical, fixed block signalling systems dating from the 1970s and 1980s. With relay-based interlockings, track circuits and line side signals for manual driving, these legacy systems limit the service frequencies to 22 trains per hour (tph) on the Bakerloo and 24 tph on the Piccadilly line. Obsolete line control systems and control room facilities on both lines are a priority for renewal.

The Central line was resignalled in the 1990s with a Westinghouse automatic train control and train protection system to enable Automatic Train Operation. At present, a peak service of up to 34 tph is achieved during the busiest half hour of each peak.



New Tube for London programme

Vision

The New Tube for London programme aims to provide extra capacity through the renewal of ageing assets by delivering a coordinated series of line modernisations for the Bakerloo, Central, Piccadilly and Waterloo & City lines. This programme supports the priorities of improving reliability and safety; improving customer service; and increasing capacity from the current network through the following:

Comprehensive line modernisation strategy

Delivering asset renewals in a more comprehensive, consistent and systematic manner than previously achieved

Technology and asset renewal

Transforming the operating and maintenance model through asset renewals and technology-enabled change; adopting resilient models of service delivery through higher levels of automation

Capacity

Catering for London's growth by significantly increasing customer capacity whilst improving energy efficiency to achieve a sustainable line upgrade solution

Customer experience

Introducing a new generation of energy efficient, air-cooled, high capacity Tube trains and adopting highly-reliable management and control systems to deliver an improved service experience

New Tube for London programme

Status

In 2011, TfL began to develop a coordinated series of modernisations for those lines not commenced under the London Underground (LU) Public Private Partnership (PPP) - the Bakerloo, Central, Piccadilly and Waterloo & City lines.

Following the completion of extensive preparatory work, the TfL Board approved the commencement of the Feasibility Stage in July 2012. After confirmation of the strategic priority and funding status of the programme in December 2012, the TfL Board approved the programme's continuation through to a defined Gateway assurance stage (Gate B).

The resulting feasibility studies, which are now complete, comprised a comprehensive programme of technical

studies, safety analysis, operational design and strategic option appraisal to assess the optimum scope, sequence and business case for line upgrades delivery, based on:

- An unconstrained view of future operations and systems design for the next generation of upgrades
- Research and benchmarking to capture global metro best practice (see blue boxes in this report for key findings)

At the end of the feasibility stage, the NTfL concept reached a sufficient level of maturity for the TfL Board to authorise the next stage of the programme, the Design and Specification Stage.



New Tube for London programme

Feasibility challenges

The Feasibility Stage was initiated to examine the key challenges in modernising the remaining deep Tube lines and to respond to the following requirements:

Capacity

The deep Tube lines have fundamental system design constraints, especially in the central area tunnelled sections. New-build metros provide high levels of capacity using long, larger-gauge trains, which are not possible on our Tube infrastructure.

Significant increases in capacity can, however, be realised through the coordinated application of new trains and control systems underpinned by changes to the physical infrastructure. The potential for improvement on each line is unique to the particular constraints of that line.

Benchmark Finding: The level of trains per hour (tph) chosen by metros is the result of a myriad of system design factors (e.g. train length, wheel type, signalling system), customer service / operational factors (e.g. dwell times, crowding levels, access / egress), and business objectives. There is an optimal level for each metro / line but this varies between applications.

The challenge is therefore to ensure that service provision on the deep Tube lines is optimised within the limits of the infrastructure constraints to provide the maximum capacity to meet future demand levels.

Saloon air cooling

Customer expectations regarding public transport vehicle temperatures have been influenced by the introduction of cooling systems on new trains and buses, including London Underground's new S-Stock being introduced on the Sub-Surface lines (Circle, District, Hammersmith & City and Metropolitan lines). The deep Tube tunnels present a constrained environment for such technology, with the need to consider the installation of cooling equipment within the restricted Tube gauge, and dissipation of heat.

The challenge is to determine whether saloon air-cooling technology can be deployed on new trains in the deep Tube environment.

Managing tunnel temperatures

Saloon air-cooling and operation of fast, high-frequency services will increase energy and heat in the tunnels.

The challenge is to determine how tunnel temperatures can be managed, whilst enabling the benefits of air-cooling and capacity enhancements.

Higher Levels of Automation

The NTfL rolling stock and signalling systems will be designed for a service life of around 40 years. The pace of technology development and the experiences of other world metros in retro-fitting legacy lines with fully automatic systems highlight the opportunity to introduce higher levels of automation on the deep Tube lines during the life of the upgraded system.

The challenge is to determine whether technology advancements now being introduced by other world metros could be applied on the deep Tube lines to enable safe and reliable fully-automatic train operation.



Project Migration

Approximately one third or 1.4m of the 4.2m people who ride the Tube everyday use the Bakerloo, Central, Piccadilly and Waterloo & City lines each day. Careful consideration of the delivery method and line modernisation sequence is therefore required to make the biggest strides in growing capacity.

The challenge is to develop an implementation strategy for this work, referred to as a Migration Strategy, comprising a pre-determined number of operational states through which the railway “migrates” to maximise the efficiency of the project, whilst minimising the impact on customers.



Summary of feasibility activities

The NTfL feasibility study challenges are closely inter-related. Therefore, their analysis required a comprehensive, system-engineered design process.

For example, delivering increased capacity is a key programme objective. However, the effort to achieve this objective should not jeopardise achieving others – e.g. increasing reliability. Therefore, the intrinsic capability of the existing infrastructure has to be understood, along with the impacts of incremental changes that can be made to improve this capability.

The natural consequence of increasing capacity is an increase in energy demand. Additional demand for energy is offset by optimising its use through the implementation of recognised strategies previously deployed on London Underground. These include regenerative braking and new technologies to further increase system receptivity and energy recovery.

Deploying all of these strategies will not fully mitigate the increase in energy demand due to the substantial increase in capacity. Without mitigation measures, there will be a consequential increase in tunnel and platform temperatures due to the increase in energy utilisation. This is further reinforced by implementing saloon cooling (a programme objective)

which discharges energy in the form of heat into the tunnels as a by-product.

Consideration must therefore be given to implementing infrastructure cooling solutions to ensure the tunnel and platform environments remain acceptable.

These can be complex in their own right, so feasibility studies for implementation were carried out and iterated through the overall system design.

London Underground has many years of experience of delivering large complex engineering programmes. Lessons learned from this experience have provided opportunities for continuous improvement in approaches and practices. NTfL has also drawn on external best practice guidance (for example from The Royal Academy of Engineering and other external expert guidance from BAe Systems) to define the approach it would take to engineering during the feasibility phase.

This approach was captured in a framework called the Railway Level Design Management Framework (RLDMF).

The key feature of the framework was to coordinate the iterative development of many work streams of activities whilst maintaining an overall integrated systems approach. This was achieved by maturing the understanding of key critical design

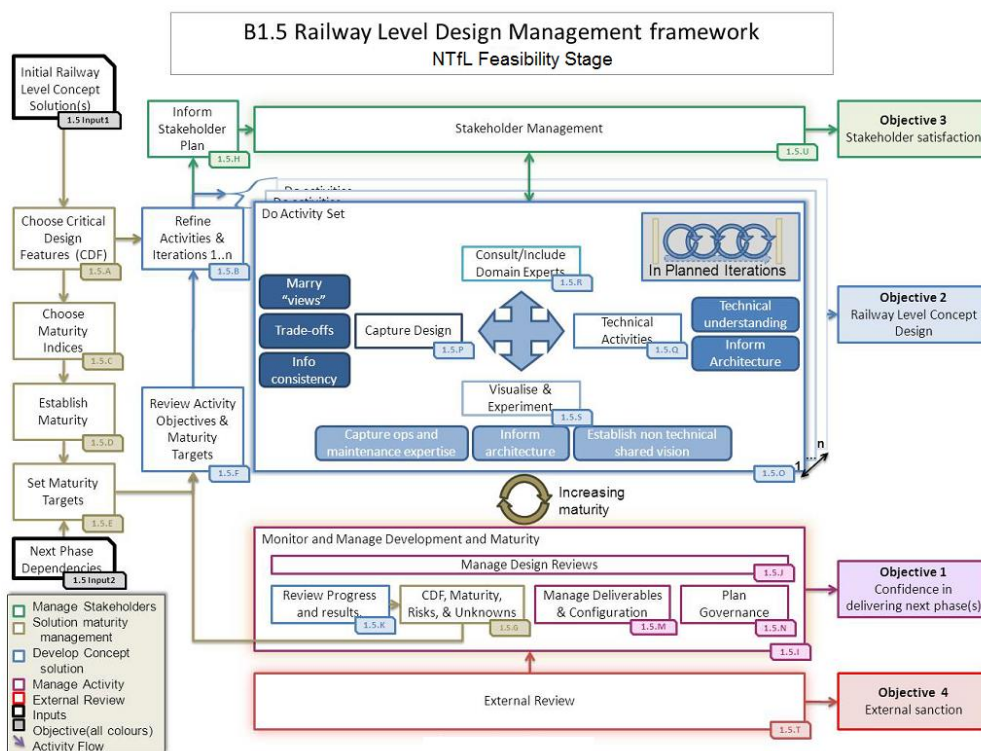
features, such as capacity and energy utilisation, of the overall system. Through effective design review processes it was possible to determine when sufficient maturity had been achieved to derive a reliable outcome to the study (see diagram below).

