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Crossrail integration

This is one of 15 case studies informing the Infrastructure Systems Review.

System: The transition from delivery to operation of a new metropolitan railway.

Systems contribution and value: A client-led programme 'reset' was initiated to overcome integration challenges, employing best-for-programme triage and commercial innovations. It supported programme recovery and strengthened operational readiness.

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Summary

Crossrail, now the Elizabeth line, converted a clear socio-economic objective into a rail programme combining civil engineering, tunnelling, digital systems, rolling stock, operations and supply-chain development.

The objective was to increase London rail capacity by about 10% and bring 1.5 million more people within 45 minutes of central London. The delivery solution joined existing Great Western and Great Eastern corridors through a new high-capacity central tunnel, requiring new trains, new stations, control systems and integration of legacy and modern signalling environments.

Crossrail drew on London tunnelling capability developed through earlier projects, notably the Jubilee Line Extension, and expanded capability for later schemes including the Northern Line Extension and Thames Tideway Tunnel. Civil construction and tunnelling formed a repeatable systems capability, supported by specialist training, deep-tunnel methods, skilled employment and a supply chain able to work across multiple packages.

The railway systems integration challenge was recognised from early stages.

Crossrail invested in systems engineering and off-site integration facilities. However, the programme underestimated the time required to integrate, test, assure and operate a software-intensive railway at full scale. Dynamic testing began in March 2018 while build activity continued. Close-headway testing was not safely assured until June 2019. Opening followed software correction, proving, operational readiness and trial running in May 2022.

Work to assess project benefits, carried out by TfL post-opening, indicates that the demand and regeneration case remains strong and relevant despite delivery overruns.[1] The central lessons concern preparation for and management of integration, assessment of complexity, and governance of integration risk.

Scope

The scope of this case study encompasses the large and complex range of assets and disciplines involved in creating, integrating and commissioning a major railway. The Elizabeth line connects Reading and Heathrow in the west through central London to Shenfield and Abbey Wood in the east and south-east.

The project aimed to provide a step change in rail capacity without creating a wholly segregated railway. The programme reused Network Rail corridors on the Great Western Main Line and Great Eastern Main Line while building a new high-frequency tunnelled section through London. Reuse of existing corridors avoided wider replacement of operating railways and created interfaces between infrastructure, trains, signalling, stations and operations.

The civil works show Crossrail as part of a wider infrastructure capability system. Jubilee Line Extension tunnelling experience supported delivery, while Crossrail added capability through sustained employment, the Tunnelling and Underground Construction Academy, training and supply-chain mobilisation.

The integration phase required different capability. The train fleet needed conventional operation on outer routes and automatic operation in the central section. The delivery organisation therefore needed to move from a civil engineering centre of gravity toward systems integration and software assurance. That transition occurred later than programme conditions required.

Outcomes

Crossrail was planned to open central-section passenger services in December 2018, within a funding envelope of about £14.8 billion. Passenger services opened in May 2022, around three and a half years later than planned, with approximately £4 billion of additional cost. In broad terms this represented a delay of around 35% on the planned delivery period and a cost increase of around 27% against the 2010 baseline.

The delay developed in a programme that had recognised integration complexity. Crossrail had systems engineering, progressive assurance and the Crossrail Integration Facility. The gap lay in the planned duration and sequencing of integration, testing and assurance. Build completion, dynamic testing, software correction and operational readiness overlapped more than planned. Programme reporting continued to carry an on-time, on-budget recovery narrative while testing evidence showed the railway required more integration cycles before passenger service.

The National Audit Office identified related issues in 2019, including compressed schedule, contractual model, loss of downward pressure on costs and absence of a realistic plan. The 2021 NAO progress update found that the revised 2019 schedule and budget had been unachievable because the programme was further from completion and more complicated than Crossrail Ltd and sponsors understood.[2,3]

The construction phase created capability benefits. Tunnelling and underground station works required management of excavations, settlement, existing infrastructure, ground risk, logistics and specialist labour. That capability drew from earlier London programmes and flowed into later projects.

The recovery programme from 2019 demonstrated adaptive systems thinking. Crossrail strengthened client-side systems integration, created the plateau, and brought client, suppliers, operator and maintainer into a joint defect triage and decision process. Commercial amendments supported a one-team approach focused on rail service readiness. This resulted in a significant acceleration of progress. It would clearly have been better if these measures had been in place from the start.

