Providing System Resilience as the Goalposts Move

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SUMMARY

This paper discusses the advances in technology in the railways that bring new challenges and opportunities for engineers to conquer, allowing them to further their expertise in delivering more comprehensive systems that enhance the daily lives of people around the world.

1 INTRODUCTION

As we move through the 21st Century the goal is no longer simply transport itself but the passenger experience on the journey[1], therefore trains are now in direct competition with all other transit modes and must have higher levels of reliability and better passenger experience, with safety as a given that is never compromised.

The aim of mass transit systems worldwide is to react to that change, to provide maximum capacity (more trains to travel on), better reliability (more certainty of arrival time) and give a better passenger experience.

As the challenges have increased, technology has advanced to meet new requirements, moving from largely mechanical to computer-based solutions. These computer-based solutions in turn bring new challenges, such as how to manage the complexity, how to ensure safety is never compromised, and how to enhance reliability. These systems are now also increasingly networked to enhance capability and usability. With the increased use of this technology comes added challenges of managing the network and its reliability and also ensuring that it is safe from the increasing threat of cyber security breaches. The next sections describe some of these challenges in more detail.

2 THE CHALLENGES

Fortunately for the passenger of today safety is a given. It is the highest priority for all professionals in the industry and at no time is it allowed to be comprised [2]

The next challenge for the industry is therefore increasing the reliability of the systems provided and therefore providing more certainty of travel for the travelling passenger.

In London passengers have experienced an availability in services in the high 90% for the last eight years, and therefore any dip in this is not an option at a time that ridership levels are under threat due to new and emerging alternatives such as electric bikes, Uber personal hire vehicles and an increased preference for cycling and walking.

At the same time as availability and reliability needs to be maintained, or enhanced, the drive for maximising capacity on the available lines requires the implementation of new technologies and new ways of delivering systems.

On the Thameslink system, that enables commuters to travel from the suburban outskirts into and through London, the need to increase the capacity from 16 to 24 trains per hour (tph) has required the delivery of Automatic Train Control and an advanced Train Management System as discussed later in this paper. [3]

As greater advances in technology and more complex systems are required to deliver more reliable systems the number of subsystem interfaces increases and the challenge of integrating those subsystems becomes ever more difficult. These challenges require larger investment in testing methods and methodologies at a time when industry is being asked to deliver more functionality for less capital spend.

In addition to larger, more complex systems, the clamour for increased performance and greater flexibility of systems requires that these subsystems are ever increasingly networked and often use commercial off the shelf (COTS) products. This move towards a more integrated IT system leads to an increase in the cyber security threat, the emerging elephant in the room for systems of today. This has long been a threat encountered in military systems where the solution has been to carry out ever-increasing levels of testing - with the resulting inevitable increased costs.

While the challenges just discussed are imposed on all delivered systems the challenge of installing those systems is also increasing as the operators look to use their assets for longer periods and strive to reduce asset footprints to reduce cost. In London the move to Night Tube (24-hour operation of a number of lines for two nights each week in order to meet customer demand for late night travel) [4] removed the possibility for weekend maintenance and upgrades and restricted access to track side to three nights of 4 hours a night each week. In addition to less availability of track access there is a continued move to reduce asset footprints in a drive to save on operational costs, by reducing land required for equipment buildings, and also to reduce on board equipment on trains to save weight and therefore amount of power required to operate the service.

In summary, at a time where industry is being asked to deliver safety that is assumed, on more reliable systems with higher performance at lower cost, we are challenged to create more complex solutions, with higher cyber security needs and allowed less access to the track for testing and less real-estate to house our solutions. Is this the perfect storm or the opportunity for exceptional people to provide exceptional solutions, the next section introduces some of the potential solutions.

3 POTENTIAL SOLUTIONS

As systems become more computer-based, more integrated and more automated, the need to employ system engineering techniques, adopted for many years in the avionics and military arenas, becomes key to success. This requires a more in-depth appreciation of the whole systems lifecycle from requirements evolution through system design, manufacture, test, commission and support. Increasingly systems not only need to be more cost-effective to produce, they also need to be cheaper to install, maintain and upgrade. Decisions made during requirement evolution and design may have an impact on all parts of the system lifecycle including support, and therefore all functions need to be represented at the beginning and throughout the lifecycle of development. The next sections discuss opportunities for enhancing the process at each stage of the system lifecycle.