The output of the work is an overall concept design of the changes we intend to make to the railway to achieve the required outcomes. This is reflected in an operational concept with a physical architecture, determining the changes alongside required assumptions made in achieving the changes. This forms the basis of the requirements that will be taken forward into further design development and technical specifications for procurement.

The NTfL Integrated Programme Team (IPT) has managed a comprehensive schedule of activities to determine the right balance of outcomes to optimise the business case benefits, including:

- Surveys
- Supplier studies
- Internal design activities
- Academic research
- Engineering simulation
- Strategic planning and modelling
- Benchmarking with comparable metros

The following sections present the key findings against the study challenges.



Summary of feasibility activities

Capacity – rolling stock

Modern rolling stock has a higher performance capability than the existing trains with better acceleration and braking characteristics. These can reduce journey times and enable a higher frequency service to be operated from a given fleet size. Higher performance capability is a core feature of a train system upgrade, and one which has been achieved on several Underground lines over the past two decades.

The Feasibility Stage has investigated provision of more novel features for Tube trains, such as open, wide gangways. These would offer a number of benefits to customers as follows:

- Additional capacity is provided with improved configurations, including walk-through rather than separate carriages, creating more floor area as compared with traditional designs
- Customers can easily transfer between carriages, meaning customers can distribute throughout the train, avoiding busier carriages where possible. This in turn, will help to reduce dwell times as a more evenly loaded train enables quicker boarding and alighting

- Customers can move through the train so they are in the optimal section of the train at their destination station, thus reducing the time spent exiting the system
- The provision of a more continuous open space within the vehicle improves security and reduces the opportunity for antisocial behaviour

Provision of through gangways on a Tube train with traditional configuration is very difficult, if not impossible, due to the dynamic behaviour of the vehicles. Tight curves, in particular, lead to large relative movements between vehicle ends. This means an inter-car gangway would not be possible without removing doors at the end of the carriages, due to the length of the gangway which would be required.

NTfL has identified that it is possible to provide an inter-car gangway by altering the Tube train design to incorporate an articulated configuration with more, shorter carriages. By positioning the vehicle bogies under the ends of two adjoining cars, the relative vertical and lateral movement of the carriage ends is significantly reduced. This enables a shorter, wide gangway to be fitted



without loss of train capacity or a reduction in the number of doors.

The repositioning of the bogies allows all train doors to be double doors. Double doors allow for rapid access and egress, which reduces dwell times. Controlling dwell times becomes a dominant factor for achieving high frequency service levels, due to reduced intervals between trains.

Laboratory trials with University College London at their PAMELA (Pedestrian Accessibility and Movement Environment Laboratory) facility were used to gather data which supported existing empirical information on the impact of train and platform features (such as door size, stand backs, seat types and platform edge doors) on dwell times. The outputs of these trials were used to inform train design options and evaluation of different configurations.



Detailed surveys were made of the existing infrastructure, including tunnels,

platforms and sidings to inform the constraints on train dimensions for each of the NTfL lines. Train length is a critical design parameter. Increasing length improves the capacity of the train, generating customer benefits, but also increases the modifications required to existing infrastructure which can be costly and disruptive.

To ensure that the configuration is future-proofed, provision for installation of Platform Edge Doors (PEDs) on platforms is required. PEDs determine the position of the end doors of the train.

This analysis confirmed the fixed maximum dimensions for train length and door spacing for each of the deep Tube lines to inform the design and procurement of the new rolling stock.

Summary of feasibility activities

Capacity – signalling and control

Modern, automated metros require a higher level of control capability to facilitate remote monitoring and management of the train service and its supporting assets and systems. For the NTfL line modernisations, a fully-integrated Railway Control System (RCS) is envisaged comprising:

- **Signalling and train control** - including vital signalling and communications systems required for real time movement control of train services
- **Operational Control Systems (OCS)** - supporting functions for efficient operation and maintenance (e.g. condition monitoring, maintenance management, staff management, degraded mode operation control, traction and ventilation control, security and customer flow management)
- **Independent communications** - high bandwidth telecommunications to support fully-automatic operation with audio and visual links between the train and the control centre

Anticipated increases in customer numbers drives a need for longer dwell times. Without intervention, a larger number of customers would reduce the number of trains per hour that could serve the line. Modern signalling and train control systems can help to offset this by enabling trains to safely operate at closer intervals as has been successfully

delivered on the Victoria, Jubilee and Northern lines in recent years.

NTfL will therefore replace the existing signalling and train control systems in order to achieve the increases in service frequency necessary to deliver the required capacity enhancements.

The Feasibility Stage looked in more detail at wider railway control elements. Multiple independent systems are already mature, but moving from disparate systems to fully-integrated functionality - in line with modern operational control philosophy - will represent an enhancement to London Underground's current line management capability.

Engagement with suppliers, other operators and internal stakeholders has indicated that at least two discrete communication networks should be deployed to deliver the NTfL requirements. One will be a vital signalling and train control network. The other will be a non-signalling (independent communications) network to support all other business and railway information.

Based on the information available today, provision of a network to satisfy the data transfer needs is feasible but very high bandwidth needs are a limitation. To determine the feasibility of utilising an integrated railway control and communications system, it was necessary to examine 'communications

connectivity', the most significant change for which is the required increase in quantity and quality of train-to-wayside communications. This required consideration of:

- Higher availability and higher bandwidth communications
- Data prioritisation: to maximise network capacity
- Approach for main or backup signalling and control data transmission
- Minimising trackside equipment to reduce whole life costs
- Higher degrees of network and system Reliability, Availability, Maintainability, Safety (RAMS) and Security

Early supplier engagement identified their preference for the use of proprietary radio operating at 2.4GHz or 5.8 GHz for control communications. As this capability is not yet deployed within the Underground environment, a trial was commissioned to understand the physics of wireless propagation in the cast iron deep Tube tunnel environment.

The trial tested single-path and multi-path losses as well as ground reflection effects in the disused tunnel between Holborn and Aldwych, which was identified as being representative of the NTfL lines' target environment.

The trial concluded that radio frequency propagation within the tunnel follows a predictable model, and that:

- Changes in tunnel geometry (e.g. cross-over caverns) cause signal loss
- 2.4GHz propagates up to 400m
- 5.8GHz propagates less than 200m
- The train in the tunnel creates a blockage for signal propagation

As part of the propagation trial, high definition video was successfully transmitted in the tunnel at distances of up to 200m.

The trial has confirmed London Underground's understanding of wireless propagation in the deep Tube tunnel environment. The resulting propagation model was then applied to the Bakerloo line, to establish typical equipment requirements for line wide network application.

This confirmed that should a higher propagation frequency, such as 5.8GHz, be used there would be a potential need for higher wayside equipment count in the tightly curved deep Tube tunnel infrastructure.

