C4R

Capacity for Rail

Towards an affordable, resilient, innovative and high-capacity European Railway System for 2030/2050

Illustration of the application of capability trade-offs using data from selected routes

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Deliverable 31.2

Lead contractor for this deliverable:

- TRL Ltd

Project coordinator

- International Union of Railways, UIC

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Abbreviations and acronyms

Abbreviation / Acronym	Description
C4R	Capacity4Rail
IM	Infrastructure manager
ETCS	European Traffic Control System
CTA tool	Capability Trade-offs Tool
HLG	High Level Goal
TRA	Taiwan Railways Administration
TpH	Trains per Hour
GQL	Graded Qualitative list
ECML	East Coast Main Line
GN/GE	Great Northern and Great Eastern Joint Railway
OPEX	Operating Expenses
CAPEX	Capital Expenditures

Executive Summary

The high-level objective of Capacity4Rail (C4R) is to support the achievement of a high-speed, high-capacity European Railway network, with increased resilience, adaptability and automation in an affordable manner, for passengers and freight. These goals are to be achieved in the context of constrained budgets for public expenditure, rapid shifts in available new technology and increasing expectations of customers.

To accommodate the growing demand, IM's often implement upgrades to bottleneck sections to improve the capacity of railway lines. It is common practice to start with existing solutions / technologies and incrementally add improvements to the network. . However, as the railway is a system and if all parts of the system are not considered, adopted solutions can turn out to be sub-optimal, high-cost solutions that do not deliver the expected increase in capacity.

A whole system approach is critical to ensuring that achieved outcomes reflect planned objectives. This is particularly the case when the capabilities of parts of the railways are improved and/ upgraded in order to deliver an increase in the available, usable and delivered capacities. This deliverable (D3.1.2) describes the Capability Trade-Offs Analysis (CTA) Tool is based around a framework that can support decision making by enabling assessments at a whole-system level, of the impact of infrastructure, operational and/or technological changes to parts of the railway system. The fundamental premise of the tool is that the inherent trade-offs between railway capabilities need to be considered in order to ensure a good understanding of the potential outcomes when changes are made to part of the railway system and thereby ensure that value for money and the planned-for objectives are achieved from the investments made.

This report describes the set-up, structure and functionalities of the on-line, web-based CTA tool. The use and application of the tool is demonstrated through a case-study consisting of the assessment of three investment options to increase capacity on the East Coast Main Line in the United Kingdom between Doncaster and Peterborough. The case study provides the results in terms of the impacts on C4R's high level goals of Capacity, Affordability, Adaptability, Resilience and Automation when considering (i) upgraded rolling stock, (ii) upgraded rolling stock and removal of freight from the line and (iii) upgraded rolling stock, removal of freight and implementation of ETCS level 2 with optimised block lengths.

The work in this deliverable shows that employing a whole systems approach ensures that the decision maker takes into account the system interactions and impacts within the railway system when considering investment options that introduce changes to parts of that system. Failure to do so can result in projected outcomes not being realised. The tool can be used by infrastructure managers and railway operators to maximise the potential benefits from investment options and increase confidence that the decisions made will deliver the planned outcome improvements.

1. Background & Objectives

The high-level objective of Capacity4Rail (C4R) is to support the achievement of a high-speed, high-capacity European Railway network for passengers with increased resilience, adaptability and automation in an affordable manner

These goals are to be achieved in the context of constrained budgets for public expenditure, rapid shifts in available new technology and increasing expectations of customers (influenced in part by innovations in other transport modes, especially the road network). The railway has added complexities due to the nature of the railway system itself. Much of the varied infrastructure across Europe is ageing and this combined with the relatively long life cycles of railway vehicles compared to road vehicles reduces the ability to implement new innovations. For example, the lifespan of rail freight wagons can be 40 years or more, so that renewal rates of the fleet tend to be slow, at an average of 2-3 % per year[1]whereas the average road Heavy Goods Vehicle (HGV) has a much shorter lifespan of around 16 years (European Commission, 2006). For rail freight wagons life-spans about 2.5 times longer than road HGVs, slows down the relative uptake of new technologies (e.g. Automation) that can deliver transformational improvements.

Whilst acknowledging these challenges, Rail Infrastructure Managers (IMs) and the wider railway industry must innovate to improve the capabilities of the European railway network to deliver the required changes intelligently and maximise returns from constrained budgetary investments.

1.1 BACKGROUND

European railway has experienced significant growth in traffic, particularly passenger traffic over the last decade. Demand is variable across the various networks in Europe but there are parts of the network with bottlenecks that are inhibiting further growth, mainly due to the resulting increase in crowding and reduction in performance. This also has a significant impact on the allocation of train paths for freight which has a consequent effect on the EU's targets to deliver significant modal shift of freight from road tp rail.

To accommodate the growing demand, IM's often implement upgrades to bottleneck sections to improve the capacity of railway lines. It is common practice to start with existing solutions / technologies and incrementally add improvements to the network. In general, schemes to improve capacity tend to include infrastructure options such as alterations and additions to track layouts, grade separation of junctions, extensions to platforms, new signalling etc. However, as the railway is a system and if all parts of the system are not considered, adopted solutions can turn out to be sub-optimal, high-cost solutions that do not deliver the expected increase in capacity. Quite often the default solution to a capacity problem appears to be the implementation of more high-tech signalling, which can add complexity to the system without necessarily solving the underlying infrastructure, rolling stock or operational issues that are constraining the exploitation of the usable capacity.

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[1] https://ec.europa.eu/transport/modes/rail/environment_en

1.2 A Whole Systems Approach to Evaluating

As described in an earlier Deliverable, D31.1, (Capacity4Rail, 2015), a whole-systems approach can provide a structured and systematic way to identify appropriate and more efficient solutions to improve capacity. The fundamental premise of systems engineering is to:

    i.   Set the anticipated future operating scenarios;
    ii.   Establish capability gaps and functional requirements; and
    iii. Select technologies (and potential specifications).

This deliverable describes the Capability Trade-Offs Tool based around a framework that can support decision making by enabling assessments at a whole-system level, of the impact of an infrastructure/operational and/or technological changes to parts of the railway system.

A holistic view of the railway system helps the planner to take into account the systemic nature of the railway and especially identify the alternatives that provide the best trade-offs between the different railway capabilities.

1.3 Railway System Capabilities

The railway system can be considered to consist of three main components:

- Railway infrastructure;
- Rolling stock; and
- Operational attributes

Each of these main components is composed of a number of individual elements (e.g. Track, Train types etc) of the system and these can be made of additional sub-categories (e.g. radius of curvature of track, signalling type freight or passenger trains, braking characteristic etc). Each of the elements or capabilities has its own attributes that drive the behaviour of the component. Detailed lists of the capabilities of the system components that are considered to have an impact on capacity and have been included in the CTA tool are provided in Figure 6, Figure 7 and Figure 8.

Each of the elements has an impact on the capacity functions that influence the overall capacity that the railway system delivers. The capacity function affected and the level of impact is different for the different elements. For example, platform lengths could impact on usage capacity, minimum headway time, dwell time, waiting time and train capacity. Changing capabilities from their existing state by different levels affects capacity functions to different levels (e.g. altering minimum headway time has a larger effect on total capacity than altering buffer time). Therefore when considering improvement to railway capacity through changes to railway system components or their elements, it is essential to consider the impact on capacity functions. In addition, the systemic impacts on the capabilities of other elements within the system should also be taken into account. For example, the number of platforms at a station plays an important part in the capacity of a railway line as it affects the headway, dwell and waiting times. However, adding more platforms at a station will increase the actual capacity only if the existing platforms have reached or are approaching their maximum utilisation, or the train lengths also can be increased to take advantage of the increased platform lengths.

1.4 Objectives

This deliverable, D3.1.2, of the Capacity4Rail project describes the results from Task 3.1.2 "Development of railway capability matrix", Task 3.1.3 "Development and use of capability trade-offs framework" and Task 3.1.4 "Integration and evaluation of concepts of future operations." This deliverable reports on:

- The railway system components and elements (and sub-elements) that underpin trade-offs and support a whole-system approach to evaluating options for capacity improvement;
- Identified characteristics of the railway system, i.e. capabilities, that impact on railway capacity;
- Interaction and interdependencies between the capabilities
- Impacts of capacity improvement options on the other high-level requirements of the C4R project – affordability, adaptability, resilience and automation;
- Description of the CTA tool and user guide
- A case study illustrating its application using data from a selected route (The East Coast Mainline, UK);

2. Whole System Approach

A whole system approach is critical to ensuring that achieved outcomes reflect planned objectives. This is particularly the case when the capabilities of parts of the railways are improved and/ upgraded in order to deliver an increase in the available, usable and delivered capacities.

2.1 MEASURING CAPACITY

Railway capacity is an increasingly prominent issue not only for government, infrastructure managers and operators but also for the users, passengers and freight. A number of definitions and explanations of railway capacity have been published and these have tended, in general, to concentrate on operational or train control systems. Deliverable 3.1.1 reviewed different capacity measures and reported the following conclusions (Capacity4Rail, 2015):

i. Railway capacity is generally defined as the ability of a railway either to accommodate trains or to transport passengers and goods;

ii. However, there is no absolute definition of capacity – the selection of an appropriate metric depends on the objectives of the service;

iii. There are many different metrics available for the measurement of capacity once an objective has been agreed, although not all of these directly address the definition given in (i) and some are too complex to be applied in day-to-day railway operations; and

iv. Although historically the railway has been heavily compartmentalised, there is increasing recognition of the need to examine the railway with whole systems approaches.

A policy-driven approach with clear objectives (i.e. defining what is wanted and what is being offered, how and by whom) is fundamental to defining "capacity" that fits in with the context of the measurement. For example urban metro systems can deliver robust and high frequency stopping services; the trade-off is generally longer end to end journey times. Maintaining the homogeneity of the services but reducing the number of stopping stations can reduce end to end journey times; the trade-off in this case would be the number of passengers carried. Providing mixed services with non-stop and stopping services, the non-stopping services may achieve higher average speeds resulting in lower end to end journey times but the increase in traffic heterogeneity will reduce the frequency of total services on the line (due to the speed differentials of the different services) and also reduce the robustness of the line. In looking at alternative options, it is important to recognise what the goal is; number of trains, number of passengers carried, end-to end journey time, robustness of the services or combinations of these.

2.2 A WHOLE SYSTEMS APPROACH TO MEASURING CAPACITY

A whole systems approach, built on a good understanding of the components or attributes which affect the capacity of a specific line (section), to the appraisal of investment options is fundamental to ensuring that the expected capacity increases can be achieved.

The two UK examples described in the following sub-sections show the need for and consequences of not using a whole systems approach when deciding on the implementation of innovations to deliver greater capacity.

2.2.1 HEATHROW AIRTRACK

A feasibility study to identify possible new rail connections to Heathrow Airport was carried out in 1984 and planning formally began in 2003. A route submitted by BAA (British Airports Authority, now Heathrow Airport Holdings), that became known as Airtrack, proposed to connect the then planned Heathrow Terminal 5 with direct rail services to Reading, Guildford and London Waterloo [2] through upgrades of existing lines.

However in April 2011, nearly 8 years after work began on the project and investment of significant resources (time and money), the scheme was dropped by BAA due to the impact of the increased train services at the 15 'level crossings' on the route. The higher frequency of train services required these level crossings to be closed to road traffic in peak traffic flow times as follows:

-   6 crossings closed ~60% of the time.
-   4 crossings closed ~50% of the time.
-   5 crossings closed ~30% of the time.