3.1 Requirements Definition and Analysis

During the requirements evolution stage the continued presence of the designers, coders, testers, commissioners and maintainers will ensure that the system built is one which most closely meets the needs of the specification throughout its lifetime. The continued presence of the whole spectrum of engineers through the whole lifecycle ensures that the system is built, tested and delivered in a manner that is most cost-effective. The additional involvement of the customer and the end user throughout this lifecycle ensures that the system that is being delivered is the one that meets stakeholder and operational needs.

From a requirements perspective the smartest and most effective question throughout is why is this needed? This is a simple question if the stakeholders and end users are part of the integrated team delivering the system. The next question that goes hand in hand with why is how much? If there are any requirements that are pushing the cost of the system exponentially then these need to be challenged and resolved.

3.2 Design

In terms of design the use of COTS products is often seen as the panacea, in that they are easier to procure, are widely available from many suppliers, and therefore easier to keep operational, but are they? It is true that Apple, IBM and HP products have a greater commonality in specification, however these same products also have a half-life and obsolescence time that is a fraction of the bespoke solutions tailored by the signalling and rolling stock main producers, so how does this affect renewal timelines? Again the integrated approach of supplier and customer working in a joint collaborative team makes the easy decision on how to balance these often contradictory requirements.

From a development perspective, there are two main development lifecycles we have used to deliver train control systems, the waterfall lifecycle, that is the traditional system engineering approach and takes 18 months to 5 years to deliver from requirements to a commissioned system, and the agile approach that seeks to take requirements through to a delivered useable system in 4 – 8 weeks.

In addition to the development cycle chosen, the design needs to embrace the challenges of whole life cost, cyber security, testability, reliability, performance and availability. Many customers of these systems require proven use in operation and therefore references of operational sites are required during the competitive bidding phase. This means that any bespoke requirements of the new system need to be added and integrated into a system that is already in operation elsewhere.

One area where the requirements of new systems is changing at a very rapid pace is that of cyber security, and whilst most current systems can be tweaked to meet other new requirements, cyber security is perhaps an area of the system that requires a major rethink. The adoption of SL3 Security standards can affect the core of a system's performance and therefore the first and second questions asked in the requirements phase of 'why' and 'how much' should again be re-iterated to ensure best value for money.

Reliability and availability can be designed into a system in one of three ways, through multiple levels of redundancy, using highly available and reliable components or through graceful degradation of the system resulting in safe operation.

In avionics the use of multiple redundancy of highly reliable components (where graceful degradation is not an option), is the accepted solution, this requires often very complex Built in Test Algorithms that can have as many as 15 redundant pathways.

In railways a straight copy of the avionics solution can lead to additional cost and over burdensome space requirements. A cheaper solution for railways would be the use of graceful degradation so that when systems fail, rather than a back-up system taking over, a reduced functionality is provided such as running trains in restricted mode or at reduced speeds. In a time where value for money is seen to be a strong requirement, it is therefore surprising that these options are often not considered as we seek to transport our customers to their destinations at ever more increasing speeds.

3.3 Implementation

Our system engineering teams are used to building systems that are safe, reliable and highly available, however the concept of whole life cost is new to signalling, what does it really mean, and how it is evaluated? If the operator or purchaser is also the maintainer of the system how does the supplier understand and build in whole life cost. This again is best answered in a collaborative environment where supplier and customer sit together to assess the balance between capital and operational expenditure (Capex and Opex). How is this achieved in a competitive procurement process and what are the risks and rewards of doing so?

The implementation of the system is based on the design that proceeds it, and many successful programmes have ensured through detailed design reviews that the system is built accordingly. The need to deliver value for money throughout the lifecycle identified early that effective coding and manufacturing is key to delivering a cost -effective system, and six -sigma optimisation groups in factories along with the use of the Software Standards, such as the Capability Maturity Model Integration (CMMI) [5] have ensured design is most effectively transitioned into code and manufacture.

Different Safety Levels are prescribed for different aspects of the train signalling systems Vital safety systems (such as interlocking and Automatic Protection Systems) being prescribed as SIL 4 and less vital systems such as Automatic Train Operation (ATO) being prescribed as SIL 2. Are these the right prescriptions, particularly as ATO is becoming more and more complex, would a SIL4 design and test regime ultimately make some of the less vital software systems more cost-effective to deliver?