The studies considered current and emerging communications technologies and concluded that given the rapid pace of evolution in this sector, London Underground will continue to keep an ongoing technology watch on developments. Future specifications, prior to procurement, will be informed by these developments.

Summary of feasibility activities

Capacity – infrastructure

To support increases in capacity, a number of significant enhancements to the infrastructure are required, as follows:

- **Power** - London Underground has a comprehensive traction power distribution network that needs to be enhanced to deliver the increased capacity demands. The power supply infrastructure feeding the NTfL lines was predominately installed in the 1960s and 1970s. Therefore the plant items are generally reaching the end of their economic lives. The NTfL study considered the necessary scale and scope of a power infrastructure upgrade required. A substantial upgrade is proposed, which will address asset renewal (e.g. replacement of transformer rectifiers) and provide the additional capacity needed for operation of faster, more frequent and more reliable services. Power enhancements will also be needed to meet the requirements of a modern railway control system.

The solution will also include upgrading of cables, switchboards, batteries and chargers, power system control and auxiliary transformers.

The overall power solution includes consideration of the most efficient means of power transmission to and between trains, which is covered in the

Managing Tunnel Temperatures section.

- **Track** - The track infrastructure, quality and configuration will need to be enhanced to support the significant increase in mileage expected such that it can be adequately maintained within the available access.

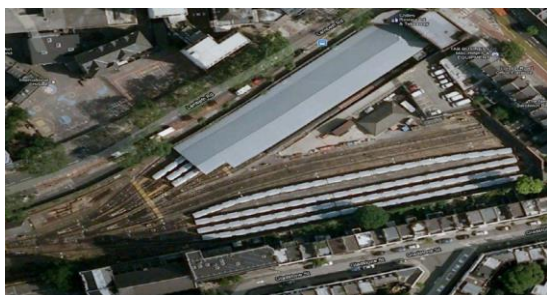
An important element of this is the Wheel- Rail Interface (WRI), which considers the interaction of the train and track in terms of performance and adhesion, ride and wear and tear. Bogie design studies have been carried out to consider the application of low track force bogies on an articulated train configuration. NTfL has engaged the University of Huddersfield to undertake academic research and specialist modelling support in this area.



The ultimate choice of bogie design and vehicle articulation will be based on analysis of the conflicting requirements of underframe space, gauging, gangway arrangement and acceptable levels of track wear.

- **Depots and stabling** – Existing depot facilities will require significant modifications to support an increased fleet size as well as the facilities necessary to maintain a modern train.

NTfL has considered a range of depot strategies, including combining depots for multiple lines, building new depots on green-field sites and developing existing depots to be fit for the maintenance of the NTfL train fleet.



Given limited availability of affordable green-field sites in greater London, the line specific requirements for depot facilities and the need for efficient access to the operational railway the strategy is to redevelop existing line-specific depot facilities, where possible.

Key lessons learnt from prior London Underground and other railway depot projects are informing the detailed plans for the NTfL depots. Examples include efficient utilisation of existing assets, consideration of all interfaces and full system integration during the 'migration' from existing trains and facilities through to new trains and new or amended facilities.

Additional stabling capacity will be required on some of the lines to enable increased fleet size.

- **Civils** - Specific capacity pinch points have been identified through extensive modelling to determine which, if any, have a case to be removed.

Amongst a number of measures expected, will be localised tunnel modifications to relieve the constraints imposed by the historic civil infrastructure, which act as a limiting factor on performance.



Summary of feasibility activities

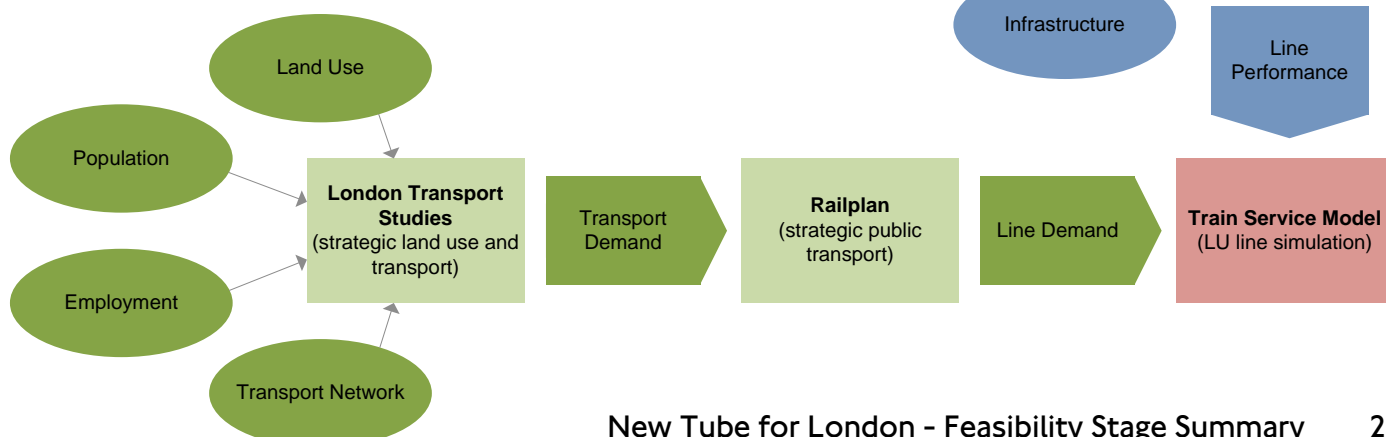
Capacity – modelling

A multi-stage modelling process was undertaken to reach a combined view of railway performance and post-upgrade demand levels, to determine the optimal capacity to be delivered (see diagram below). Four main capacity modelling stages were completed:

- 1) **London Transport Studies (LTS):** a TfL-owned transport model that takes forecast population and employment data from the GLA together with assumptions of land use and transport network provision, and produces estimates of public and private transport usage by mode of transport.
- 2) **Railplan:** this model takes the public transport demand forecast from LTS and allocates or ‘assigns’ it between the different possible routes and modes, to optimise total customer journey time. It produces assignments of demand for given future years, for different levels of planned service across all modes of Public Transport, including estimates of the number of customers using

each London Underground line.

- 3) **Railway Engineering Simulator (RES):** this model assesses the system performance of an Underground line based on the design parameters of the train, signalling and infrastructure. It produces performance outputs such as run times and available service headways, which can also be used for power, energy and cooling modelling.
- 4) **Train Service Model (TSM):** this model simulates the post-upgrade railway to understand the interactions between the technical capability of the modernised railway (fed from RES) and forecasts of customer numbers on the lines post-upgrade (fed from Railplan and LTS). This has enabled the optimal capacity provision to be understood and line-specific targets to be set.