The consequent increase in road congestion was deemed unacceptable. Whilst there was enough "capacity" on the railway network to accommodate the extra number of trains, the scheme had not addressed the wider systems impact of unacceptable traffic delays on the roads due to longer closures of level crossings. BAA investigated the possibility of constructing road bridges or tunnels at these locations but concluded that such construction was "not feasible or justifiable"[3]. A whole systems approach that had examined impacts at the level crossings would have identified this issue sooner and thereby reduced spend on planning or looked for alternative solutions sooner.

2.2.2 REOPENING OF THE GN/GE LINE TO FREIGHT

In 2010, Network Rail's Route Utilisation Strategy (RUS) highlighted capacity constraints on the East Coast Main Line between Doncaster and Peterborough (Network Rail, 2010). Increased passenger services were required due to growth in demand but the high traffic heterogeneity on the route (consisting of intercity, regional and freight services) restricted the number of trains per hour.

Reducing the traffic homogeneity by significantly reducing the number of freight services over this part of the ECML was one of the possible solutions. However the trade-off of reduced freight services was not acceptable. Network Rail developed the GN/GE Joint Line Scheme – this consisted of upgrading GN/GE (Great Northern/Great Eastern) Joint line to enable freight to be redirected away from the ECML between Doncaster and Peterborough. The scheme provided a £280 million package of upgrades allowing the GN/GE line to be gauge cleared for intermodal traffic up to Route Availability 8 (RSSB, 2015) at a ruling linespeed of 75mph and other freight trains

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[2] http://democraticservices.hounslow.gov.uk/documents/s42481/AIRTRACK.pdf
[3] http://www.bbc.co.uk/news/uk-england-london-13042740

including those up to Route Availability 12 (RSSB, 2015) at a ruling linespeed of 60mph[4]. This has enabled the GN/GE Joint Line to become the primary route for daytime freight traffic and allow parallel growth in passenger services on the core ECML route.

A systems approach to finding solutions to the capacity needs between Doncaster and Peterborough resulted in the identification of the GN/GE joint line scheme was identified. Turning the GN/GE line into a de-facto ECML avoidance line removed 1 freight path an hour and allowed 2 additional passenger train paths (Network Rail, 2014). This increased the resilience of both the GN/GE (by upgrades to infrastructure e.g. new signalling systems) and the ECML by reduced traffic heterogeneity[5].

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[4] https://www.railengineer.uk/2014/06/12/rebirth-stage-renewing/
[5] http://www.railwayoperators.co.uk/wp-content/uploads/2014/04/GNGE-Network-Change.pdf

3. Capability Trade-Offs Analysis Tool

This chapter describes the functionalities of the CTA tool. The railway system is decomposed into its component functions (Infrastructure, Rolling stock, Scheduling). Each function has elements with its own capabilities that influence capacity outcomes. The capabilities of the elements for the current railway and the changed capabilities following the application of an innovation or innovations or investment are used to evaluate the impact on the five HLGs (Capacity, Affordability, Adaptability, Resilience and Automation). The tool takes into account the interactions between capabilities which may affect potential outcomes. For example if the permitted linespeed of a track is 120 kph, improving speed capabilities of the rolling stock beyond 120 kph will not reduce journey times.

3.1 OVERVIEW

The CTA Tool is a web-based application (https://www.captain.oltisgroup.cz) that can evaluate the impact on outcomes of different combinations of railway capabilities. It can therefore be used to assess outcomes of user-selected sections of railway, in its current state and with the addition of one or more innovations/investment options that changes some of the capabilities. While it would be possible to use the CTA tool to compare different sections of railway, this is not its intended use. Rather, it is designed to assess and compare the outcomes for sections of railway in terms of the C4R goals. Figure 3 gives an overview of the component parts of the CTA tool.
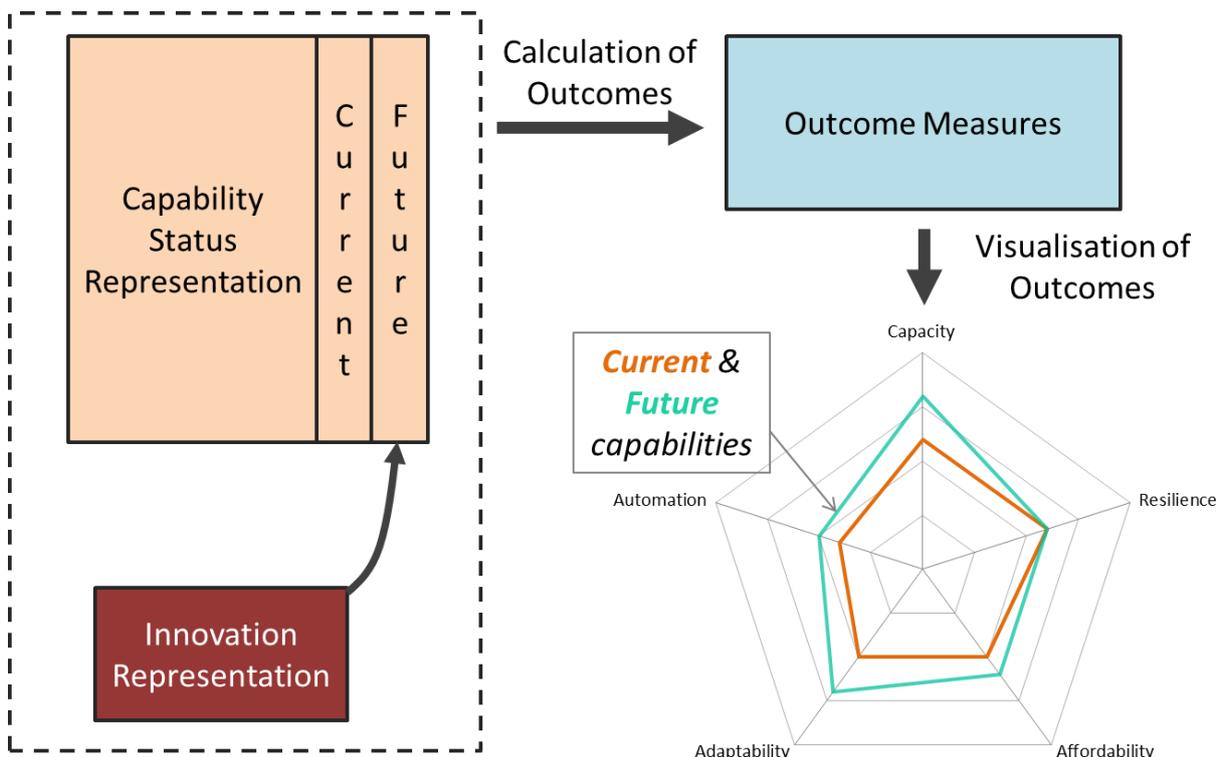

FIGURE 1 DIAGRAM OF CAPABILITIES TRADE-OFFS TOOL PROCESS

The user is guided to select the status of each capability associated with the section of railway being looked at and arriving at a complete description of that selected section pre- and post-application of the planned improvement. The outcome is then reported in terms of C4R's high level goals of affordability, adaptability, and resilience, automation and capacity.

The outcome measurements are made via a combination of a series of mappings between capability interactions and their outcomes. The user is guided to directly enter information or select appropriate statements/options and the mapping is performed automatically.

The tool contains several options for the visualisation and reporting of the outcomes. A headline view in terms of the C4R high level goals summarises the results, while the components of the scores can be visualised at a more detailed level for a deeper analysis.

Undoubtedly, trade-offs will be required in terms of the C4R high level goals (as well as capabilities). The overall outcome aims for different sections of railway may vary; for example, the focus of one may be 'high capacity for passenger throughput' while for another it could be 'increased network resilience'. The visualisation part of the tool allows the representation of the 'wished for' targets in terms of the C4R high level goals alongside the results of the calculations made for the section under consideration. Thus, the visualisation module of the CTA tool provides an overview of the extent to which an innovation /investment contributes to the achievement of a defined target. A user guide to help the user navigate through the tool is provided in Appendix E.

3.2 STRUCTURE AND COMPONENTS

The CTA tool is made up of the following basic components:

- Analysis Description;
- Current Capability Description (for Current Railway);
- Innovation Representation & Future Capabilities Description (for the elements associated with the innovation);
- Calculation of Capabilities Outcomes (for post-innovation railway, e.g. due to system interactions);
- Visualisation of Outcomes.

The section of railway under consideration is defined in the Analysis Description component. The corresponding capabilities of the relevant elements under consideration are contained in the Function Description component. It has two parts to it – the current status and the future status. The Innovation Representation component is used to define which elements are affected by a particular innovation, and thus, which parameters change between the current and future condition. The Capabilities Outcomes component provides a measure in terms of the C4R high level goals for the capability statuses (current and future). The mapping between the Innovation Representation and the Capabilities Outcome forms the main functionality of the CTA tool; a significant proportion of this functionality takes place in the background. Finally, the Results visualisation and reporting component allows the outcomes to be viewed. The following sections in this chapter detail the different components of the CTA tool.

3.3 LOGGING IN TO THE TOOL AND ANALYSIS DESCRIPTION

After logging in to the web-based tool (https://www.captain.oltisgroup.cz), the user is guided through a number of pages in the tool to enter information about the railway section being analysed.

3.3.1 LOGIN

When the user accesses the tool, a login screen with be presented (see Figure 2). Only authorised users with a valid login can gain access to the tool.
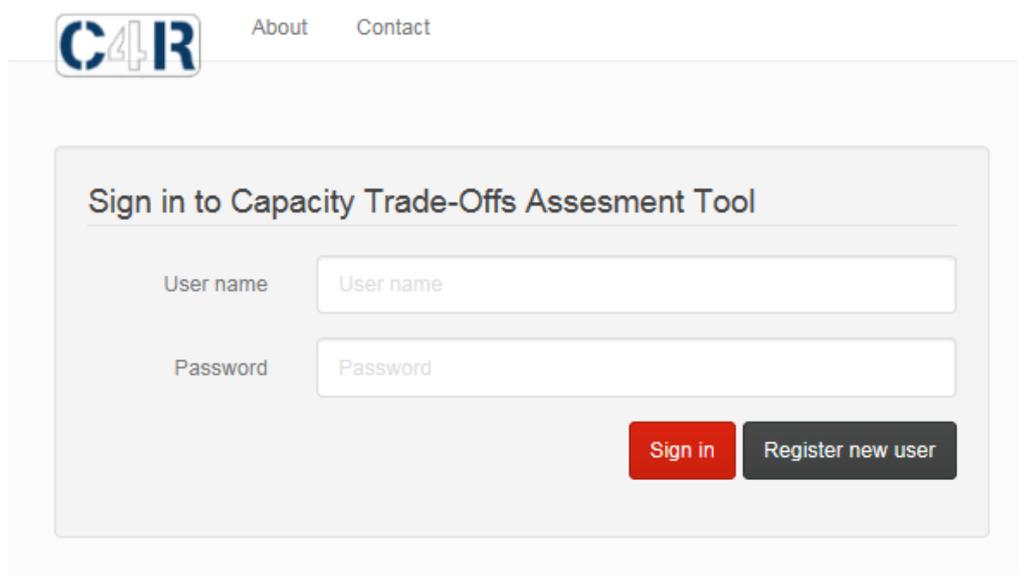