Alongside these safety levels different aspects of the system are also now being prescribed security levels (SL Levels). These Security Levels require a new level of thinking in the design and implementation of a system. Whereas a safe system requires that in the event of a failure a safe solution is found (usually by stopping the system that is perceived as out of control), a secure system must ensure that a wilful attempt to break the system is unsuccessful, is detected and reported. These security requirements have been present in many military systems for many years, and the manner in which they are implemented and tested is well documented [6], however Military Systems are often ten times the cost of Train control systems, and at a time that value for money is key there is there little opportunity to increase the cost of Train Control Systems to facilitate the need of security. Therefore the acceptance and implementation of security requirements needs to be carried out in a pragmatic and measured approach, what is the risk and what is the most effective solution? All major manufacturers of train signalling products are on a technology roadmap that delivers SL 3 components early in the 2020s however the compliance of these products alone does not guarantee the compliance of a system made up of these components. The weakest link or interface between components is the hackers' best route into compromising the system, therefore a holistic approach to system security needs to be adopted, understanding risk levels and mitigation procedures.

3.4 Test

One of the areas that has seen most significant investment in recent years is that of testing, bringing train control systems more in line with avionic testing regimes, ensuring the most is made of automated test rigs, operational know-how and offline readiness of the system. This trend has been pursued due to the ever-increasing cost and lack of access to on-line real environment testing.

As operators need to ensure maximum use of their assets; access to the railway for testing has diminished and therefore there is an increasing need to ensure the system is robust before taking it to the final environment.

In line with avionics programmes, the opportunity to test operational envelopes rather than single, or sets of, requirements alone, has led to hugely more robust systems on delivery. The involvement of end-users along with key stakeholders during the testing process creates a massive step towards ensuring the system will operate as specified and as required in operation. Once more a collaborative environment incorporating a team comprised of customer, supplier and end user is a strong catalyst in ensuring the system is robust and fit for purpose when delivered. The maturity of the individuals and companies within that collaborative environment will determine the likely success or failure of the programme. An immature team can lead to escalating costs, requirements creep and potentially a breakdown in delivery and contract, whereas a focussed mature team can reduce costs, focus on the system needed and succeed together in delivery.

Once the need for significant operational testing is accepted, the ability to stress the system prior to delivery can be exercised in full. Different types of operational testing test different scenarios, from peak loading to introducing broken components, unusual operational modes and a mixture of all eventualities. The goal of the test team should be to break the system if possible, only with that mindset can the required reliability of systems be realised prior to operational testing on the track.

Once rig testing has been exhausted and all operationally possible errors been corrected, the final stage of testing prior to accessing the operational track is the use of a test track. The composition of this track can vary hugely from a straight few hundred metres in which the train barely obtains operational speed to a continuous loop fully equipped with the signalling system that is going to be delivered. The amount of risk reduction is proportional to financial outlay associated with such a system.

One area of testing that is new to train control system is that of Cyber Security. Cyber security testing has been a cornerstone of military systems for many years and is focussed on preventing individuals from wilfully breaking or corrupting systems or manipulating systems to the advantage of another party. It is more than possible that train systems could mimic military systems to achieve the same objective, the challenge is that a blind copy would result an exponential increase in testing time and cost, so a more pragmatic method needs to be found. This pragmatism is, not surprisingly best found in a collaborative environment where supplier, customer and end user work in harmony to understand the real risks, and therefore the testing that is absolutely necessary to mitigate or eliminate those risks.

A method of testing yet to be fully engaged in signalling is the use of so-called 'digital twins'. This method has been used successfully for the testing of single physical products such as engine turbines for some time, and is also used in the world of Formula 1 motor racing where budgets are somewhat more generous and time is of the essence. It enables testing to destruction in a safe manner, where the testing is undertaken on the twin and therefore neither the physical unit or the testers are harmed in any way. While expensive to set up if signalling systems became more of a commodity, and consistent, this may enable faster more effective testing in the future.

3.5 Support

Increasingly train control systems are being procured with a design, build and maintain contract such that whole life costing is part of the solution. Providing representatives from the support team have been involved and listened to in the whole lifecycle from requirements through to support, then the ability to support the system should not be onerous. The challenge is that systems engineering teams have for many years considered testability as part of developing the system, however considering support requirements is more novel and therefore not intuitive, therefore the support staff involved in the early development of the system need to be robust characters in order to get their voices heard.