Summary of feasibility activities

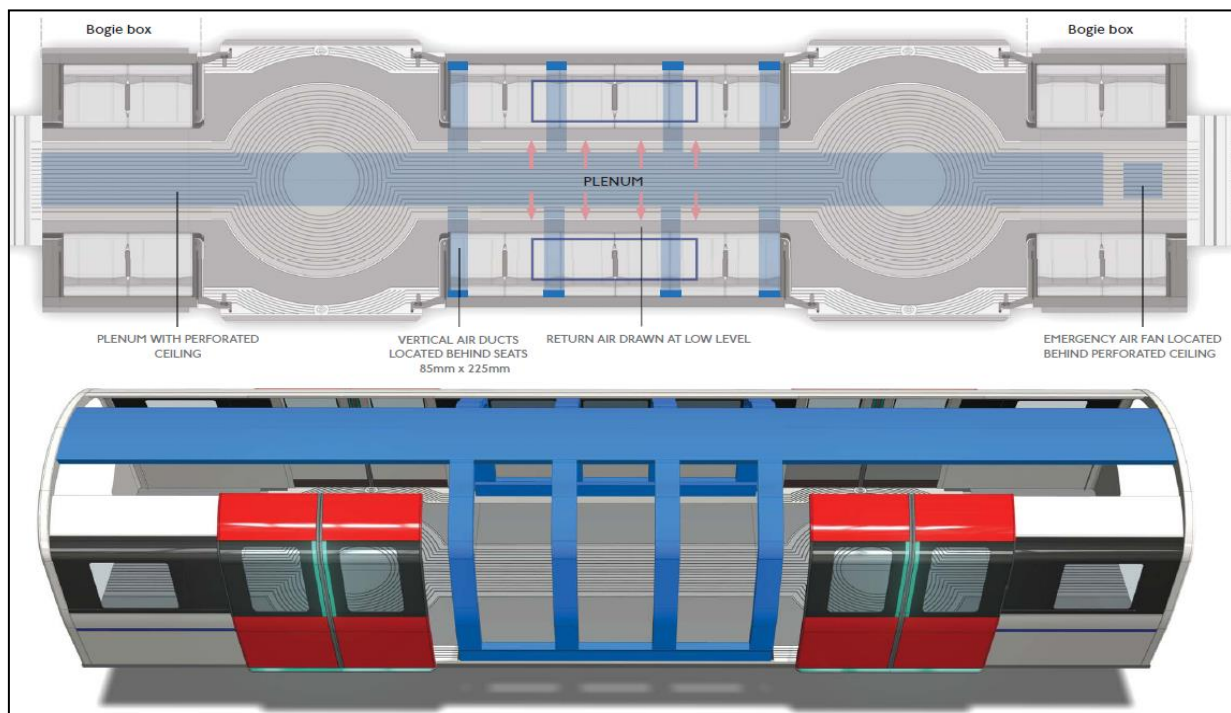
Saloon air-cooling

Conventional Tube train design cannot accommodate air cooling equipment without taking up customer capacity in the vehicle interior since there is insufficient space available on the vehicle underframe for the air cooling modules. The traditional rolling stock approach of placing this equipment in the roof space is not viable on Tube trains given the tunnel size and the need for sufficient headroom for standing customers.

Detailed development studies have determined the viability of configuring and reducing the size of the equipment such that it can be both accommodated and maintained. A concept design study was carried out and this has provided sufficient information for London

Underground to conclude that a saloon cooling system could be fitted onto the new train within the space, weight, energy and capital cost assumptions envisaged for the new train. The key requirement to create space on the vehicle underframe can be met by altering the train configuration to be 'articulated' which reduces the number of bogies required along the length of the train.

The consequence of discharging waste heat energy into the tunnels has been assessed and taken into consideration in the overall system design. This is covered in more detail in the following section on Managing Tunnel Temperatures.



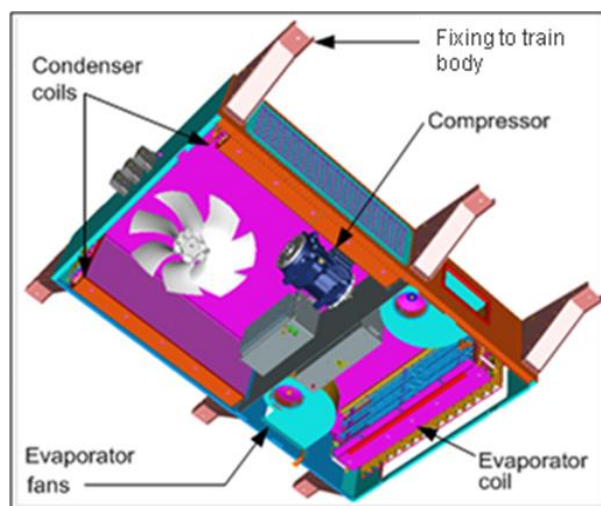
Comprehensive and ongoing dialogue with train manufacturers has given confidence that we can include requirements for saloon cooling as part of the train procurement.

Benchmark Finding: Air cooling is common on modern trains with systems typically located in roof spaces. The challenge for NTfL is to apply this standard industry functionality in the constrained environment using under-floor modules, and managing dissipated heat in the tunnels.

Studies completed to date have been based on 'conventional' cooling systems which use refrigerants to cool air which is then pumped into the saloon. As a minimum, conventional cooling will be specified in new train procurement.

NTfL is continuing studies into alternative "hybrid" cooling systems as a potential adaptation of conventional saloon cooling. Hybrid systems allow generation and storage of thermal energy whilst trains are operating outside of tunnels. This store is then used to cool the air for circulation in the saloons when the trains operate in the tunnels (the areas of the line where customer comfort levels can be most improved). This would enable

less heat to be discharged into the tunnels and Underground stations, which would potentially reduce the need for infrastructure cooling and/or reduce temperatures. Work continues to confirm the viability of including this novel type of cooling system in the specification for new train procurement.



Summary of feasibility activities

Managing tunnel temperatures

The original design of the Edwardian deep Tube tunnel infrastructure did not address ventilation such that it could be scaled for current demand. When originally built, the ground around the tunnels varied with seasonal changes in temperature. Over time the ground has become permanently heated. Any increases in temperature are consequently difficult to mitigate; a unique challenge for London Underground.

The overriding principle is to avoid generating waste heat as far as is practical. London Underground has successfully deployed strategies to optimise energy use in an attempt to do so. The following elements have been considered in the overall design:

Train - Maximising the use of regenerative braking, thus avoiding the braking energy being dissipated as heat by either friction or resistor grids. More sophisticated train regulation systems can exploit opportunities for more energy efficient run profiles.

Transmission - Increasing the traction supply voltage to 750 Volts helps reduce losses, along with increasing the regenerative voltage and current. Re-sectionalisation of the network increases the probability of energy recovery by a receiving train. The conductor rails can also be replaced by modern composite

extra low loss rails. Adopting these strategies has been shown to increase energy efficiency by up to 30 per cent.

NTfL has also instigated a trial of an inverting substation on the Victoria line to determine if this technology has a role to play in the NTfL power solution. The trial is ongoing and due to report during the current programme stage.

Infrastructure - If unmitigated, there will be consequential increases in tunnel and platform temperatures caused by higher energy utilisation and fitment of saloon cooling on the trains. The train air cooling discharges energy in the form of heat into the tunnels as a by-product of the cooling.

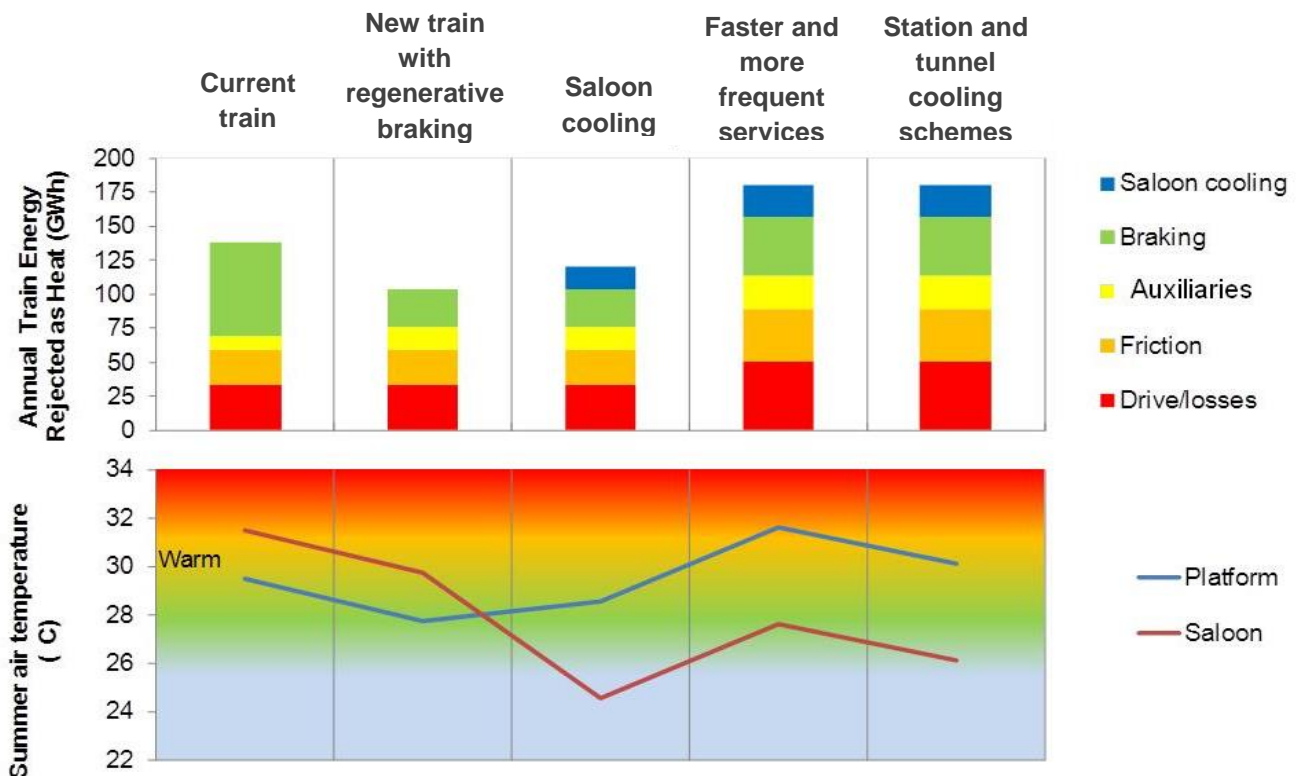
Consideration must therefore be given to implementing infrastructure cooling solutions, such as the over-platform air handling units shown below, to ensure the tunnel and platform temperatures remain acceptable for our customers.