1 Transport for London: Elizabeth line – benefits framework https://tfl.gov.uk/cdn/static/cms/documents/tfl-elizabeth-line-benefits-framework.pdf
2 National Audit Office, Completing Crossrail, 3 May 2019.
3 National Audit Office, Crossrail - a progress update, 9 July 2021.

The evidence base for systems change Crossrail



Route and service facts

41
stations — 10 new • 118km • 19 boroughs

21km
of twin-bore tunnels under central London

70
purpose-built trains • 1,500 passengers per train

24tph
Paddington to Whitechapel

Signalling and train control architecture



TPWS

Supports conventional lineside signals, automatically applying the brakes if a train passes a protected red signal or approaches certain hazards too quickly.



ETCS

Used on the Heathrow route, ETCS displays permitted speed and movement limits in the cab, continuously supervising speed



CBTC

Used in the central section, CBTC maintains safe train separation and supports automatic acceleration, braking and precise station stopping, enabling frequent services.

The recovery programme from 2019 demonstrated adaptive systems thinking. Crossrail strengthened client-side systems integration, created the 'plateau', and brought client, suppliers, operator and maintainer into a joint defect triage and decision process.

Integrating complexity: collaborative 'plateau'



Leadership · Collaboration · Trust
Best practice · Agile · Focused

Technical and programme integration

Defect triage · Software correction · Operational priorities
Shared decisions focused on the whole railway

Membership

Crossrail project team

Signalling
Rolling stock
Testing and commissioning
Assurance

Operators

Transport for London
MTR
Network Rail
Heathrow

Major suppliers

Alstom
Siemens

Systems

The signalling and train control architecture illustrates the systems-economic trade-off. Crossrail had to connect existing railway corridors in the west and east with a new high-frequency central section.

- The Great Western route included legacy train protection arrangements and the Heathrow branch required ETCS (European Train Control System, a digital signalling system).
- The central section required metro-style performance, platform screen door integration and automatic operating functions unavailable from mainline ETCS products at that stage. It instead employed a CBTC (Communication-Based Train Control) system.
- The Great Eastern route continued to use TPWS (the Train Protection and Warning System common across the UK rail network) and was expected to remain outside ETCS for many years.

The resulting architecture required Elizabeth line trains to support three signalling environments: TPWS on the eastern legacy network, ETCS on the western and Heathrow side, and CBTC in the central operating section. These systems had to transition automatically and reliably so drivers could operate an end-to-end railway without interruption. Speed, control and protection information had to appear through an integrated driver-machine interface, with trainborne and trackside electronics enabling the correct system at the correct location.

It was judged that integrating different systems into a common train and operating model offered a preferable route to either the wholesale resignalling of the outer networks, or reduction of the central-section performance specification. The programme understood the system interfaces. The underestimated element was the time needed to test, prove and assure the integrated railway once train, trackside, station, control centre and operating processes came together.

Interventions

From 2019 onwards Crossrail moved from a construction completion model toward a whole-system recovery model. The client called on senior management from major contractors to participate directly in bringing the railway into operation. Bombardier proposed the plateau approach, based on techniques used in aerospace to bring suppliers together around final system proving.

Crossrail asked engineering consultant WSP to mobilise an augmented systems integration team of more than 20 people. WSP helped establish and lead the plateau, with representatives from Crossrail, Siemens, Bombardier, MTR, Network Rail and Rail for London. The purpose was to create a structured environment for defect triage, software correction, operational prioritisation and best-for-programme decisions.

The plateau addressed a common management challenge in complex software systems: the first supplier allocated an issue may not be the owner of the root cause. Faults were investigated, reallocated and resolved through a shared whole-system process. The shared process reduced friction where suppliers might otherwise optimise for completion of

The evidence base for systems change Crossrail

Programme milestones

2015
CONSTRUCTION
Last tunnel boring machines buried at Farringdon

Jun 2017
ROLLING STOCK
Class 345 trains in Great Eastern service

Jun 2017
SYSTEMS
Central Operating Section track complete (except Whitechapel – East)

Oct 2017
SYSTEMS
Supervisory control and data acquisition live at the Route Control Centre

Nov 2017
SYSTEMS
First Class 345 train hauled by locomotive into the Central Operating Section