3.6 Agile versus Waterfall Lifecycle

The Waterfall model was proposed by Royce in 1970 which is a linear sequential software development life cycle (SDLC) model. The various phases followed are requirements analysis, design, coding, testing and implementation in such a manner that the phase once over is not repeated again and the development does not move to next phase until and unless the previous phase is completely completed. The waterfall model is a sequential design process, often used in software development processes, in which progress is seen as flowing steadily downwards (like a waterfall) through the phases of Conception, Initiation, Analysis, Design, Construction, Testing, Production/Implementation and Maintenance[7].

One of the first agile methodologies was the spiral model [8] defined by Barry Boehm in his 1988 article A Spiral Model of Software Development and Enhancement. This model was not the first model to discuss iterative development, but it was the first model to explain why the iteration matters. As originally envisioned, the iterations were typically six months to two years long. From the idea of an iterative methodology came the birth of agile techniques, the most often used being SCRUM [9], as developed K. Schwaber and J. Sutherland, in the early 2000's. This technique seeks to turn around requirements into working code within 4 -8 weeks, a method that has been used extensively by Siemens development teams. It has the major advantage that the customer knows within a very short timescale if the requirements specified have resulted in the desired system outcome.

In the next section we describe a very specific instance of when a combination of waterfall and agile lifecycle was used in parallel, with great success to achieve a very significant reliability impact on the London Underground Victoria Line.

4 EXAMPLE PROGRAMMES

Here we look at how some of the potential solutions have been applied in systems delivered around the world, what lessons we have learned and how we can capitalise on those learned moving forward. The examples are taken from Mass Transit systems, some metro and some urban.

4.1 Victoria Line Metro System – Combination of Agile and Waterfall Development Methodologies – In a Collaborative Team

The upgrade programme replaced all the London Underground's Victoria Line's rolling stock and signalling, all dating back to the 1960s. The programme faced a number of significant challenges, requiring migration from the legacy Automatic Train Operation (ATO) system to the new system (the world's first ATO-on-ATO upgrade), with Siemens' Distance to Go-Radio (DTG-R) trackside equipment being overlaid on to the legacy signalling system, transmitting the new radio messages and legacy track circuit codes during the migration period for the new rolling stock fleets.