The Railway Engineering Simulator (RES) was used to provide a forecast of energy usage in tunnel sections. This was then applied in comprehensive Tunnel Ventilation Model (TVM) simulations, to predict the temperatures within the tunnels and stations and the consequential environment in the train saloon given energy and heat emitted by the train service, tunnel temperatures and forecasts of customer numbers and climate conditions. This analysis included Computational Fluid Dynamic (CFD) simulation to assess the mixing of air between the track-way and platform which is caused by the movement of the trains through the Tube tunnels.

The graph below illustrates the TVM modelling process for the Piccadilly line. In summary, summer season platform temperatures can be managed to similar levels as pre-upgrade. Delivery of energy efficiency features in the train (such as regenerative braking capability), and station and tunnel cooling schemes (such as new Platform Air Handling Units) will help to reduce platform temperatures, which would otherwise increase due to the provision of saloon air-cooling, and faster and more frequent services.

In addition, provision of saloon cooling will result in a step-change reduction in summer season train saloon temperatures.



Summary of feasibility activities

Higher levels of automation

NTfL line upgrades will deliver new train systems for operation over at least the next 40 years, and consequently require the system to be future-proofed with the capability for fully- automatic operation.

The renewal of train systems provides the opportunity to build in the capability for higher levels of automation. The new assets and systems will provide detailed information about their status which combined with enhanced levels of situational awareness of the railway will allow more informed operational decision making and enhanced levels of predictive and preventative maintenance.

Benchmark Finding: Industry trends and the plans of other metros support increasing levels of predictive maintenance, and the programme plans to investigate further the maintenance techniques being adopted by other leading metros.

London Underground has a long history of technology-enabled change from the world's first Underground electric railway in 1890, the introduction of air-operated doors in the 1920s (which allowed train operation by just a driver and a guard) to the Victoria line which opened in 1967 as the world's first automatically controlled railway (with one person operation). These pioneering developments have led

to huge improvements in customer service and efficiency.

London Underground now operates the Jubilee, Central, Victoria and Northern Lines in automatic mode where the speed of the trains, the distance between them, their acceleration and braking performance are under computer control.

Benchmark Finding: Fully Automatic operation is proven, scalable and adaptable to a variety of metro environments and is a growing reality in the industry. Globally, over 100 examples of existing or planned fully automatic lines are known.

This enables a much higher level of service consistency to be achieved compared to those lines with manually driven trains.

Worldwide, Metro operators have followed London Underground's early lead and adopted automatic train control systems to improve service capacity and operating efficiency. With the advent of new technologies many new metros are now being built for fully-automatic train operation where all train movements and door operation are under the control of the system. This improves reliability by the elimination of human variability and errors. It also allows much greater

flexibility of operations since the scheduling of trains for service can be decoupled from the planning and rostering of train operators' duties.

The NTfL programme can provide the capability for this level of automation for use as required during the lifetime of the upgraded system.

The key changes that would be required to enable this functionality are:

Train - The train design includes focus on significantly reducing the probability of extended delays between stations by increasing the reliability of components and increased automatic handling of defects. Real time information about train health will be available with remote diagnostics, without the need for operator intervention.

Open Section Security - Enhancements to track or guide-way security in the open sections are required. Investigations have found that the key areas which may require enhancement are as follows:

- Upgrade of some boundary fencing and provision of appropriate barriers between NTfL and adjacent rail lines
- Review of landscaping and vegetation management
- Review of bridge and tunnel parapets and caging
- Identification of site-specific measures to prevent trespass or incursion

Platform to Train Interface - The area of highest risk in London Underground's operation is the Platform-Train Interface (PTI). Assessment has determined that physical barriers (e.g. Platform-Edge Doors) would be required to effectively and reliably manage the PTI under fully-automated operation.

Benchmark Finding: PEDs are the dominant track protection system for modern fully automatic railways, with very few operating without them (those that do are predominantly older systems).

Platform Edge Doors - the NTfL Feasibility Study evaluated both full height Platform Edge Doors (PEDs) as installed on parts of the Jubilee line, and half height Passenger Safety Gates (PSGs) as installed on Paris Line 1, and concluded that full-height PEDs offer the best solution for NTfL.



Data confirmed that PEDs offer at least double the reliability of PSGs based on their simpler design which incorporates fewer components. The simplicity and robustness of the door guidance systems of PEDs is also known to be a contributor to the increased reliability compared to PSGs.

PEDs provide much greater integrity of separation of the platform and track environment. No track intrusions have been recorded from platforms fitted with PEDs on the Jubilee line. 1.7m high PSGs have not been proven to stop all track intrusion on other metros. The lower height also leads to a greater number of false alarms where secondary detection is deployed to mitigate the risk of entrapment on curved platforms. In addition, it is comparatively easier for customers to drop rubbish over the top of a PSG which can have a negative impact on service reliability.

PED Installation - half height PSGs were developed for ease of retrofitting to existing platforms, and are supplied as factory assembled and tested modular units. These have successfully been retrofitted on other metros at a rate of two to three doorways per night within a typical three hour window. Doors are generally installed and commissioned in the same shift.

Full height PEDs, as installed on the Jubilee line, have traditionally been built and tested on the platform, making them more suitable for new line construction. Preassembled and

tested headers reduce the time requirements, but not to the point where a doorway can be assembled and commissioned during engineering hours.

Over the last few years some manufacturers have developed and successfully installed modular PED systems specifically for fitment during a 3.5 hour night time closure. From the door system perspective these are identical to traditional PEDs, but they incorporate a structural frame capable of resisting the stresses associated with transportation and installation. The doors are transported to site on engineering trains and installed onto the platforms utilising mechanical handling equipment mounted on the engineer's wagons.

Investigations have confirmed that full-height modular PEDs can be transported through the structure gauge of London Underground's smallest Tube tunnel using specially designed wagons.



Obstacle detection trials - Extensive trials were undertaken to understand the effectiveness of Obstacle Detection systems which could be used on an automated railway to ensure the safety of customers, maintenance and operating staff.

Obstacle detection systems offer a potential means of mitigating the risk of incursion onto the track at stations, in tunnels and in open section areas as a possible alternative to PEDs. Such systems are in use as part of integrated control systems on other automated metros including Nuremberg.

Four systems were trialled as follows:

- Light Detection And Ranging (LIDAR) or laser scanners
- RADAR radio frequency scanning units
- Video analytic systems
- Ultrasonic transponders

All of the trialled systems detected defined objects to varying degrees although none to a level that would support the reliability requirements of NTfL. The predominant finding was that whilst the technology is effective, a high number of 'false positives' occurred (i.e. system alarming when no object, trapping or dragging incident is replicated). When linked to the Railway Control System, each occurrence would automatically stop the train with unacceptable service disruption impacts.