FIGURE 2 LOGIN SCREEN OF THE CAPABILITIES TRADE-OFFS TOOL

To create a new account, the user selects the "Register new user" and is taken to a new page (see Figure 3) where the following details are required; a unique user name, user's name, users organisation and a password.
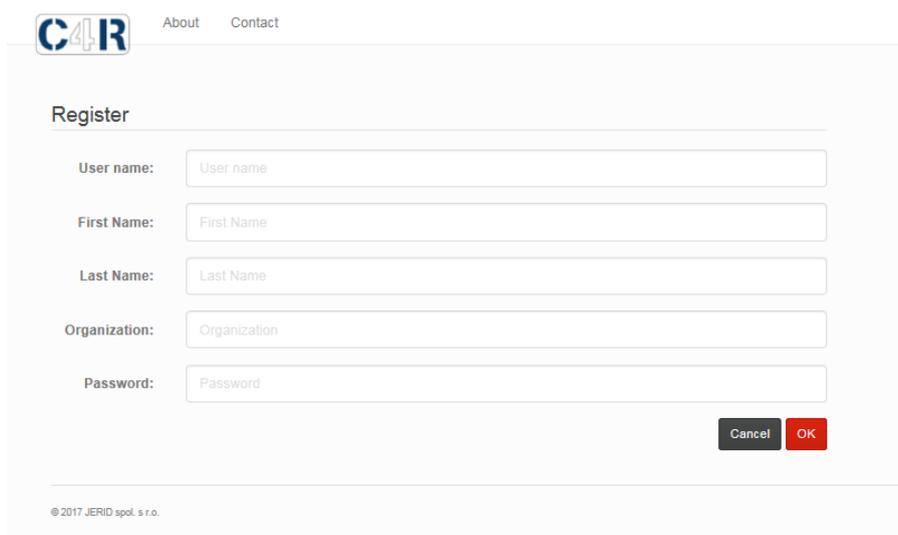
FIGURE 3 REGISTRATION PAGE

3.3.2 HOME PAGE

A successful login takes the user to the main Home page (see Figure 4). On this page the tool t welcomes the user by the username. The user is presented with a list of previous analyses (if any exist) that can either be edited or copied. Copying forces the user to create a new name for the copied analysis which must be unique. To start a new analysis, the user clicks "Create New button" button.
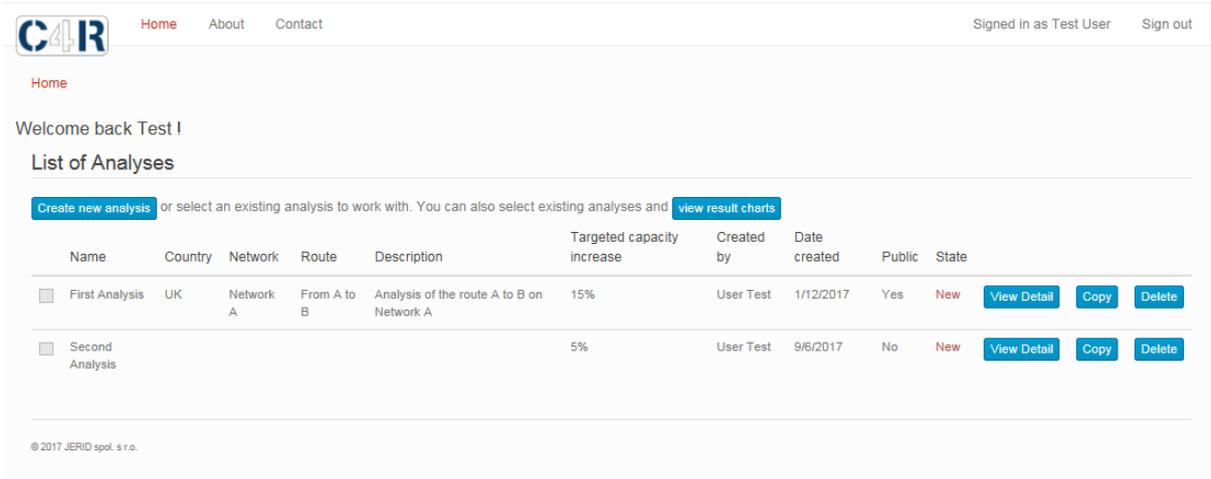
FIGURE 4 HOME PAGE OF THE CAPABILITIES TRADE-OFFS TOOL

3.3.3 ANALYSIS SET-UP

The analysis setup page (see Figure 5) is the formal record of the part of the railway route being modelled. If editing an existing analysis or creating a new analysis the user is prompted to enter some data. When a user creates a new analysis (or edits an existing analysis) they are required to provide: a unique analysis name, country, network, route, description of the analysis and targeted capacity increase.
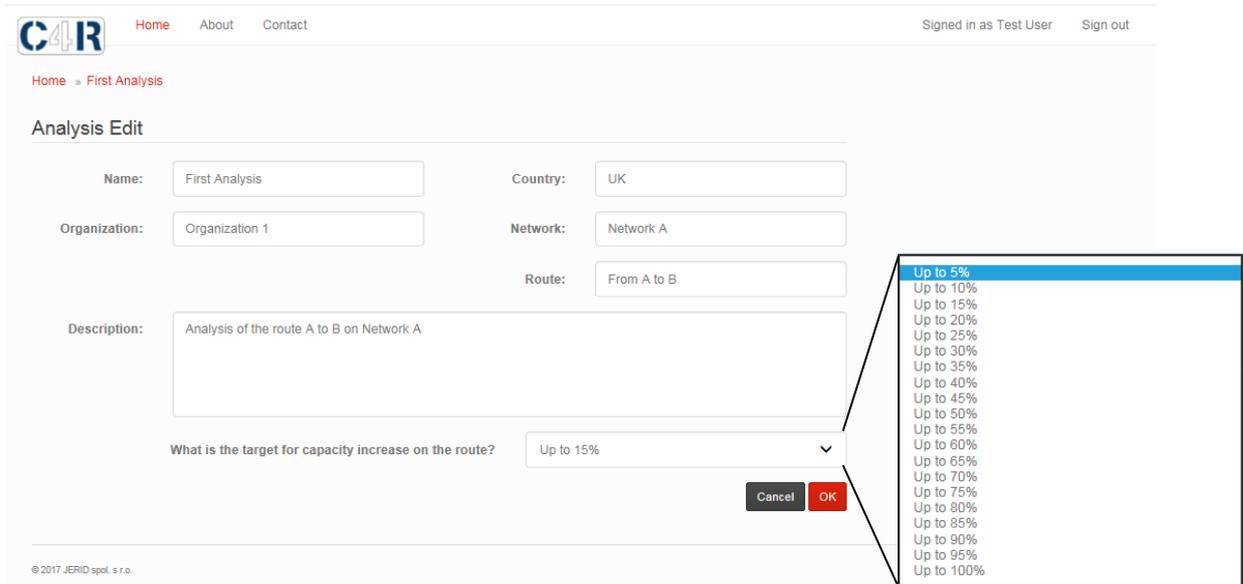
FIGURE 5 ANALYSIS SET-UP PAGE OF THE CAPABILITY TRADE-OFFS TOOL

The "What is the target for capacity increase on the route?" data input option is a drop down list with values from 5% to 100% with increments of 5%. The option chosen is used in the calculation step to visualise the capacity outcome across the analysis route, this is discuss further in 0.

Once the data has been entered, the user is taken to the analysis page by click the "ok" button. This is the home page for an analysis where the user defines the railway being explored (the capabilities status representation).

3.4 CURRENT RAILWAY CAPABILITIES DESCRIPTION

The current capabilities description component is set up as a framework for the formal representation of the status of an analysis route. The user creates sections and within these the user enters information that describes the capabilities. The following sub-sections describe the capabilities representation for capacity outcomes. Capabilities representations for the other C4R goals are discussed in 0.

3.4.1 CAPACITY CAPABILITIES REPRESENTATION

To measure outcomes for capacity, the user is required to define the capabilities listed in Figure 6, Figure 7 and Figure 8.

The user enters data for these capabilities by either directly entering data into a text box or by choosing a pre-defined option from a drop down box. The user defines these capabilities on a per track basis for all sections within the analysis (discussed further below).

Infrastructure		Section Length (km)		
	Track	Direction of track		
		Track Loading Gauge		
		Permitted axle Load (tonne)		
		Rail Support		
		Line Speed (km/h)		
		Minimum Curve Radius (m)		
	Start node	Station or Junction		
		Node Type		
		Platform length, if station (m)		
		Average gradient of the track in the 2 blocks after the start node (1 in x) x =		
		Block Length	Length of start node block section (m)	
			Length of 1st block section after start node (m)	
			Length of 2nd block section after start node (m)	
		Average speed limit over the 2 block sections after the start node (km/h)		
	End node	Station or Junction		
		Node Type		
		Platform length, if station (m)		
		Average gradient of the track in the 2 blocks before the end node (1 in x) x =		
		Block Length	Length of end node block section (m)	
			Length of block section before end node (m)	
			Length of block section penultimate before end node (m)	

			Average speed limit over the 2 block sections before the end node (km/h)	
	Signalling		Signalling Type	
			Total Operating time for changing signals and switching turnout (s)	
		if aspect signalling	Speed limit for signal state before stop (km/h)	
			Speed limit for signal state after clear signal (4-aspect only) (km/h)	
	Railway Electrification Infrastructure		Type	
			Peak Demand on Supply (%)	
	Structure	Bridges	Number present on the line	
			Permanent Speed Restriction (km/h)	
			Permitted axle Load (tonne)	
		Earthworks	Number present on the section	
			Permanent Speed Restriction (km/h)	
			Track Loading Gauge	
			Permitted axle Load (tonne)	
		Tunnels	Number present on the line	
			Permanent Speed Restriction (km/h)	
			Track Loading Gauge	
		Level Crossings	Number present on the line	
			Restricts increased service levels	
			Permanent Speed Restriction (km/h)	

FIGURE 6 INFRASTRUCTURE RAILWAY FUNCTIONS

Scheduling	Operational Hours (hrs)			
	Train categories	Passenger 1 trains	Number of Trains per hour	
			At Start node	Scheduled stop
				Travels on the same track as Passenger 2 trains
				Travels on the same track as freight trains
				Distance between the head of train to starting signal (m)
				Distance between the tail of train to turnout (m)
			At End node	Scheduled stop
				Travels on the same track as Passenger 2 trains
				Travels on the same track as freight trains
				Distance between the head of train to starting signal (m)

				Distance between the tail of train to turnout (m)
		Passenger 2 trains	Number of Trains per hour	
			At Start node	Scheduled stop
				Travels on the same track as Passenger 1 trains
				Travels on the same track as freight trains
				Distance between the head of train to starting signal (m)
				Distance between the tail of train to turnout (m)
			At End node	Scheduled stop
				Travels on the same track as Passenger 1 trains
				Travels on the same track as freight trains
				Distance between the head of train to starting signal (m)
				Distance between the tail of train to turnout (m)
		Freight trains	Number of Trains per hour	
			At Start node	Scheduled stop
				Travels on the same track as Passenger 1 trains
				Travels on the same track as Passenger 2 trains
				Distance between the head of train to starting signal (m)
				Distance between the tail of train to turnout (m)
			At End node	Scheduled stop
				Uses the same track as Passenger 1 trains
				Uses the same track as Passenger 2 trains
				Distance between the head of train to starting signal (m)
				Distance between the tail of train to turnout (m)