Dec 2017
SYSTEMS
Westbourne Park connection commissioned

Feb 2018
SYSTEMS
Traction power commissioned in Zones 1 and 2

Mar 2018
DYNAMIC TESTING
Daytime dynamic testing begins

May 2018
SYSTEMS
Traction power commissioned in Zones 3 and 4

2018
SYSTEMS
High-voltage non-traction power commissioning

Jan 2019
DYNAMIC TESTING
Plateau formation

Jun 2019
DYNAMIC TESTING
Multi-train close-headway testing begins

Dec 2020
DYNAMIC TESTING
Bond Street — Station Completion 1

Mar 2021
TRIAL RUNNING
Start of trial running, ramping up from 4 to 12 trains per hour

Nov 2021
TRIAL OPERATIONS
12 trains per hour, maximum 20 people per train

Jan 2022
TRIAL OPERATIONS
Volunteer trials involving 2,000 people

May 2022
PASSENGER SERVICE
Passenger service, central section

Nov 2022
PASSENGER SERVICE
Through running

May 2023
PASSENGER SERVICE
Full service

individual scope rather than safe and economic operation of the integrated railway.

The integrated team structure created a route for decisions previously slowed by contract boundaries, supplier interfaces and separate assurance processes. Client, supplier, operator and maintainer representatives could review defects against railway-level consequences, agree priorities, align software release and test plans and manage operating restrictions.

The plateau approach initially addressed the railway systems integration issues, but the same technique was applied for Crossrail's stations, to address integration of the complex digital systems supporting the station infrastructure and station control rooms.

Economic assessment

The economic assessment should distinguish between the rationality of the original architecture and the cost of proving the architecture late in delivery.

Crossrail accepted integration complexity because the business case depended on reuse of east and west rail corridors, a high-capacity central tunnel and a through-running service. A fully standardised solution would probably have required wholesale resignalling of the outer networks or a lower-performance central section. Both choices would have changed the economics and potentially reduced the benefits case.

The adopted architecture avoided large interventions across the wider rail network and transferred complexity into trainborne systems, signalling transitions, software interfaces, control centre integration, testing and proving.

Risks were recognised, but the programme underestimated the resources and time required for integration. The magnitude of the risk may have been revealed if an attempt had been made to quantify and contrast the complexity of the two approaches, rather than the prima facie costs.

By 2018, dynamic testing had begun while construction and fit-out activity continued. Remaining work required repeated cycles of software updates, test evidence, assurance review, operational rehearsal and defect closure.

The economic impact was material. Against the 2010 funding envelope of about £14.8 billion, the programme required around £4 billion of additional expenditure and opened about 41 months late.

Cost growth and schedule delay do not automatically demonstrate poor value for money. TfL benefits reporting indicates strong early demand, housing and employment signals, supporting the view that the completed railway continues to deliver benefits despite additional expenditure from delay.[4]

The NAO findings support a further policy lesson. Systems integration uncertainty should be treated as a distinct programme risk. Future business cases should include ring-fenced cost and schedule allowances for integration, testing, assurance and operational readiness. Consumption of these allowances should be monitored separately from construction contingency and reported through programme governance.

Separate visibility of integration contingency consumption would have given earlier warning of variance between planned and actual integration progress. Earlier warning would have supported earlier resource mobilisation, more realistic forecasting and timely sponsor decisions. The point is governance of uncertainty as much as size of contingency.

The practical Green Book implication is that ring-fenced systems integration allowance should be a managed control. Programme boards should see planned burn-down of integration contingency against evidence from defect closure, trial operations, software maturity, safety assurance and operator readiness. Variance against that burn-down would identify cost and programme pressure earlier than aggregate reporting. That visibility would support earlier choices on scope, resources, opening strategy and sponsor funding, while protecting value for money by preventing construction progress from masking operational readiness risk.

The assessment should also recognise capability benefits. Crossrail expenditure sustained tunnelling expertise, training capacity, specialist labour and supply-chain capability used by later schemes. Conventional appraisal can miss this portfolio value because benefits accrue across programmes rather than solely to the project being assessed. Meanwhile, the one-team approach reduced transaction costs within the recovery programme by moving defect ownership, software release planning and operational workarounds into joint resolution.

Systemic assessment

Crossrail demonstrates two forms of systems capability. The civil engineering programme drew on accumulated London tunnelling knowledge and developed it further. Deep excavation, logistics, ground movement, adjacent assets, utilities interfaces and work under a dense city were managed through a tunnelling ecosystem with training, apprenticeships and labour mobility across packages.