LIDAR scanner on trial at Bank



None of the detection systems trialled or considered on other metros, prevent the hazard occurring, they only mitigate the effects. By contrast, physical separation of the track would prevent accidental and deliberate track incursion so increasing safety and reducing service affecting incidents.

Although it is acknowledged that technologies are developing rapidly, the trial and industry/metro engagement indicate that current detection technologies do not appear to offer a practical solution to PTI risk mitigation with its particular infrastructure characteristics and demanding reliability requirement.

The PED systems being considered by NTfL will require secondary detection at some curved platform locations to ensure the gap between the PED and Train is clear prior to train dispatch. This is a much simpler scenario than investigated during this trial. A scanning laser would appear to offer the best solution and is the system used on overseas metros with good reliability.

Gap Fillers - Mechanical gap fillers were identified as an integral part of the platform-train interface (PTI) solution for the NTfL programme, as they will be necessary at various locations on the Piccadilly and Central lines where curved platforms result in large horizontal stepping distances. Analysis of the Piccadilly line identifies 14 platforms which will require around 100 mechanical gap fillers, based on working assumptions of the PTI concept design and the candidate train design.

Platform-based mechanical gap fillers have so far been used in four metro systems worldwide, the most extensive use being in Tokyo, where over 200 units have been installed in the last ten years. All four metros have had mechanical gap fillers provided by different manufacturers.

NTfL engaged a gap filler manufacturer to undertake a series of tests designed to prove the reliability and suitability of mechanical gap fillers for use on the NTfL lines. In particular, these tests were

undertaken to better understand gap filler deployment cycle/timings and its impact on train service operation, as well as to identify any abnormal behaviour caused by prolonged intensive use, such as excessive noise, wear and other potential technical malfunctions.

Gap filler module built for NTfL trial



Accelerated life tests have been running without failure for approximately 3,000,000 cycles to date, an equivalent of 15 years of operational life. The current reliability rate is higher than the original target of five service-years between failures. Testing with contaminants including railway dust, grit and sugary drinks has revealed no detrimental performance impacts. Tests continue to accurately represent continuous rainfall conditions at the appropriate volumes for the accelerated testing regime.

Railway Control and Management - The feasibility study was focussed on the deployment of new technology to deliver a higher capacity, more reliable train service. Best practice from benchmarking studies of other metros around the world also highlighted the opportunity for London Underground to consider new and more flexible operations, made possible by the introduction of systems for higher levels of automation.

Benchmark Finding: Metros have reported that higher levels of automation have allowed them to significantly improve their response to changes in customer demand – and are able to introduce special service at hours notice, rather than weeks.

Provision of the capability for fully-automatic train operation would allow train movement and normal operations to be brought fully under the control of the train control system. It would also allow traditional operational roles to become more flexible and customer-facing. With a new control system, the train service can be overseen and managed remotely from the Service Control Centre where staff can monitor the state of the railway, the performance of the assets and the deployment of staff to keep the train service running

smoothly. With real time audio and visual communication links to the trains and stations, staff can take action in the event of disruption or incidents to ensure a swift response and recovery.

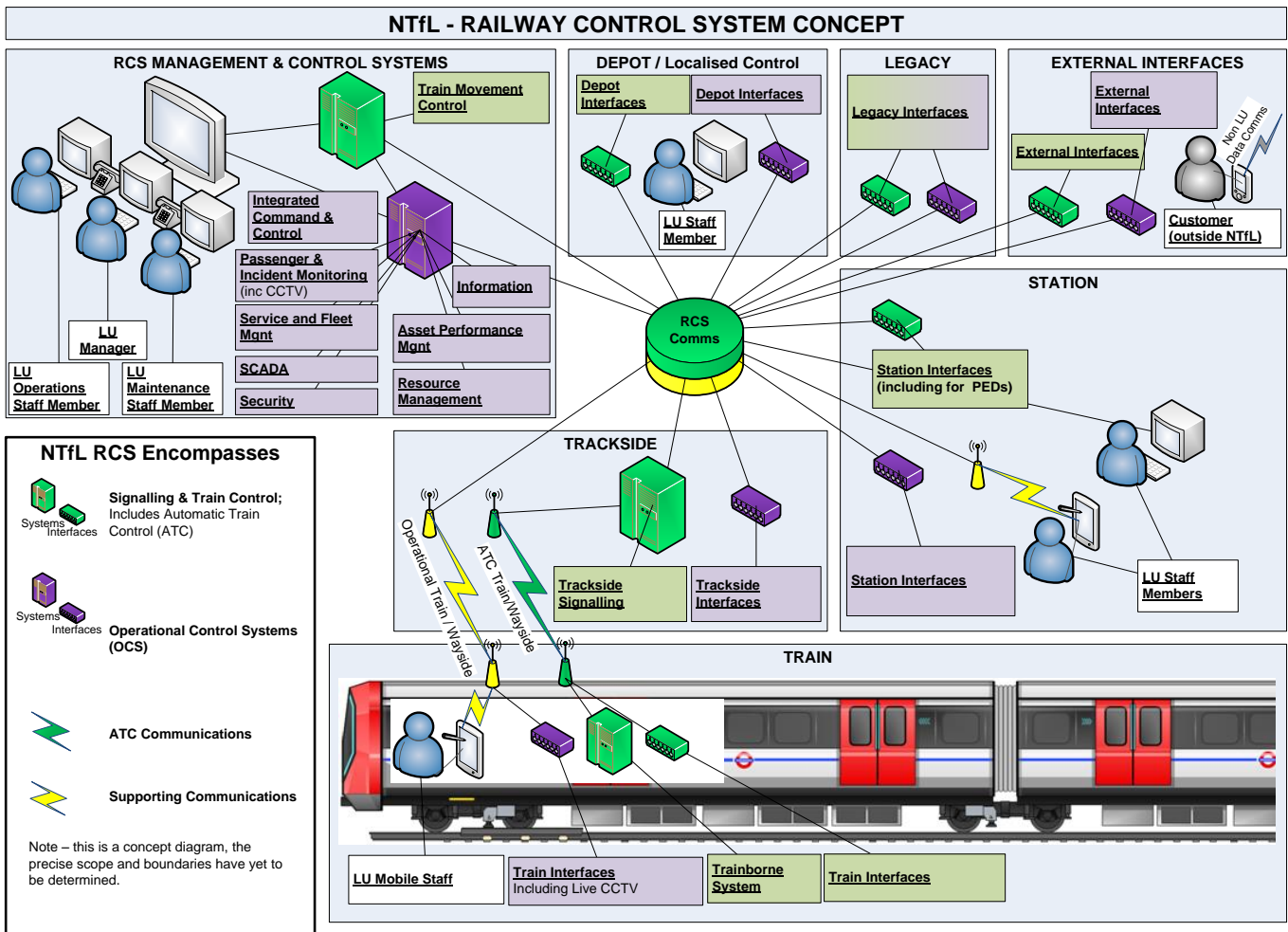
With staff duties no longer tied to the timetable, it is much easier to respond to perturbations or sudden changes in demand. This flexibility allows the train service to be increased at very short notice for special events where more trains are required to deliver an enhanced service. The automatic train control system needs to be extended to cover depot reception and stabling tracks to allow the automatic entry and exit of trains to meet service requirements.

Automated metro systems demand very high levels of service reliability and asset availability to maintain high service levels and meet capacity needs. This means that the railway system overall must be highly reliable and resilient to failures which lead to service suspension or delay, and that the need for maintenance interventions when failures occur must be reduced.

Feasibility studies have confirmed that through the adoption of modern diagnostics and communications and reporting systems, a 'predict and prevent' approach to system design and maintenance can be introduced to support higher levels of reliability.

Sub-systems can have the capability to continuously report their condition and performance such that asset maintenance activities can be predicted and scheduled 'just in time' to eliminate unnecessary periodic inspections and prevent failures in service. Benchmarking has highlighted the opportunities for reduced asset down-time by increased levels of modularity in design to enable defective sub-systems to be easily removed and replaced.

A high level view of principles of a fully-coordinated railway control system is shown in the diagram below. This is intended to show the type of information and data flow which modern control systems could provide for fully automatic operation.