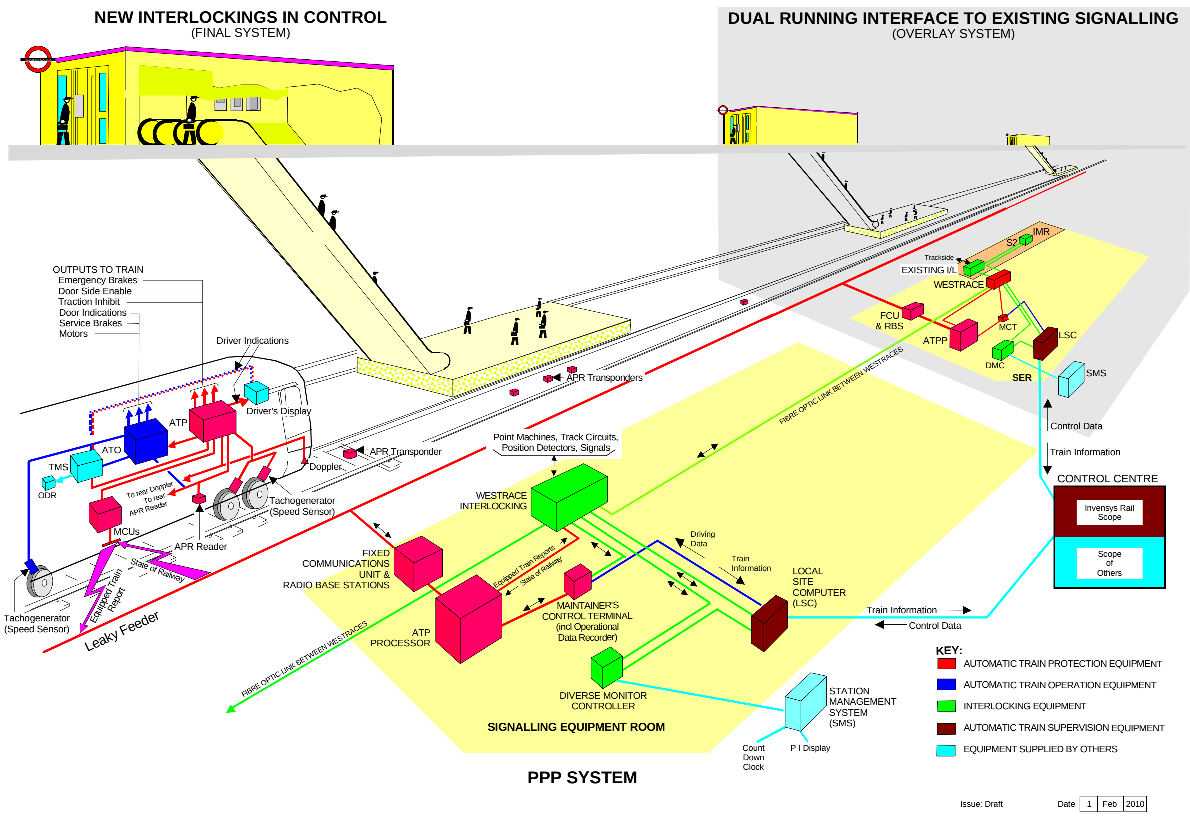

Figure 1: Schematic Architecture of Victoria Line Showing Overlay Implementation

The migration concept for the project required two phases of work; an overlay phase followed by a renewal phase. This was driven by the need to introduce a completely new fleet of 47 Electric Multiple Units (EMUs) without impacting passenger service, and the decision to dual fit the trackside rather than the trains. The existing signalling system needed to remain untouched during this fleet upgrade so the previous ATP / ATO system could continue to operate.

Once the system went into service it was clear that the reliability growth required for acceptable passenger use needed to be accelerated. The system as delivered had two key challenges, a number of operational failures existed due to a multitude of small issues and there was also an underlying issue with the software on one of the more complex modules on the ATO.

As described earlier in this document there are two methodologies that we have used for development, Agile and Waterfall. The agile methodology is best suited to make small changes quickly, and the waterfall method to do more significant development over a longer period of time.

Due to the urgency and magnitude of the reliability growth needed, we took the unusual and significant challenge to carry out both development methodologies in parallel and then piece the software together in an integrated build. On this basis we could make incremental improvements and deliver into operation at eight-week intervals, and then after re-designing some of the more significant software changes, we integrated the two packages together to deliver the overall reliability growth required.

In addition to changing our design and development methodology we also enhanced our testing processes, firstly to create operational scenarios in consultation with the end user and customer stakeholders, and then automate those operational scenarios, to enable testing to be undertaken faster, and then to introduce pseudo random errors into those automated tests, to facilitate unexpected operational events. The mindset of the test team was to break the system.

In parallel with these technical innovations one major game-changer was surfacing, necessity being the mother of invention and the looming of the 2012 London Olympics. This one event changed the mindset of the team, failure was not an option and contracts became less important than delivery. A multi- company collaborative team was developed and empowered to deliver, and that is exactly is what the team did. Rated the highest in customer satisfaction for the Olympics the Victoria Line has now gone from strength to strength to become one of the highest capacity railways in the world.

4.2 Victoria Line Upgrade 2 – Collaborating to Produce a Improved Solution giving the customer a smoother journey with greater reliability.

The VLU2 programme delivered overall signalling and control system performance improvements to the Victoria Line Upgrade 1 (VLU1) project which Siemens commissioned in June 2012.

The main driver behind the VLU2 programme was to assist LU in improving the Victoria Line's capacity during peak hours, from 34 to 36tph. LU modelling, supported by Siemens, demonstrated that train service frequency improvements were feasible at key pinch points on the Victoria Line and, in order to enable the achievement of these improvements, LU contracted Siemens via a modified New Engineering and Construction (NEC) 3 contract.

Siemens was contracted to design, install, test and commission a number of signalling and control system enhancements to enable the predicted capacity improvements to be achieved. However, as the operator of the Victoria Line (VL), the responsibility for achieving capacity improvements laid solely with LU.

In order to predict train performance, Siemens used its simulation expertise and extensive simulation packages, in particular the Siemens own simulation systems PACA and SST (Scheme Simulation Tool). For VLU2, the prime means of determining performance was the SST system, which uses specialist software running on standard desktop PCs to simulate the movement of trains through the network.