FIGURE 7 SCHEDULING RAILWAY FUNCTIONS

	Passenger 1 trains	Vehicle Type	Power	

Train Category Characteristics		Physical Characteristics	Train Length (m)
			Train weight (metric tons)
			Loading Gauge
			Axle Load (tonne)
		Performance	Acceleration (m/s2)
			Acceleration Efficiency
			Braking (m/s2)
			Braking safety factor
			Braking Reaction time for driver and system (s)
			Maximum Speed (km/h)
			Cruise Speed (%) of maximum speed
		Passenger Boarding	Dwell Time (s)
			Selective Door Operations
		Passenger capacity	Maximum Capacity (number of people per train)
			Capacity Usage (per train as a %)
	Passenger 2 trains	Vehicle Type	Power
		Physical Characteristics	Train Length (m)
			Train weight (metric tons)
			Loading Gauge
			Axle Load (tonne)
		Performance	Acceleration (m/s2)
			Acceleration Efficiency
			Braking (m/s2)
			Braking safety factor
			Braking Reaction time for driver and system (s)
			Maximum Speed (km/h)
			Cruise Speed (%) of maximum speed
		Passenger Boarding	Dwell Time (s)
			Selective Door Operations
		Passenger capacity	Maximum Capacity (number of people per train)
			Capacity Usage (per train as a %)
	Freight trains	Vehicle Type	Power
		Physical Characteristics	Train Length (m)
			Train weight (metric tons)
			Loading Gauge
			Axle Load (tonne)
		Performance	Acceleration (m/s2)
			Acceleration Efficiency
			Braking (m/s2)

			Braking safety factor
			Braking Reaction time for driver and system (s)
			Maximum Speed (km/h)
			Cruise Speed (%) of maximum speed
		Scheduled stopping time	Dwell Time (s)
		Carrying capacity	Maximum Total Load

FIGURE 8 ROLLING STOCK RAILWAY FUNCTIONS

3.4.1.1 SECTIONS

Sections are defined by two consecutive nodes connected by a link. Nodes include stations, junctions or significant line events (e.g. change in the number of tracks) and links are the line segments between two consecutive nodes. A section can consist of one or multiple tracks. In the latter case, the user will have to describe or enter capabilities data for each track in the section.

FIGURE 9 SECTIONS PAGE

All sections for an analysis are listed on the 'Sections' page (Figure 9); a new section is created by clicking "Add new section". Sections can be copied or deleted. Each section must have a unique name (e.g. Section 1 and Section 2).

3.4.1.2 TRACKS

The user selects "View Detail" to be taken to the Track Page (Figure 10). The user has to enter data for each track and can navigate to additional track by selecting the "Add new Track" option. Tracks data can be copied (e.g. if the capabilities are identical, the copy facility removes need to enter same data repeatedly) or deleted. Each track must have a unique name (e.g. "Track 1" and "Track 2").
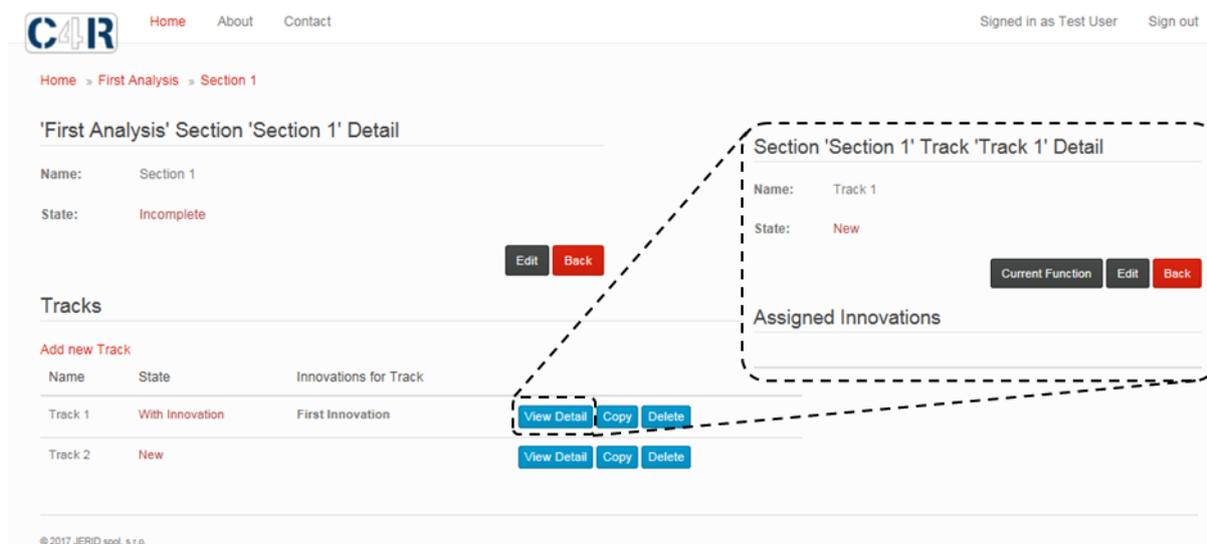
FIGURE 10 TRACK PAGE

The user views and enters information about individual tracks by selecting the "View Detail" option on the track page. Here the user describes the status of the track by selecting the current capabilities of the track and entering the required data (shown in Figure 6, Figure 7 and Figure 8). Track names can also be edited on this page. The user-defined innovations already applied to the track are displayed in the assigned innovations section of the page (Figure 9).

3.5 INNOVATION REPRESENTATION & FUTURE CAPABILITIES DESCRIPTION

3.5.1 DESCRIBING AN INNOVATION

After completing the capabilities representation for the current railway with regard to track, the user can at this point describe an innovation. Additional Innovations are entered by selecting the "Add Innovation page" on the sections page, where a name and description has to be provided. Innovations already defined within an analysis are listed on the sections page (Figure 9) under Innovation definitions.

3.5.1.1 DEFINING FUTURE CAPABILITIES FOR CAPACITY

The user defines specific elements (referred to as functions in the tool) affected by each of innovations by selecting the Innovation (Figure 11). The user can select anything from one single element (as shown in Figure 11, where only line speed has been selected) to the full list that describes the railway sections being analysed.

FIGURE 11 DEFINING FUNCTIONS IMPACTED BY THE INNOVATION

Innovations are assigned to individual tracks and the expected future capability values are defined (Figure 12). When the user views the innovation assigned to a track, the list of the functions defined as being impacted by the innovation is presented (Figure 11). The current values for the selected function as defined by the user are also visible for clarity. The example in Figure 12 shows that the innovation has facilitated an increase in line speed from 150 to 200 kilometres per hour.
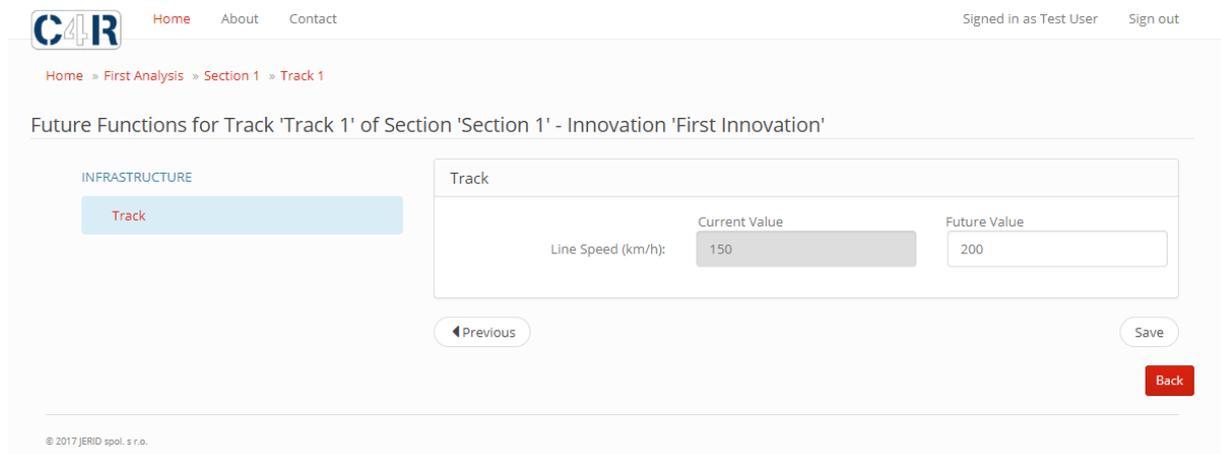
FIGURE 12 APPLICATION OF AN INNOVATION ON A TRACK

The user can apply multiple innovations to a track but these cannot contradict each other, for example, if the first innovation sets the future function of line speed to 200 kilometres per hour a second innovation cannot subsequently define the future line speed as 250 kilometres per hour.

3.5.2 DEFINING CAPABILITIES FOR AFFORDABILITY, ADAPTABILITY, RESILIENCE AND AUTOMATION

Outcomes are also measured in terms of the other Capacity4Rail (C4R) high level goals (HOG); adaptability, affordability, automation, and resilience. The user can also enter monetary values (if available) for infrastructure and rolling stock in terms of planning, CAPEX, OPEX and Decommissioning costs. The user accesses these questions via the Capability Home page (Figure 13); accessed itself, by selecting the Capability Home option on the Sections page (Figure 9).
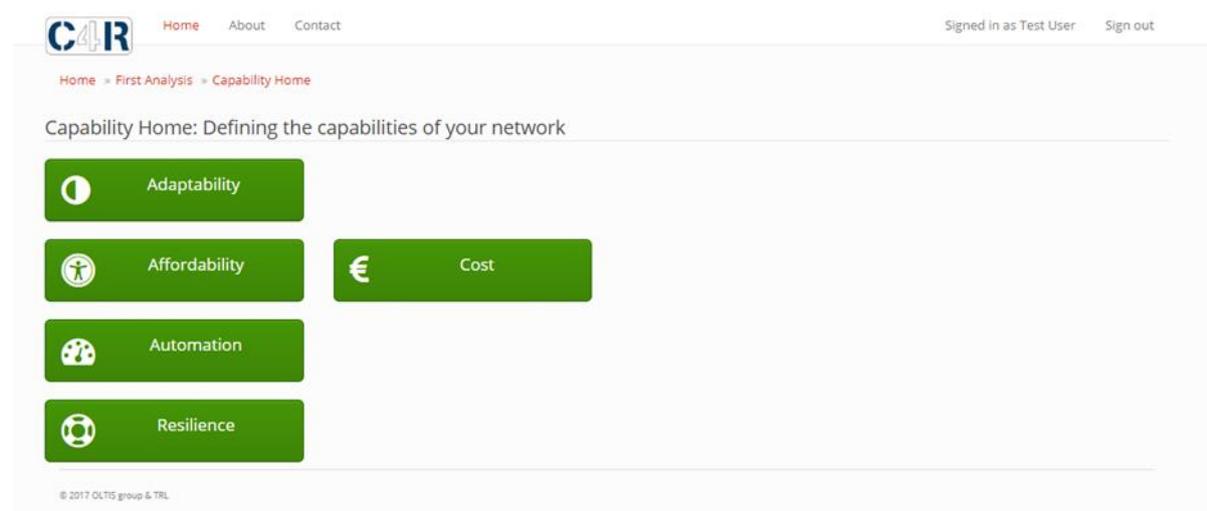
FIGURE 13 CAPABILITY HOMEPAGE

Each HLG is broken down into several sub-topics (these are listed in Table 1). For each sub-topic the user is required to select (key measures) a response from a list of pre-defined questions and associated drop down list of answers. Pre-defined questions and answers apply to both the current and future (post-innovation) railways and relate to affordability, resilience, adaptability and automation. The pre-defined questions and answers can be changed and added to (by an administrator) to allow regional /local differences and/or priorities to be represented in the future.