Summary of feasibility activities

Project migration

An overarching Generic Migration Strategy was developed which could be applied to any of the NTfL lines, to form the basis for Line Specific Migration Strategies. These documents will then form the basis for development of detailed requirements and plans for each line implementation. The aim of the strategy is to align the high level implementation phases of numerous workstreams required to upgrade the railway in such a way that interim states can be defined and validated.

A number of key principles emerged from this exercise, either derived from specific technical requirements / engineering constraints, or application of lessons learnt on similar projects implemented by LU and other leading metros, as follows:

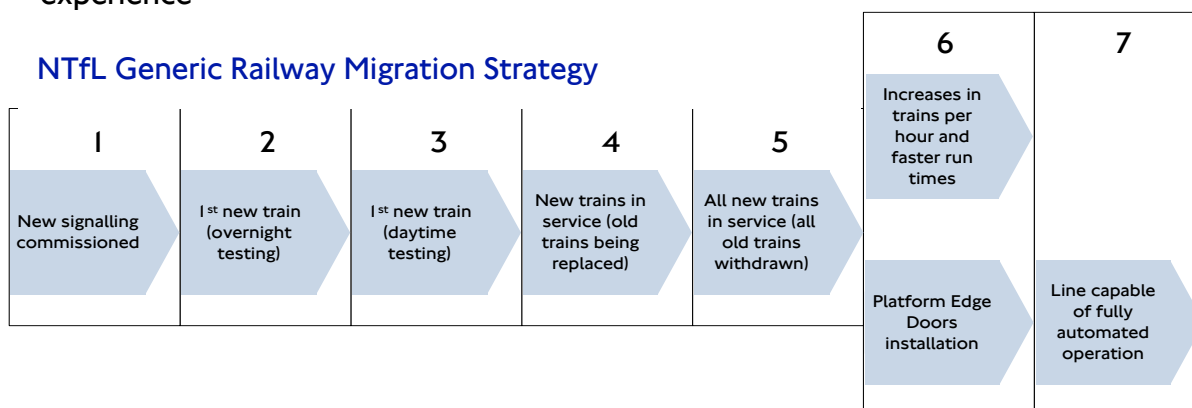
- If possible new trains should operate on new signalling from the outset to minimise train configuration stages
- An initial phase of testing should occur on the railway, but outside of traffic hours to gain real railway interface experience

whilst minimising customer impacts

- Replacement of existing service trains with new trains should be a gradual process, to ensure service continuity, resulting in a period when there are both existing and new trains operating in service at the same time
- Increases in services levels (trains per hour) should occur after the line is operating a full fleet of new trains; i.e. once the constraints on performance and efficient energy consumption which existing trains impose (lower voltage and no regenerative braking) have been removed
- Platform Edge Doors cannot be installed until all existing trains have been withdrawn due to differences in door spacing between new and existing trains
- The line will not be capable of fully-automated operation until Platform Edge Doors are installed

The resultant generic migration strategy, with seven stages of implementation is shown in the diagram below.

NTfL Generic Railway Migration Strategy



Feasibility outcomes

The New Tube for London Feasibility Study has determined that a world class modernisation of the remaining deep Tube lines is possible and that all of the key challenges under consideration as part of the programme can be overcome.

A railway level system concept design has highlighted how a high capacity modern metro service can be achieved in spite of the constraints imposed by the deep Tube Edwardian infrastructure. Line specific variations are expected to deal with unique structural factors on some of the lines but the core premise will remain similar:

New Tube for London - At the heart of the design is the New Tube for London train concept which represents an evolution of traditional Tube train configuration such that walk-through, air-cooled customer saloons can be achieved.

Quicker journeys - Customers will experience significant improvements in journey times due to faster and more frequent services.

Capacity - Greater capacity, up to 60 per cent on the Piccadilly line, will be delivered to cater for London's growth.

Platforms - The platform experience will be transformed at the majority of the stations on these lines with full platform to train level access and Platform Edge Doors, providing modern and safer waiting environment.

Temperature - Station cooling will also be implemented at a number of sites providing a cooler temperature for customers waiting on platforms.

Reliability - High levels of reliability are being targeted based on benchmarking with other world class metros. An NTfL upgrade target of 5 incidents per million car kilometres has been selected for the system design.

The following sections step through elements of the potential NTfL outcome which customers could experience during the coming decades.



Feasibility outcomes

Functional concept

The New Tube for London will build on the success of the London Underground S-Stock and Overground Class 378 trains, which have enhanced the customer experience through provision of through gangways and saloon air-cooling.

Our extensive feasibility investigations have demonstrated these features to be viable in the deep Tube environment as part of the NTfL train concept, which would offer:

- A 10 per cent capacity increase over an equivalent length conventional train design
- Fewer bogies, thus reducing overall train weight and energy consumption;
- Under-frame space for fitment of saloon air cooling systems
- A fully walk-through saloon to reduce crowding in the busiest carriages;
- Accessibility
- All double doorways to improve boarding and alighting times

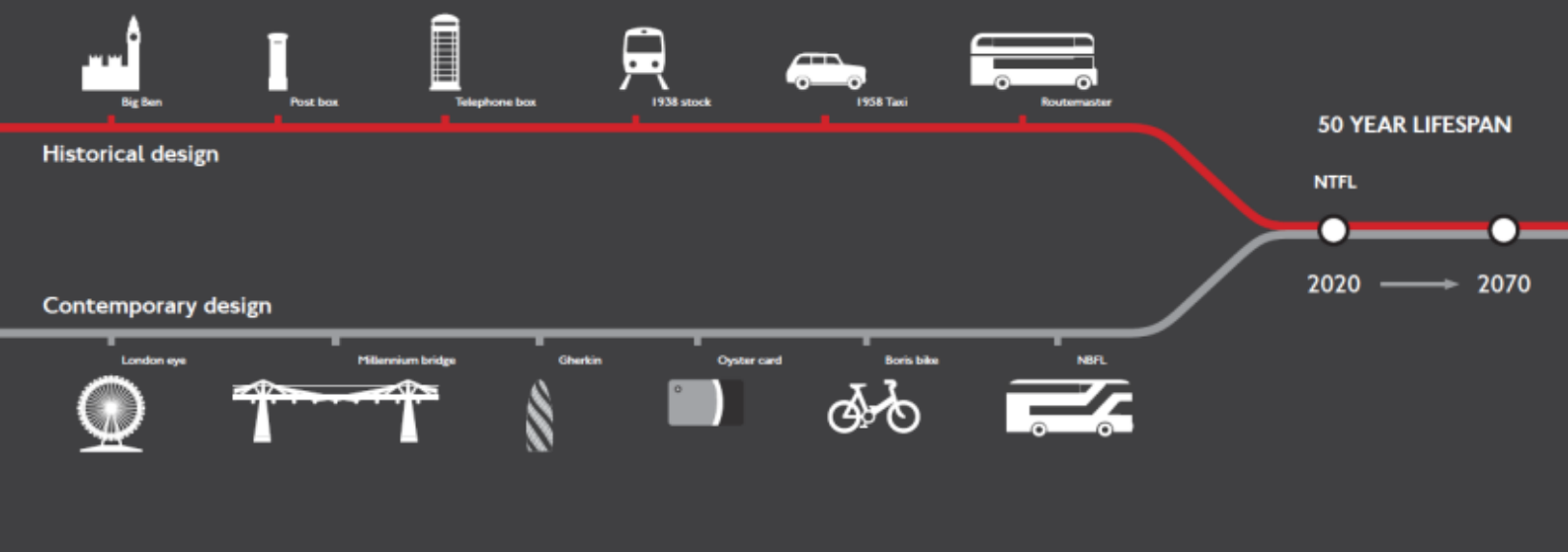
Extensive engagement has taken place with train manufacturers to confirm the viability of these elements of Tube train design.

This has been positively received and industry now has a high level of confidence in offering these features as in response to the NTfL train procurement.