Train data (predicted and actual) including train weight and weight distribution, train length, tractive effort vs speed, braking effort vs speed, emergency brake rates, rolling resistance and coefficient of rotating masses is combined with geographical data such as gradients, station positions, curvature, and points position to allow accurate Newtonian physics simulation. Dwell times were also used within the simulation, varying across the network from 30sec – 50sec. A PC-based implementation of the ATP and ATO algorithms was then used to allow the motion of the train under control of the signalling system to be modelled.

As part of the overall solution the train cruising function was implemented (constant speed function). The way in which this was implemented spoke volumes for the collaboration of the teams. The final solution proposed by LU and implemented, being superior to original one proposed by Siemens. Not only was the agreed solution easier to implement, and more cost-effective it also required less change to software and therefore reduced the risk of the overall programme.

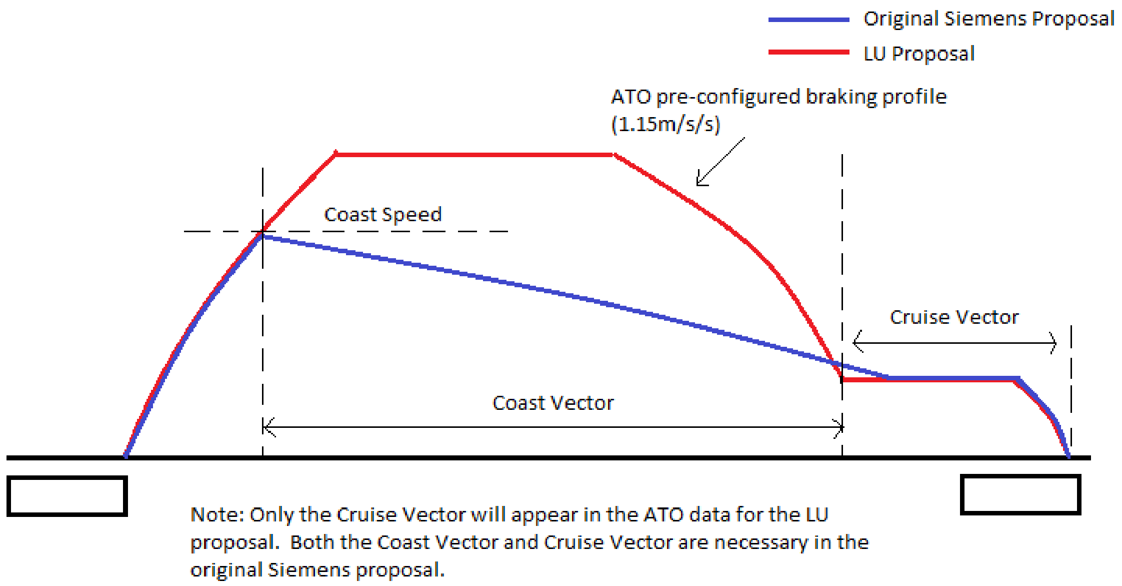

Figure 2: Implementation of Cruising – Resulting in an improved solution through collaboration

The Programme was implemented in conjunction with the Victoria Line operating Night Tube a 24-hour service on every Friday and Saturday. This additional service pattern meant that the engineering hours usually available at weekends were no longer, and therefore access to the railway for testing purposes was now at a premium. Understanding this constraint, the team used its collaborative working environment to ensure that all projects needing access to the railway were co-ordinated such that the maximum use was made of all available track time. This collaborative working ensured that despite the normal frustrated access experienced during such programmes, Siemens actually received more track time than was set out contractually, ensuring the testing was completed and the system was delivered ahead of the programme.

4.3 Thameslink – Implementing a Shared Vision in Testing

Figure 3: London Bridge – Showing the multiple track configuration – requiring stringent test and implementation

The GB Government-sponsored £7bn Thameslink Programme is an ambitious ten-year programme of extensive infrastructure enhancements and the delivery of 115 new trains that will bring faster, more frequent, more reliable, better connected journeys for passengers - transforming north-south travel through London.

The Programme is delivering new infrastructure, better stations, new technology and new trains on an expanded Thameslink network to deliver significant improvements that respond to the growth in passenger demand now and into the future. Siemens is delivering the trains and ETCS signalling solution

Early in the Thameslink programme it was decided that there would be significant benefit to be realised from the creation of a fully featured integration and test rig.