Sub-Goal Topics	
Affordability	Topic 1: Infrastructure Costs
	Topic 2: Rolling Stock Costs
	Topic 3: Barriers to Entry
	Topic 4: Infrastructure Environmental Costs
	Topic 5: Operation Environmental Cost
	Topic 6: Noise and Vibration
Resilience	Topic 1: Performance (related to punctuality)
	Topic 2: Train delays due to weather events
	Topic 3: Train delays due to infrastructure failures and maintenance
	Topic 4: Train delays due to rolling stock/train operational failures
	Topic 5: Speed of recovery from timetable perturbation
	Topic 6: Accessibility to network during disruptions
Adaptability	Topic 1: Seamless Train Movement
	Topic 2: Interoperability
	Topic 3: Adaptable Infrastructure
	Topic 4: Legalities when implementing change
Automation	Topic 1: Operations
	Topic 2: Operations-related Communications
	Topic 3: Monitoring and Maintenance
	Topic 4: Automation for Passengers

TABLE 1 SUB-GOAL TOPICS FOR AFFORDABILITY, RESILIENCE, ADAPTABILITY AND AUTOMATION OUTCOMES

3.6 CALCULATION OF CAPABILITY OUTCOMES

The mapping between the capability representations and the capacity outcome is automated within the tool; the user does not need to do any calculation. For each High Level Goal (HLG), the combination of scores are mapped into weighted outcomes is also performed automatically these computational process are defined below.

3.6.1 CAPACITY

Capacity is evaluated using the TRA capacity model introduced by Lai et al. and used for Taiwan Railways Administration (Lai, et al., 2010; Lai & Wang, 2012). This model was selected as it uses a systematic methodology for estimating hourly capacity without the need for simulation and is based instead, on a number of calculations (described in the following sub-section). The TRA capacity model has been expanded to accommodate multiple types of signalling technology and track layout configurations which are more typical in the European context. Capacity on a route is computed on a node-link-node basis per track, i.e. the C4R capacity calculation process considers the track and adjacent station/junction characteristics at the same time.

3.6.1.1 CALCULATING CAPACITY

Capacity is estimated via a series of headway calculations producing a trains per hour (TPH) value on a per track basis. For every node-link-node, the model determines the critical signal headway via a number of steps (explained in more detail in Appendix A):

   i.   Services are grouped (put into categories) according to their characteristics i.e. train length, speed, acceleration, deceleration and service stopping pattern. The model allows for three train categories per track (two passenger train categories and one freight train category);

   ii.   Calculates the travel time between each node-link-node for each train category. This is calculated in the model by using the train category characteristics speed, acceleration, deceleration and service stopping pattern as well as the distance between the two nodes;

   iii. Calculates the cruise speed for each category from the average operating speed (calculated in step ii) and maximum speed over the node-link-node sub-section;

   iv. Identifies the timetabled dwell time at each station for each train category;

   v.   For all possible service pairs (see Appendix A Table 6 for definitions) compute the following:

        a.   Average signal headways (A.1);

        b.   The critical signal headway (A.1);

        c.   Lost time due to overtaking (A.2);

        d.   Operating margin (A.3);

        e.   Operational Headway (A.4).

   vi. Calculate the average operation headway for each node-link-node sub-section (A.5);

   vii. Calculate the capacity from the average operation headway (A.6).

The capacity over the route (per direction) is then calculated by the following steps:

   viii. Calculate the capacity for each section (A.7);

   ix. Determine the route capacity.

The capacity over the entire route is defined by the most restrictive section on the route for the direction, i.e. with the lowest calculated capacity. This process is undertaken for the current railway and the future (post-innovation) railway to determine the change capacity following the investment/innovation.

3.6.2 EFFECTS OF DEPENDENCIES ON CAPACITY CAPABILITY OUTCOMES

When calculating capacity (e.g. the number of trains per unit time), the modified TRA calculations take into account a number of complex interactions between different parameters of the railway system (e.g. acceleration, signalling system, block lengths, gradients at station approaches and departures etc); these are described in Appendix A.

Furthermore when determining the capability values to be used in the calculation further dependencies are taken into account. For example the actual acceleration of a train on a section is calculated taking into consideration the track gradient on that section. This systems approach which underlies the CTA tool allows the decision maker to consider the interactions of the different components and their elements.

3.6.3 REPORTING ON CAPACITY IN THE CTA TOOL

TPH values for the current railway are normalised to a base value (0), the future capacity score is normalised based on the user defined target for capacity increase (defined at the analysis set-up (Figure 5). Normalised values range between -2 and 2. The capacity value for current is normalised to a baseline value of "0".

On the normalised scale 1 is defined as the capacity value for current plus the value of the desired percentage increase in capacity (as entered when the analysis was initially set-up) and 2 is defined as the double the desired percentage increase in capacity. -1 is defined as the capacity based on current minus the value of the desired percentage increase in capacity and -2 is minus double the value of the desired percentage increase in capacity.

Future values will be normalised to a value between 2 and -2. If a future value is less than or greater than the minimum and maximum values respectively, they will be given a value of -2 and 2 respectively. See Table 2 for an illustrative example.

Value from Inputs	Normalised Score
User defined target increase = 20 %	
Current capacity = 10 Trains per hour	**0**
*Normalised score of 1 = current capacity+ current capacity * target increase = 10 +(10*20%) =12*	*1*
*Normalised score of 2 = current capacity current capacity * 2*target increase = 10 +(10*40%) =14*	*2*
*Normalised score of 1 = current capacity-current capacity * target increase = 10 - (10*20%) =8*	*-1*
*Normalised score of 2 = current capacity-current capacity * 2 *target increase = 10 - (10*40%) = 6*	*-2*
Estimated Future capacity = 11 Trains per hour	**0.5**

TABLE 2 NORMALISING CAPACITY VALUES, ILLUSTRATIVE EXAMPLE

3.7 AFFORDABILITY, RESILIENCE, ADAPTABILITY AND AUTOMATION

Calculation of the capability outcomes with regards to affordability, resilience, adaptability and automation is achieved via a graded qualitative list (GQL) scoring system. This consists of a set of qualitative statements, termed the GQL key measures. Each key measure has a weighting value so that the measures can be weighed against one another. These weightings can be changed (by the administrator) to account for different priorities between countries/regions within the EU. Each GQL key measure is linked to a further set of statements (GQL key measure levels) that describe the degree to which the key measure is satisfied. Every statement has a score associated with it.

Before the high level goal outcomes are passed to the visualisation component of the tool, the values are normalised, such that each outcome varies between overall maximum, $O_{max,}$ and overall minimum, $O_{min,}$ performance values.

$$\text{Normalised score} = \frac{((\text{weighting}_1.\text{score}_1) + (\text{weighting}_2.\text{score}_2) + (\text{weighting}_n.\text{score}_n))}{(\text{weighting}_1 + \text{weighting}_2 + \text{weighting}_n)}$$

The scores associated with all selected GQL key measure levels give the value for a particular goal outcome sub-goal which is used for visualisation (see Section 3.8). The scoring method will result in individual scores for all sub-goal measures. Each HLGs outcome is the weighted average of its sub-goal measures. The illustrative example below shows how the Affordability HLG score is calculated

Affordability High Level Goal Normalised Score

$$= \frac{(weighting_1.T_1) + (weighting_2.T_2) + (weighting_3.T_3) + (weighting_4.T_4) + (weighting_5.T_5) + (weighting_6.T_6)}{(weighting_1 + weighting_2 + weighting_3 + weighting_4 + weighting_4 + weighting_5 + weighting_6)}$$

Whereby:

T1 =	Normalised score for Infrastructure Costs GQL key measures
T2 =	Normalised score for Rolling Stock Costs GQL key measures
T3 =	Normalised score for Barriers to Entry GQL key measures
T4 =	Normalised score for Infrastructure Environmental Costs GQL key measures
T5 =	Normalised score for Operations Environmental Cost GQL key measures
T6 =	Normalised score for Noise and Vibration GQL key measures

3.8 VISUALISATION OF OUTCOMES

Visualisation of the performance outcomes are accessed through the "Chart" option on the section page (Figure 9). This option can only be selected by the user once all capabilities status representation information required for the analysis has been entered. The user will be taken to a page which displays the high level goal outcomes as well as options to visualise the outcomes for the sub-goals.

3.8.1 HIGH LEVEL GOAL OUTCOMES

The outcomes for the five HLGs, i.e., Capacity, Adaptability, Affordability, Automation and Resilience are the principal outcomes of the CTA tool. After the normalisation process described in 0 (for Capacity) and 3.7 (for the other HLG), the performance outcomes are visualised on a single five armed spider diagram. Figure 14 shows an example visualisation of the outcomes, if the user has entered costs for the current and future railways for infrastructure and rolling stock, these are also presented on this page.
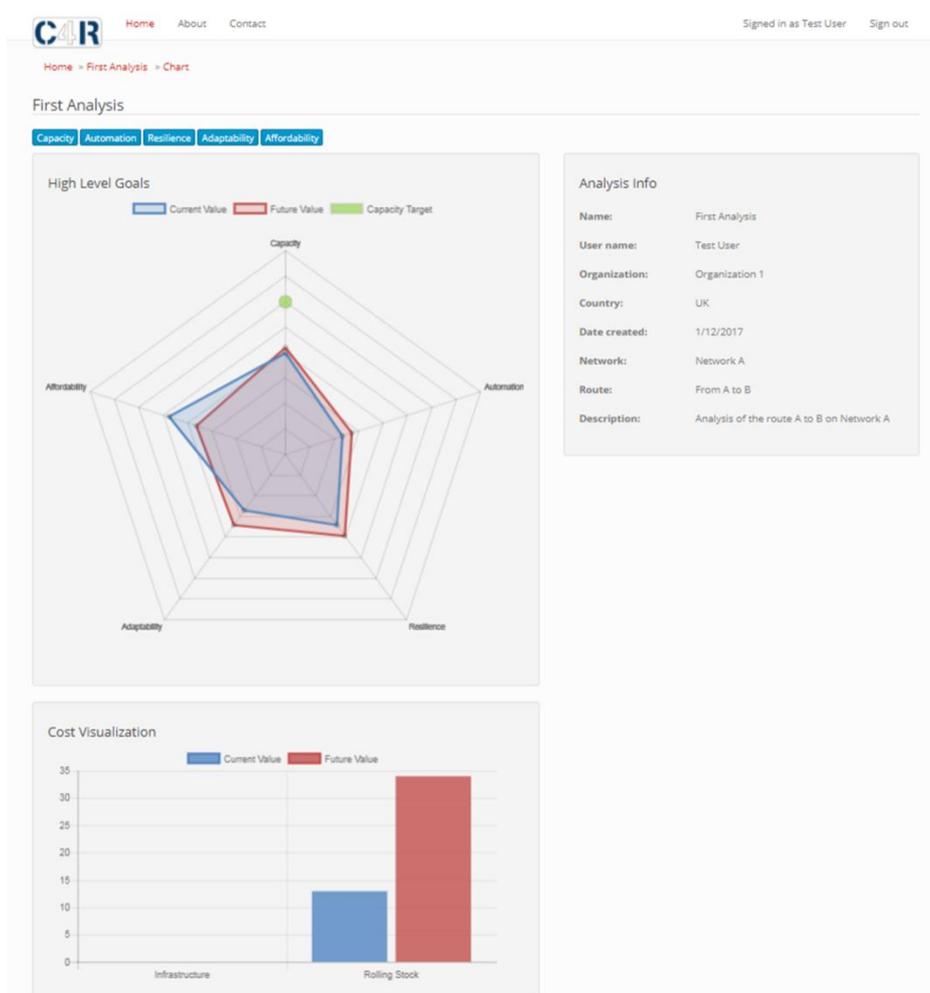
FIGURE 14 HIGH LEVEL GOAL PERFORMANCE OUTCOMES VISUALISATION PAGE

For the capacity outcome, the visualised current value (in blue) shown in the spider diagram in Figure 14 has been normalised to the baseline as described in 0. The Capacity Target (green dot) on the graph is the normalised value of the current capacity value plus the percentage increase. The future value (in red) has been normalised using the scale defined by the baseline and capacity target scores

3.8.2 Sub-Goal Outcomes

The user is also able to visualise the outcomes of the sub-goal for each High Level Goal. These are accessed via the Capacity, Adaptability, Affordability, Automation and Resilience buttons at the top of the High Level Goal outcomes Visualisation page (Figure 14).