Key benefits of NTfL concept	Conventional Tube Train	New Tube for London *
Number of cars	7	10
Number of seats	238	Up to 248 (+4%)
Standing spaces (at 4/m ²)	501	566 (+13%)
Estimated total capacity per train	739	814 (+10%)
Space for air-cooling units	No	Yes
Walk through train	No	Yes
All double-leaf doors	No	Yes

* Indicative design for Piccadilly line



Feasibility outcomes

Design concept

The feasibility study included a design exploration with industrial designers to develop a concept or reference design to inform procurement specifications.

A study was commissioned and awarded to industrial designers PriestmanGoode to develop, with TfL, a concept of the look and feel of the interior and exterior of a new deep Tube train.

This concept design was created within the constraints of existing infrastructure and reviewed the best configuration and design from customer and operational points of view.

The study was organised and delivered in three distinct stages: research, concept design and design development. These elements culminated in a finalised industrial design concept.

Stage I: Research

This stage verified the engineering data and physical dimensions to ensure that the requirements were established for reference trailer and driving cars. This included:

- The physical outer shell dimensions
- The door dimensions and capacity requirements
- Human factors
- Railway Vehicle Accessibility Regulations (RVAR) requirements
- Customer information systems including placement, sizes and number of structure apertures
- Ventilation grilles for cooling and heating



Piccadilly line
Westbound platform

Caledonian Road
King's Cross St. Pancras

Bakerloo line

Heathrow



256

PICCADILLY LINE



38000





14.35
Accompanying text
is a friendly line train to NorthEast

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The next station is
**King's Cross
St. Pancras**
Change here for:
Glasgow From London Newcastle

London
Kings Cross

London
Kings Cross





Feasibility outcomes

Time savings and capacity improvements

A high frequency fast service is possible on all of these lines post-upgrade which will generate a step-change improvement in the number of customer spaces and journey times.

Piccadilly and Central - peak period services are expected to operate at between 33 and 36 trains per hour in central London (a train nearly every 90 seconds, which would approach the most frequent metro service operated globally, in spite of our constrained infrastructure).

Bakerloo - a peak service of around 27 trains per hour is expected. This is equivalent of a train nearly every 2 minutes, and although a lower service than proposed on the other lines, will be a significant increase from today, commensurate with future demand and crowding predictions on this line.

Waterloo & City - A 30 trains per hour peak service could be offered on the Waterloo & City line with remodelling of the track layout at Waterloo, although further investigations continue to confirm the operability of such a high frequency of service on this constrained line.

Off-peak services - would also be increased, complementing the high peak services, and, on the Piccadilly and Central lines, 24 hour running on Friday and Saturday nights.

Line	Forecast peak capacity increase
Piccadilly	60%+
Bakerloo	25%+
Central	25%+
W&C	Up to 50%

Journey times - Waiting and travelling times on the upgraded lines will reduce too. As an illustration, on the Piccadilly line customers could experience following approximate reductions in typical journey times (including waiting time):

Heathrow - Leicester Square	7 mins
Hounslow - King's Cross	6 mins
Finsbury Park - Hammersmith	6 mins

Feasibility outcomes

Service patterns

The feasibility study included a review of the strategic function of each line.

On the Piccadilly line, this involved consideration of a number of opportunities to ensure that the service offering in west London is optimised for the long-term. The feasibility study concluded the following:

Rayners Lane to Uxbridge - Both the Piccadilly and Metropolitan lines should continue to serve the section between Uxbridge and Rayners Lane. Curtailing either line at Rayners Lane or more radical options to extend the District line from Acton Town to Uxbridge in place of the Piccadilly cannot be justified.



Ealing Broadway - The Ealing Broadway branch of the District line could in future be served by the Piccadilly line. The Piccadilly line upgrade would provide sufficient train paths through central London to enable this change, which would allow a significant uplift in District line services to Richmond and Wimbledon, greatly benefiting

customers on those branches. In order to achieve this, Chiswick Park platforms would need to be relocated to the Richmond branch of the District line. This would increase the number of trains stopping at this station from the current 6-7tph to 12-15tph.

Turnham Green - In conjunction with this change, Piccadilly line trains will stop at Turnham Green throughout the traffic day post-upgrade, increasing the peak tph at this station from the current 12-13tph to upwards of 40tph.



Bakerloo - Similarly, the strategic role of the Bakerloo line and London Overground services in North West London were considered as part of the feasibility study. The conclusions of this work were to retain the current service patterns on both these services, as a case for change was not found.

Whilst not directly delivering it, the upgrade of the Bakerloo line will allow for a southern extension of the line should this be progressed in the future.

Feasibility outcomes

The platform experience

NTfL can transform the platform experience for customers.

Not only can waiting times be reduced significantly but the waiting environment can be improved too.

It is expected that ultimately Platform Edge Doors (PEDs) will be implemented on the majority of platforms served by the New Tube for London. This will provide a safer and more modern space for customers who are waiting for their trains, much like that provided on the underground stations on the Jubilee line extension.

PEDs cannot be implemented in the initial stages of the modernisation as they have specific door spacing to match the trains in service, and during the introduction of the new trains, two different stock types (existing and new) will be in operation on the lines. Hence PEDs would be installed after all of the existing trains have been withdrawn.

Platform Edge Doors are not suitable for the Bakerloo line between Kensal Green and Harrow & Wealdstone or the Piccadilly line between Rayners Lane and Uxbridge where Tube trains will continue to share platforms with larger gauge



trains with different door spacings and floor heights.

At platforms to be fitted with PEDs, platform heights would be raised or lowered to create level access between the platform and the train at all doorways.

At platforms where curvature results in an increased horizontal gap between the train and the platform, mechanical “gap fillers” are expected to be used. These are metal extensions of the platform which move out to fill the gap between the train and platform on curved platforms after the train arrives, retracting before it then departs.

Northfields
Northfields
1 min
4 min
11:10:23



Conclusions

A comprehensive Feasibility Study has been carried out for the upgrade of the remaining deep Tube lines.

Modernisation of the Piccadilly line will deliver the greatest capacity uplift and journey time savings. It therefore should be the first major line for deployment of the New Tube for London.

Bakerloo and Central line modernisation will follow, with the current expectation that the Bakerloo line will be second, to complete the replacement of London Underground's oldest rolling stock.

The Waterloo & City line will probably be modernised alongside the Central line, however consideration is being given to using this line as part of the trialling and testing plan for the NTfL concept. This would mean earlier modernisation alongside the Piccadilly line.

The programme expects to deliver saloon air-cooling for customers in London's deep Tube tunnels for the first time.

High capacity, walk-through trains will be procured and introduced. Additionally, the system can be designed with the capability for fully-automatic operation, should this mode of operation be needed in the future.

On the Piccadilly line, between Rayners Lane and Uxbridge, and significant proportions of Bakerloo line (where platforms are shared with larger gauge trains) PEDs cannot be fitted; fully automatic operation is not considered feasible on these parts of the network.

Work continues apace to implement these line upgrades at the earliest possible date, delivering significant benefits to customers of these deep Tube lines.

The next steps are currently as follows:

- 2015 [New Tube for London rolling stock Invitation to Tender to be issued](#)
- 2016 [New Tube for London rolling stock contract to be awarded](#)
- 2019 [Railway Control System installation on Piccadilly line begins](#)
- 2022 [First new train delivered for pre-production testing](#)
- 2023 [First new train in service](#)
- 2025 [Piccadilly line capacity enhancements begin](#)



NTfL proposes to work towards the following outcomes when modernising the Bakerloo, Central, Piccadilly and Waterloo & City lines:

Piccadilly line

A peak service level of 33-36tph, with air-cooled, walk-through Tube trains, by 2025, over the current line geography, and possibly the Ealing Broadway branch currently served by the District line. The line will have PEDs and be capable of fully-automatic operation (except between Rayners Lane and Uxbridge).



Bakerloo line

A peak service level of 27tph with air-cooled, walk-through Tube trains by 2027.



Central line

A peak service level of 33-36tph, with air-cooled, walk-through Tube trains by 2032. The line will have PEDs and be capable of fully automatic operation.



Waterloo & City line

A peak service level of up to 30tph, with air-cooled, walk-through Tube trains by 2032. *The line will have PEDs and be capable of fully-automatic operation.



* Subject to the role of W&C in the NTfL trialling and testing plan

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