Two instances were created, one in Chippenham, one in the client's premises in London, both using an underlying train movement simulator to allow testing of the overall system architecture.

The intention was always that all parts of the integration rig could use either target hardware (i.e. physical hardware identical to that used on site in later phases) or hosted versions of the underlying software. This meant that as each element of the integrated system became available it could be connected together to demonstrate that the system functioned properly. The rig in London went as far as having physical tachogenerators picking up speed signals from rotating wheels to mimic train movement, and a live GSM-R connection from the RBC to the test rig's on-board equipment. A driver's desk was mocked up with a large screen mock- up of the view from the front of the cab so that an accurate emulation of the driver's view could be created.

The advantages of this approach were multi-fold. Firstly it allowed system interfaces to be proven, and confidence built that each element of the system could work together with each other, secondly it allowed real 'scenarios' of operation, for example a mode change or an emergency scenario, to be created on the rig and tested through. For a complex station area such as London Bridge it was also important to be sure that a large number of on-board units could communicate with a radio block centre, again this scenario could be created and tested exhaustively on the rig.

The resulting customer benefit was that extensive testing of the system had been completed long before installing equipment on site. With scenarios tested and proved to be manageable, and with confidence that performance would be as anticipated, the test rig was a powerful tool for allowing new product introduction on a very complex site with managed risk.

4.4 Copenhagen – Creating a Collaborative Model from the Outset

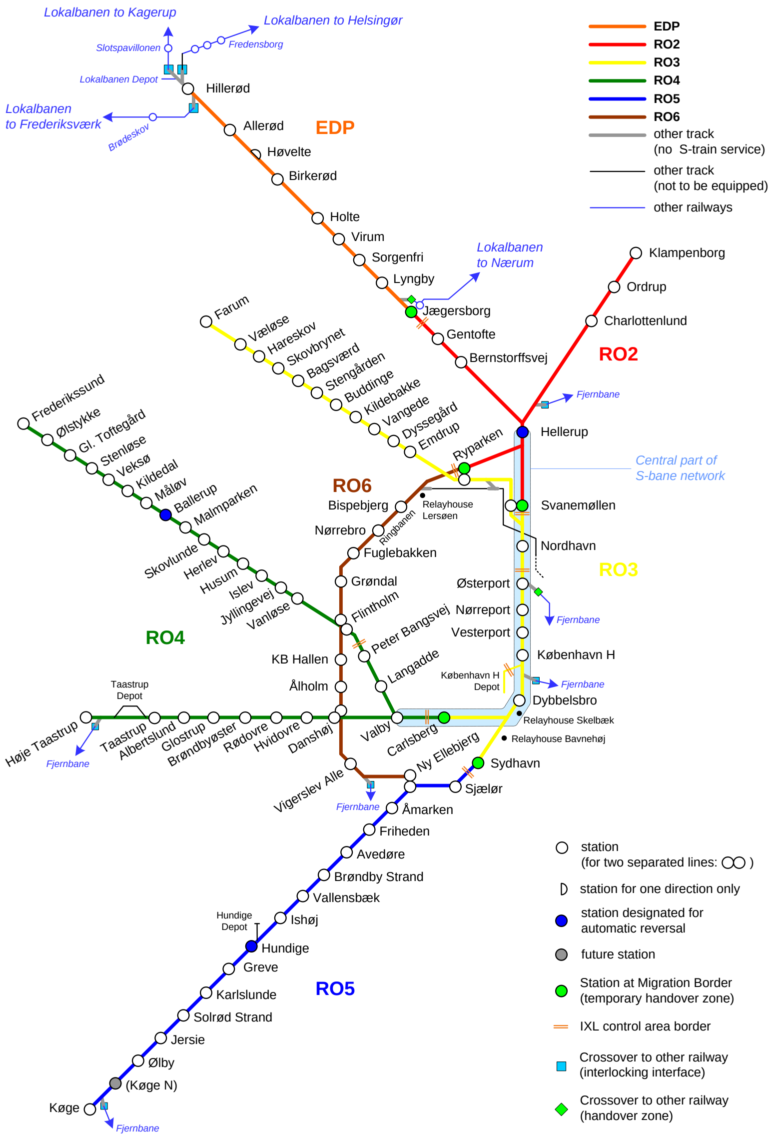

Figure 4: The six lines of the Copenhagen S-bane – Showing the complexity of the railway and number of intersections

The purpose of the S-bane Signalling System project is to renew the existing signalling systems on the Copenhagen S-bane, the Danish capital's extensive urban railway system. The renewal is a complete replacement of the existing signalling systems with a new CBTC signalling system. The project delivers a number of operational benefits derived from implementing a modern signalling system including improved punctuality, a high uniform safety level on all lines and lower life cycle costs.