3.8.2.1 Capacity

The capacity sub-goal visualisation gives a breakdown of capacity per train category per direction. A breakdown is produced for every section defined in the analysis. Figure 15 shows a visualisation of the capacity sub-goal spider, where the analysis route consists of two sections.

FIGURE 15 CAPACITY SUB-GOAL VISUALISATION

3.8.2.2 AFFORDABILITY

The affordability sub-goal visualisation (Figure 16) breaks down the affordability outcomes into the 6 topics defined in Table 1. The outcomes for affordability are reported on a per-analysis basis unlike the capacity outcomes which are reported on a per-section basis.
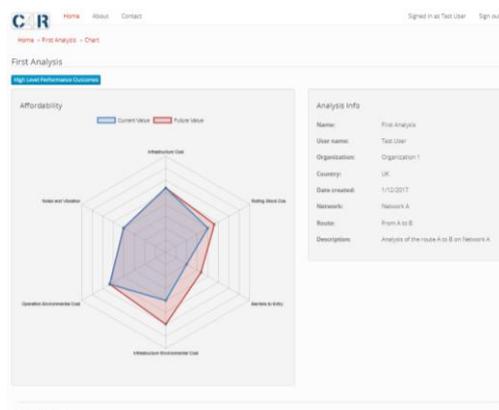
FIGURE 16 AFFORDABILITY SUB-GOAL VISUALISATION

3.8.2.3 RESILIENCE

The resilience sub-goal visualisation (Figure 17) breaks down the resilience outcomes into the 6 topics defined in Table 1. The outcomes for resilience are reported on a per-analysis similar to affordability outcomes.
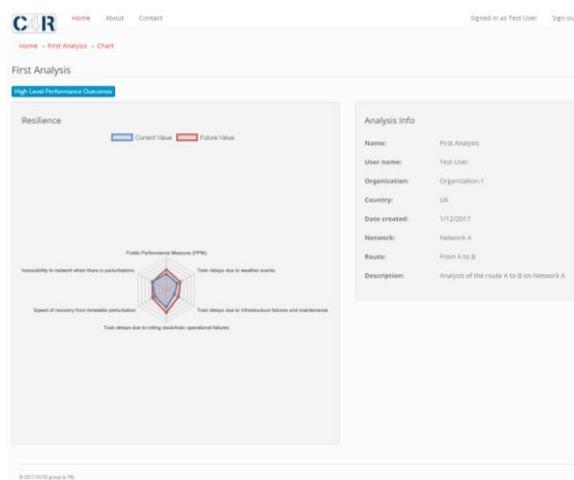
FIGURE 17 RESILIENCE SUB-GOAL VISUALISATION

3.8.2.4 ADAPTABILITY

The adaptability sub-goal visualisation (Figure 18Figure 17) breaks down the resilience outcomes into the 4 topics defined in Table 1. The outcomes for resilience are reported on a per-analysis as per the affordability and resilience outcomes.
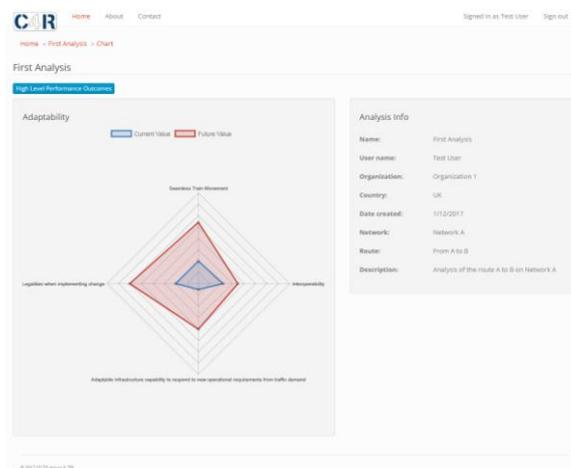
FIGURE 18 ADAPTABILITY SUB-GOAL VISUALISATION

3.8.2.5   AUTOMATION

The automation sub-goal visualisation (Figure 19Figure 18Figure 17) breaks down the automation outcomes into the 4 topics defined in Table 1. The outcomes for resilience are reported on a per-analysis similar to affordability, resilience and adaptability outcomes.
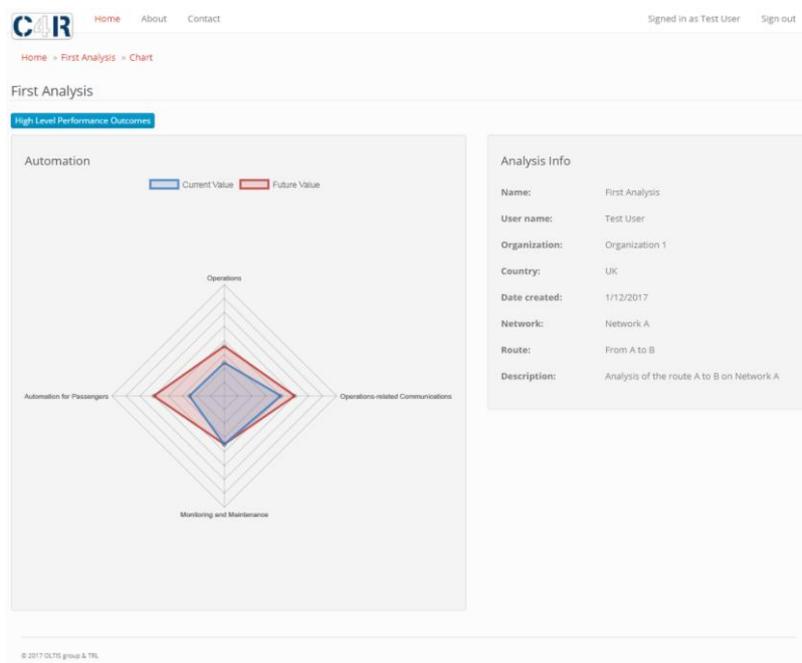
FIGURE 19 AUTOMATION SUB-GOAL VISUALISATION

4. Case Study

The East Coast Mainline (ECML) is a 632 km major railway artery carrying services between London and Edinburgh via Peterborough, Doncaster, York and Newcastle and also has branches to other key locations in the North of England (Network Rail, 2017).

The ECML is part of Network Rail's (UK's Rail Infrastructure Manager) strategic network and serves around 20 per cent of the UK's travelling public. As well as intercity passenger services, the ECML also carries key commuter flows for the north side of London, local passenger services and heavy tonnages of freight traffic.

Table 3 shows the traffic volumes and loadings per year for the entire East Coast Main Line. Journeys undertaken over the ECML has seen a large growth since 2011-12 with 2.8 million additional passenger journeys undertaken by 2017 (ORR, 2017). Intercity services along this are particularly in great demand. Significant passenger capacity increases are required if the railway is to meet the projected passenger demand to 2050.

2016-17 Traffic volumes on the East Coast Main Line			
Traffic volumes	**Passenger**	**Freight**	**Total**
Train Km per year (millions)	37	6	43
Train tonne km per year (millions)	13,108	5,825	18,933

TABLE 3. CURRENT TRAFFIC LOADING PER YEAR ON THE ENTIRE EAST COAST MAIN LINE

The route selected for this case study demonstrating the application over the Capability Trade-Offs Tool is the portion between Peterborough and Doncaster on the ECML.

4.1 PETERBOROUGH TO DONCASTER

The railway corridor between Peterborough and Doncaster consists of two separate branches, one via Grantham and the other via Spalding (Figure 4). The branch via Grantham is dedicated to main line services with mostly Intercity, fast regional trains and a small number of long distance freight trains. It is mainly equipped with 4-aspect ATWS (the British Automatic Track Warning System) along a mix of double and single-track layouts in each direction. The branch via Spalding is actually considered not part of the main line but part of a sub-route named Great Northern-Great Eastern (GN/GE) where slower regional trains and mostly freight trains operate with 3-aspect ATWS along a single-track layout in each direction. The GN/GE has recently undergone a £280M (€315M) upgrade which increased the gauge clearance to allow larger, heavier freight to run along the branch line as well as resignalling works[6]. The case study considers traffic along the "*via Grantham"* branch.

4.1.1 CURRENT INFRASTRUCTURE

Heading south from Doncaster the route is single-tracked in each direction up to Stoke Tunnel; it is then double-tracked in each direction for the rest of the way to Peterborough (Network Rail, 2017). It has permitted line speeds of predominately 200 kph on main/fast tracks and 130 kph on slow tracks (south of Stoke Tunnel). It is electrified with 25 kV AC OHLE and train detection is via Track Circuit Blocks. The line has a Route Availability of "*RA9"* and can accommodate *"W10"* freight trains (Network Rail, 2016)*,* i.e. freight trains with an axle load of ≤24.1 tonne, carrying containers with a height and width of ≤9 ft. 6 in (2.90 m) by ≤8 ft. 2 in (2.55 m). RA is Network Rail's grading system describing permitted maximum axel loads (RSSB, 2015) and W is its freight Wagon series of gauges relating to standard BR wagon profiles; it assumes a common freight platform at 43.31 in (1100mm) above rail (RSSB, 2015). There are 51 level crossings, 4 tunnels and over 100 bridges (Network Rail, 2017; Network Rail, 2016).

FIGURE 20. PETERBOROUGH-DONCASTER RAILWAY NETWORK ON THE ECML ADOPTED FROM

4.1.2 CURRENT TIMETABLE (SCHEDULING)

Between Peterborough and Doncaster, typical per hour traffic flows in 2017 are as follows:

i.   6 Long Distance High Speed (LDHS) trains, between London, the North and Scotland;

ii.   2 Regional Trains, one service between Norwich to Liverpool (which joins the ECML on the Peterborough and Grantham section) and one service between Birmingham and Stansted Airport (joining the ECML between Peterborough and Helpston Junction);

iii. 1 Freight service between London, the Midlands and the North.