The railway systems phase required a different operating model. Crossrail had invested in the Crossrail Integration Facility (CIF) in 2015, creating an off-site testing and simulation environment that acted as a virtual railway. The CIF allowed engineers to integrate software and data from multiple suppliers before physical implementation and later supported operator training, control room familiarisation and degraded-mode rehearsal.

Conventional appraisal can miss portfolio value because benefits accrue across programmes.

4 Elizabeth Line post-opening evaluation, TfL https://content.tfl.gov.uk/elizabeth-line-post-opening-evaluation-full-report.pdf

The evidence base for systems change Crossrail

Crossrail should have been seen as a system integration programme, with civil engineering as a means to an end, not an end in itself.

Programme challenge emerged because the organisation remained weighted toward construction delivery as the dominant risk shifted toward integration, operational readiness and assurance. The on-time, on-budget mantra supported recovery effort and milestone discipline, but also reduced visibility of the scale of remaining integration work until late in the programme. The later reset recognised the changed nature of the task.

The Crossrail CEO for the final phase of the project has argued[5] that Crossrail should have been seen as a "system integration programme, with civil engineering as a means to an end, not an end in itself". If supported by sufficient bandwidth to consider systems integration issues in parallel with the real and pressing civil engineering issues, this could have resulted in both a more accurate assessment of and mitigation of the integration issues to come. Such a shift of mindset may be regarded as applying systems thinking to the programme as well as to the delivered system.

The plateau, enhanced systems integration function, CIF, operator involvement and revised commercial arrangements created a new delivery system. The programme moved from managing assets and contracts toward managing the performance of an integrated operational railway. The one-team model enabled defects to be triaged by railway impact, allocated across supplier boundaries and resolved through shared operational priorities.

The chronology of London infrastructure delivery also matters. The Jubilee Line Extension created experience in deep mined and bored tunnelling, station construction, settlement control and delivery beside operational assets. Crossrail converted this experience into a larger industrial programme, including the Tunnelling and Underground Construction Academy at Ilford, apprenticeships, common methods and repeatable safety practices. Later programmes, including the Northern Line Extension and Thames Tideway Tunnel, benefited from the workforce, methods and institutional memory created.

The project therefore demonstrates a systems principle with direct economic consequences: building components, proving an operational railway and sustaining an industrial capability are different system tasks. Each requires governance, skills, resources, risk allowances and incentives.

Recommendations

Crossrail provides a balanced lesson for future programmes. The tunnelling and civil works phase shows the value of sustained infrastructure capability across a portfolio of projects. TfL benefits reporting also indicates that post-opening outcomes can remain strong despite delivery overruns. The railway systems phase shows the need to plan the transition from construction to integration before late-stage testing exposes the duration of system proving.

Major programmes should include an explicit assessment of the complexity of the options being considered at option selection. The costs associated with this complexity including testing, assurance, transition, operational readiness and residual restrictions should be estimated, looking at other sectors for comparable experience. These costs should be taken into account when selecting options.

Where integration is selected over standardisation, the business case should state why this is economically preferable to a simpler architecture, what risks transfer into later stages, and how they will be funded and governed.

Business cases for programmes with significant systems integration requirements should include ring-fenced cost and schedule allowances for integration, testing, assurance and operational readiness. These allowances should be reported separately from construction contingency and protected for that specific purpose.

Appraisal should include what-if scenarios for slower defect closure, additional test cycles, delayed software maturity, extended operational readiness and delayed assurance. Scenario outputs should inform risk allowance, governance triggers and sponsor reporting.

The process of integrating the system should run throughout the lifecycle of the project and all parties to the project should understand that their work must contribute to successful integration. Client governance should include a planned transition from civil engineering delivery methods to those appropriate for systems integration and operational readiness, with skills, reporting, incentives and decision rights adjusted before dynamic testing becomes the controlling activity.

The client must retain prime systems integrator accountability because only the client can take some of the decisions that will be required when getting the parts of the system to work together. To do this, the client needs to hold the risk contingency and have a properly resourced systems integration team.

Contractors should have whole-system incentives during final integration and bug fixing, so defects are triaged on a best-for-programme basis. Minimum viable product thinking should distinguish functionality required for safe benefit realisation from functionality that can follow opening without undermining reliability or safety.

5 Wild, M. (2023). "Project leadership: Getting Crossrail back on track." Crossrail Project 2019-2023: Completing the Elizabeth Line.

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