Copenhagen's S-bane is a nearly closed railway system comprising 176 km field length (432 km track length) and about 90 stations.

One of the main characteristics of this project is the collaboration agreement between Banedenmark (BDK) and Siemens. BDK and Siemens entered into a collaboration agreement shortly after contract award with formally recorded rules and regulations for application during the project. It is important to note that the collaboration has been agreed for all levels of the project from senior management to on-site teams. The project teams are co-located at the customer's premises in Denmark.

Our experience on this project proves that collaboration succeeds when supported by openness. When issues and risks are known by each other and shared, the most effective mitigations be found. The S-Bane project has one MPS (Master Project Schedule) showing, on a monthly basis, the true status of the project. The co-located team share access to the MPS which is a live document that is fully representative of the project status.

Siemens and the client managed challenges, risk and opportunities at all stages using collaboration. An early dialogue in case of upcoming difficulties helped to find rapid solutions where necessary. Requirements and their implementation have been discussed and agreed from the outset. This helped to ensure that new implementations in the software met the customers' expectations. At all stages of the project, issues were openly discussed between the parties. Examples are difficulties in the newly defined approval chain, delays in the provision of functionality, and issues with trackside data. In all cases a mitigation or solution has been agreed and implemented.

4.5 Riyadh - A Fully Integrated and Tested Turnkey System – Utilising a World Class Testing Facility

With six lines and a total route length of 176 kilometres, Riyadh is constructing one of the world's largest metro projects. Riyadh currently has a population of 6.5 million people which is set to increase to 8.3 million by 2030 due to its rapid urban growth. As part of a consortium with the US company Bechtel and the local construction firms Almabani and Consolidated Contractors Company, Siemens Mobility is responsible for building lines 1 (Blue Line) and 2 (Red Line). Siemens Mobility, as Engineering and Maintenance partner, is supplying the rolling stock for driverless operation. Moreover, the scope includes project management, signalling, power supply, communication systems, depot and workshop equipment, platform screen doors, testing and commissioning and system integration in a turnkey approach.

To enable fully automated, driverless, and conductor-less operation a variety of systems need to work hand in hand smoothly. Thus to guarantee the necessary performance and functionality of the overall rail system testing is done on the respective single concepts as well as on the interfaces of different subsystems. The rolling stock was tested in combination with the signalling system, onboard communication system and a simulator for platform screen doors in Siemens Mobility's ultramodern certified Test and Validation Center Wegberg Wildenrath, Germany. Offshore testing is about ten times faster than doing everything on site, thus speeding up installation times in Riyadh. Following extensive offshore testing all systems are finally verified during commissioning onsite to enable a safe and unobstructed start.

Figure 5: Riyadh Signalling Implemented on the Wildenrath Test Track – A purpose-built installation to enhance testing and reduce the amount access to the operational track

Building Information Modeling (BIM) was used for the digital prototyping of the infrastructure. Interdisciplinary design reviews with the civil partner safeguarded the efficient integration of the transit system into the civil infrastructure. System conflicts were avoided consistently and the risk of delays reduced and execution speeded up addition ally. The data included in the BIM model provides the base for predictive maintenance.

5 CONCLUSION

As we push the envelope in terms of time to deliver, performance and capacity of the system, and our eagerness to have the system we are trying to update continuously in operation, we will need to question what we are doing, why we are doing it and how we are carrying out in a more and more rigorous manner. We will need use automation to a greater extent and make use of digital twins where applicable.

We can use all the smart technology described earlier in this paper and will most likely invent new technologies that we cannot think of today.

We will make use of all the off-line test rigs and all the test track facilities available, incorporating varied amounts of real and simulated equipment.

The one thing we must do is work together, as in all the example cases above it was a collaborative team working with a single and agreed purpose that delivered success.

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