4.1.3 CURRENT ROLLING STOCK

Intercity, LDHS services are primarily operated by a fleet of diesel-powered InterCity 125 (HSTs) and electric Intercity 225s. Regional services between Peterborough and Grantham are operated by class 158s and services between Birmingham and Stansted Airport are operated by class 170. Freight services are operated by class 66 locomotives hauling a mix of containers, oil, coal and aggregates ranging in weight from 600 to 3200 tonnes. The Capabilities Trade-Offs Tool handles three train types (two passenger trains and one freight) as such the case study considered the train categories and capabilities described in Table 4.

Train Category	Passenger Trains 1	Passenger Train 2	Freight Train
	InterCity 225[7]	Class 158[8]	Class 66[9]
Power	Electric (AC)	Diesel	Diesel
Total Length (m)	254	46	292
weight (tonne)	524	77	360 *(class 66)*
Loading Gauge	W7	W7	W9
Height above top of rail (m)	3.76	3.81	3.90 *(class 66)*
Width (m)	2.74	2.70	2.65 *(class 66)*
Axle Load (tonne)	12	9	22
Acceleration (ms^{-2})	0.21 *(average to 200 kph)*	0.7	0.2
Braking (ms^{-2})	0.6	0.8	0.4
Max Speed (km h^{-1})	200	145	95
Dwell Time (seconds)	90	90	N/A
Seating Capacity (passenger only)	535	151	N/A
Maximum Carried Load (freight only)	N/A	N/A	1800

TABLE 4 ROLLING STOCK CAPABILITIES

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[7] https://www.eversholtrail.co.uk/upload/class-91.pdf
[8] https://www.porterbrook.co.uk/brochure/158/issue1/html5/index.html?page=1&noflash
[9] https://www.eversholtrail.co.uk/upload/class-66.pdf

4.1.4 RECENT DEVELOPMENTS AND FUTURE PLANS

In recent years, a large amount of investment has been made to increase capacity between Doncaster and Peterborough. The Allington Chord was constructed near Grantham in 2006, this removed local traffic from the ECML, and instead trains now pass under the line. Investments since then include enhancements to the GN/GE line which is now gauge cleared for intermodal freight traffic with Route Availability 8 at a ruling linespeed of 75mph and other freight trains including those up to Route Availability 10 at a ruling linespeed of 60mph. This means freight is now typically diverted onto the GN/GE from the ECML leaving fewer freight services on the ECML reducing traffic heterogeneity and allowing the number of passenger services to be increased[10]. In spite of the investments, the existing crossing movement causes constraints on the timetable as the freight trains, and occasional passenger service, have to cross the high speed East Coast lines onto the GN/GE northbound via the at grade Werrington Junction. Other more recent investments include station remodelling at Peterborough and Doncaster to reduce the number of crossing train paths (Network Rail, 2010).

The double section between Stoke Tunnel and Doncaster remains a key bottleneck suppressing capacity on the ECML. This was identified in Network Rail's East Coast Main Line Route Utilisation Strategy but quadrupling the track along the section was considered prohibitively expensive due to tunnelling requirements (Network Rail, 2010).

The Intercity Express Programme is an initiative of the DfT in the United Kingdom to procure new trains (IETs) to replace the ageing InterCity 125 and InterCity 225 fleets on the East Coast Main Line. The IETs reach top speed (200 kph) 40 seconds quicker than the current fleets and will enter service from 2018. Analysis suggests that their superior acceleration and breaking capabilities over the InterCity 125 and InterCity 225 will part-facilitate an increase in the number of trains per hour along the line in conjunction with timetable changes (Network Rail, 2014).

A further investment solution to increasing capacity on the ECML is the implementation of European Train Control Systems; it is being trialled between London and Peterborough with the option to expand over the ECML.

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[10] https://www.gov.uk/government/news/claire-perry-officially-opens-280-million-lincolnshire-rail-improvements

4.2 CAPACITY REQUIREMENTS AND EVALUATION OF FUTURE INVESTMENT OPTIONS

The UK has seen a substantial and sustained rate of passenger mile growth seen over the last 20 years (116 % between 1995-96 and 2015-16) and the number of UK rail passenger miles is forecast to double again over 30 years from 2009 levels[11]. Similarly freight transportation has been predicted to double over the same period[12] with projected annual growth in total rail freight volumes of about 3% per annum to 2043[13].

For purpose of this case study, it is assumed that capacity for passenger trains between Peterborough and Doncaster for passengers will need to be doubled by 2050 to meet growth. The case study uses the Capability Trade-Offs Tool to evaluate outcomes of the following potential investment options with reference to Capacity4Rail's five high-level goals (Capacity, Resilience, Automation, Adaptability and Affordability), the current status of the route is as described in 4.1.1, 4.1.2 and 4.1.3 and the targeted increase in capacity has therefore been set to 100%:

i. **Investment Option 1: Upgraded rolling stock;**

As described in 4.1.4, the intercity express programme will see the InterCity 125 and InterCity 225 units replaced with the IETs. As part of the case study, the tool is used to evaluate the resultant outcomes of the new rolling stock's acceleration (0.7 ms^{-2}) and deceleration (1.0 ms^{-2}) capabilities with particular reference to capacity outcomes (Rogers, et al., 2014).

ii. **Investment Option 2: Upgraded rolling stock and all freight diverted onto GN/GE;**

With the enhancements to the GN/GE line, much freight traffic is already pathed via Spalding taking it off the ECML between Peterborough and Doncaster. This has reduced traffic heterogeneity over these sections of the ECML but introduced additional crossing movements around Werrington Junction associated with northbound trains transferring from the ECML to the GN/GE.

Pathing all freight services on via the GN/GE line will further reduce traffic heterogeneity north of Werrington Junction but increase the number of crossing movements. The construction of Allington Chord in 2006 removed a similar crossing movement over the ECML and this provided sufficient extra capacity for 12 additional services between Leeds and London each day[14]. Upgrading Werrington Junction from an at-grade junction to grade separated could remove these timetable-restricting movements.

The tool is used to evaluate the resultant outcomes from investment option 2 whereby all freight traffic is diverted onto the GN/GE via a new grade separated Werrington Junction as well as deployment of the IETs in combination with investment option 1.

iii. **Investment Option 3: Upgraded rolling stock, all freight diverted onto GN/GE and implementation of ETCS level 2 (with optimised blocks);**

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[11] Network Rail, Long Term Passenger Rolling Stock Strategy for the Rail Industry (5th Edition), March 2017
[12] Network Rail, Freight Network Study, Long Term Planning Process, April 2017
[13] Network Rail, Long Term Passenger Rolling Stock Strategy for the Rail Industry, February 2013
[14] https://www.railwaypeople.com/Page/project-allington-chord-22

ETCS Level 2 has been deployed over numerous routes within the E.U. with each seeing an increase in delivered useable capacity. Various lines on the Austrian rail network have seen a 30% capacity increase after ETCS level 2 was implemented alongside a traffic management system and major stations in Germany have seen significant improvements over 15% after deployment of ETCS Level 2 in conjunction with traffic management and C-DAS or ATO (Calvert, 2017).

In a UK context, ETCS level 2 is being implemented over the Thameslink mainline route to improve capacity. A 20% increase from the current 20tph is required by 2018. It is expected that deployment of ETCS level 2 with traffic management and ATO will provide a peak theoretical capacity of 30tph, thereby creating a reliable 24tph service with acceptable recovery margins. More widely over the UK network, it is suggested that a potential released capacity of between 10% and 20% can be expected from ETCS level 2 deployment in in conjunction with TM, civil engineering and signalling intervention (Calvert, 2017).

The tool is used to evaluate the resultant outcomes from Investment option 3 in conjunction with investment options 1 and 2. Whereby ETCS level 2 is deployed along the route with optimised block lengths (250m), new passenger rolling stock is used and freight paths are diverted via the GN/GE.

4.3 RESULTS

The current capabilities were defined for the railway between Doncaster and Peterborough with the route split into the following sections based on the node-link-node methodology:

Section	Length (km)	Tracks	
		Up	Down
Peterborough East Jn - Werrington Jn	5	3	2
Werrington Jn - Helpston Jn	4	3	2
Helpston Jn - Stoke Jn	29	2	2
Stoke Jn - Highdyke Jn	3	1	1
Highdyke Jn - Grantham	6	2	1
Grantham - Newark North Gate Jn	24	1	1
Newark North Gate Jn - Carlton on Trent	9	1	1
Carlton on Trent - Retford	21	1	1
Retford - Ranskill	8	1	1
Ranskill - Rossington Colliery	13	1	1
Rossington Colliery - Doncaster	7	2	1

TABLE 5 ROUTE SECTIONS BETWEEN PETERBOROUGH AND DONCASTER

Analysis of the three investment scenarios was the performed using the by the CTA tool. All calculated costs in British pounds (£) have been converted into euros (€) using the European Commission's InfoEuro currency converter for January 2017[15].

4.3.1 UPGRADED ROLLING STOCK

The UK Government has procured a fleet of Intercity Express Trains in a contract worth €6.68 billion[16]. This will replace trains on 2 major intercity routes (East Coast Main Line and Great Western Main Line) with 407 carriages destined for the East Coast Main line (169 bi-mode and 240 EMU carriages). Capital costs were calculated at approximately €3.28 million per carriage for bi-mode versions and €2.81 million per carriage for electric versions (Barrow, 2014). This equates to a capital cost totalling €1.37 billion for the vehicles operating over the ECML. Analysis in 2014 showed that train operators will pay an estimated total of £4.16 billion over a "usage guarantee" lease of 27.5 years (National Audit Office, 2014).

The IC225s currently running along the ECML last underwent a major refurbishment between 2001 and 2006 over 10 years ago (as of 2017). It is estimated that the 94 trains will cost €82M refurbish to this standard with a further €23M required to ensure continued operation and increased reliability performance over a 10 year extended life of the Class 91 locomotives [17]. Typical rolling stock costs (i.e. total maintenance costs, and capital leasing costs) per vehicle mile for the IC225s were estimated at €3.31 based on average values for electric rolling

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[15] http://ec.europa.eu/budget/contracts_grants/info_contracts/inforeuro/index_en.cfm
[16] https://www.gov.uk/government/news/all-aboard-the-new-intercity-express-trains-that-will-transform-journeys-across-britain
[17] https://www.railengineer.uk/2013/01/21/a-new-lease-of-life/

stock (Long Term Passenger Rolling Stock Strategy Steering Group, 2014). We estimate from reports[18] that the IC225s travel a combined distance of 7.75 million miles a year and so OPEX costs for the 10 years equates €256M.

In this scenario, the tools evaluation of introducing new intercity rolling stock with improved acceleration and breaking capabilities delivers just over 10% of the targeted capacity increase (see B.1). Automation outcomes are nominally increased through some automation of passenger boarding, replacing manual opening doors with guard operated doors (B.3). Resilience outcomes are increased by replacing the close to life-expired rolling stock with new models, reducing predicted delays due to train failures (B.4). Resilience is also improved due to the hybrid nature of the new rolling stock therefore reducing delays due to OHLE failures. The trade-off in delivering this innovation reduces affordability through increased CAPEX and OPEX costs although environmental costs are reduced due to the lighter more energy efficient nature of the new rolling stock (B.2).

In order to delivered the targeted capacity outcomes different or additional innovations will need to be considered such as removing freight from the ECML between Doncaster and Peterborough.

4.3.2 UPGRADED ROLLING STOCK AND ALL FREIGHT DIVERTED ONTO GN/GE

This analysis compares the current railway capabilities between Doncaster and Peterborough and the future capabilities after the intercity rolling stock has been upgraded and the Freight heading northbound onto the GN/GE from ECML via an at-grade junction. These movements disrupt potential traffic flows over the ECML reducing capacity. Moving more freight onto the GN/GE crossing the Down tracks of the ECML will further exacerbate this problem. A dive-under solution at Werrington Junction would see construction of a grade separated junction where the diverging GN/GE would pass below East Coast Mainline removing the disruptive pathing. Assuming a new 3km length of double track is required for the junction, this scheme would cost ~€445 million (including contingency). On-going operating costs are estimated at €1.8 million per year with a further €220 million required for renewal costs over a 60 year period[19]. There is no infrastructure cost in the current railway this infrastructure doesn't exist.

In this scenario, the tools evaluation shows nearly 30% of the targeted capacity can be delivered (C.1). Resilience outcomes are increased through moving freight paths to a semi-dedicated freight line and removing the potential conflicts as freight crosses the ECML onto the GN/GE (C.4). Removal of freight from the ECML also reduces wear on the infrastructure reducing maintenance needs and reducing potential network downtime. Adaptability is increased as more freight is able to run along the GN/GE with greater gauge clearance than the ECML. Automation outcomes are only nominally improved as in investment option 1 (C.3). The trade-off in this scenario is affordability where substantial increased in rolling stock and infrastructure costs reduce the affordability outcomes (C.2). Affordability is also reduced in terms of environmental costs associated with construction and maintenance of additional infrastructure. Additionally the GN/GE passes by a number of towns and villages (e.g. Sleaford); pathing more freight along this line will increase the amount of noise and vibration incurred by these residents.

4.3.3 UPGRADED ROLLING STOCK, ALL FREIGHT DIVERTED ONTO GN/GE AND IMPLEMENTATION OF ETCS LEVEL 2 (WITH OPTIMISED BLOCKS)

Moving from conventional 4-aspect signalling to an ETCS with GSM-R could improve passenger capacity across the route by reducing headways between trains potentially leading to an increase in the number of trains per

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[18] https://www.railmagazine.com/trains/current-trains/no-rest-for-the-91s
[19] http://bailey.persona-pi.com/Public-Inquiries/werrington/nr-docs/poe/nr-poe-1-2.pdf

hour. Network Rail calculated costs of ETCS deployment between Doncaster and Peterborough at €791M between 2020 and 2050 (Capacity4Rail, 2017). The analysis for the current status of the railways assumes the all current signals will need renewal during this period; renewal costs of multi-aspect signalling are estimated at €110M for the 129 km route using average CAPEX costs per km for the UK railway network (Parsons Group International Limited, 2011). The cost of operations is assumed at a yearly percentage of the investment; 4% (Baumgartner, 2001) giving an annual OPEX of €4.4M and a total of €132M over that period.

In this scenario, the evaluation shows the capacity target is surpassed by an additional ~20% (D.1). The resilience outcomes are vastly improved by the introduction of the new signalling system which improves the speed of recovery over and above the improvements identified in investment option 2 (D.4). Adaptability outcomes are also improved through increased flexibility in rolling stock lengths that can be accommodated over the line without adversely affecting capacity outcomes (D.5). The substantial reduction in block size produces a net increase in signalling infrastructure across the network, this has large cost implications for CAPEX and OPEX as well and as an increase in environmental costs. While the capabilities of the network are improved in a way that exceeds the required outcome, i.e. whilst the gains in capacity are significant, with increased resilience, automation and adaptability, this is a high-cost solution with low affordability.

The decision makers can use the information to decide whether investment option(s) meet their desired outcomes and whether the trade-offs between capabilities identified and the associated costs are acceptable.

5. Conclusions

While there are a number of reported approaches to defining and measuring the capacity of a line/route, there is no reported study on the use of a systems approach that looks at the interdependencies of different components and the benefits of trade-offs between different capabilities when looking for a solution to improve the capacity of a particular line. There is therefore the risk that changes implemented may not deliver the expected increases in capacity. The whole systems approach which underlies the CTA tool provides novel decision support to infrastructure managers and operators by evaluating the inevitable trade-offs that will need to be made when considering different investment aoptions.

The tool's outcome measures have been stress tested using a case study based on a route on the UK railway network, Peterborough to Doncaster on the ECML. The ECML case study has shown that the CTA tool is capable of enabling a system-wide approach. It allows an initial assessment to identify and highlight the key capabilities on a particular line that need to be investigated in greater detail to build greater confidence that the planned for increase in capacity can be realised.

In this version of the model, modified versions of the relationships from the TRA Capacity Model have been used to evaluate capacity. However the tool is structured to allow flexibility to incorporatre additional or new relationships when expanding the model to account for different capability interactions and dependancies. Additional sophisticated capability calculations should be investigated to further improve the tool's performance and customise it for use on networks with specific characteristics. For example, it may also be appropriate to drill down further into some of the systems so as to offer subsets of options, e.g. increased automation, new signalling concepts, provision of platform edge doors, location of station exits, reversing facilities etc.

6. Bibliography

Parsons Group International Limited, 2011. *Low Cost Signalling. Rail Technical and Professional Directorate – Rail Systems.,* London: Department for Transport.

Barrow, K., 2014. Britain's Intercity Express Programme reaches financial close. *Interational Railway Journal*, 25 July.

Baumgartner, J., 2001. *Prices and Costs in the Railway Sector,* Lausanne: Ecole Polytechnique Federale De Lausanne.

Capacity4Rail, 2015. *Deliverable D3.1.1. Review of existing practices to improve capacity on the European rail network,* s.l.: s.n.

Capacity4Rail, 2017. *Deliverable D5.3.2 Migration scenarios and paths,* s.l.: s.n.

Digital Railway, 2017. *Digital Railway.* [Online] Available at: http://digitalrailway.co.uk/wp-content/uploads/2017/02/Digital-Railway-Suppliers-Conference.pdf

European Commission, 2006. *Proposal for a Directive of the European Parliament and of the Council on the retrofitting of mirrors to heavy goods vehicles registered in the Community Full Impact Assessment,* Brussels: s.n.

Lai, Y.-C., Shih, M.-C. & Jyh-Cherng, J., 2010. *Railway Capacity Model and Decision Support Process for Strategic Capacity Planning.* Washington, DC, Transportation Research Board, pp. 19-28.

Lai, Y.-C. & Wang, S.-H., 2012. Development of analytical capacity models for conventional railways with advanced signalling systems. *Journal of Transportation Engineering,* 138(7), pp. 961-974.

Long Term Passenger Rolling Stock Strategy Steering Group, 2014. *Long Term Passenger Rolling Stock Strategy for the Rail Industry,* London: s.n.

National Audit Office, 2014. *Procuring new trains,* London: House of Commons.

Network Rail, 2010. An addendum to the East Coast Main Line. *East Coast Main Line 2016 Capacity Review*, December.

Network Rail, 2014. Group Strategy - Capability Analysis. *ECML 2020 Capacity - Timetable Assessment*, pp. 37-41.

Network Rail, 2016. Delivering a better railway for a better Britian. London North Eastern and East Midlands. *Route Specifications 2016*, March, pp. 19-22.

Network Rail, 2017. *London North Eastern Route Sectional Appendix,* London: Network Rail.

ORR, 2017. *Passenger journeys by train operating company - Table 12.12.* [Online] Available at: https://dataportal.orr.gov.uk/displayreport/report/html/2b2e2c38-c822-4e1f-9fb4-b049b3c13899

Rogers, A. et al., 2014. Development of Class 800/801 High-speed Rolling Stock for UK Intercity Express Programme. *Hitachi Review,* 63(10), pp. 39-46.

RSSB, 2015. Requirements for the Application of Standard Vehicle Gauges. *Railway Group Standard GE/RT8073*, December, pp. 11-24.

RSSB, 2015. Working Manual For Rail Staff: Freight Train Operations. *Railway Group Standard GO/RT3056*, December, pp. 25-26.

Appendix A. Capacity Calculations

A.1 COMPUTING AVERAGE AND CRITICAL HEADWAYS

The following calculations are used to determine the average headway and subsequent trains per hour (TPH) value for each track along one section.

The calculation determines the headway between 2 trains; the preceding train "I" and the following train "j". These two trains make up a "service pair" and can either be from the same train category or different ones. The tool accommodates up to 3 train categories in a section (passenger 1, passenger 2 and freight 1) I.e. up to 9 service pairs (Table 6) are possible.

Preceding train "I"	Following train "j".
Passenger 1	Passenger 1
Passenger 1	Passenger 2
Passenger 1	Freight 1
Passenger 2	Passenger 1
Passenger 2	Passenger 2
Passenger 2	Freight 1
Freight 1	Passenger 1
Freight 1	Passenger 2
Freight 1	Freight 1

TABLE 6 ALL POSSIBLE SERVICE PAIRS

The critical signal headway at the most bottleneck place (T_s) is calculated for all preceding (i) and following (j) trains for service pairs being considered for the analysis. The T_s is a function of the average departure signal headway, in seconds, at departure station ($T_s^B{}_D$) and the average arrival signal headway, in seconds, at arriving station ($T_s^B{}_A$). This is dependent on the time taken to travel from the start to the end node of the preceding train "i" (hitherto known as; t_i) and the following train "j" (hitherto known as; t_j), see Table 7. This is determined for each service pair, creating average critical signal headway for each.

Condition	Critical Signal Headway
When $t_i = t_j$	$T_s = \max(T_s^A{}_D, T_s^B{}_A)$
When $t_i < t_j$	$T_s = \max(T_s^A{}_D, T_s^B{}_A - (t_i - t_j))$
When $t_i > t_j$	$T_s = \max(T_s^A{}_D - (t_i - t_j), T_s^B{}_A)$

TABLE 7 DETERMINING THE CRITICAL SIGNAL HEADWAY (T_s)

Average signal headway is highly dependent on signalling systems and station layouts. Calculation of the average signal headway is performed by using Table 8 and Table 9. $T_s^B{}_D$ is calculated as follows:

Node layout	$T_s^B{}_D$
Type I - Two exclusive or more tracks for each direction	$T_s^B{}_D = T_s^B{}_{D2}$
Type II - One exclusive track for each direction and an additional track shared by two directions without interruption from the mainline	$T_s^B{}_D = (1/3(T_s^B{}_{D1})) + (2/3(T_s^B{}_{D2}))$
Type III - Similar layout to that of Type II but where use of the shared track would encounter interruption from the mainline	$T_s^B{}_D = (3/4(T_s^B{}_{D1})) + (1/4(T_s^B{}_{D2}))$
Type IV - Only one track for each direction (stations only)	$T_s^B{}_D = T_s^B{}_{D1}$

TABLE 8 DETERMINING THE CRITICAL SIGNAL HEADWAY ($T_s^A{}_D$)

$T_s^B{}_A$ is calculated as follows:

Condition	$T_s^B{}_A$
Type I - Two exclusive or more tracks for each direction	$T_s^B{}_A = T_s^B{}_{A2}$
Type II - One exclusive track for each direction and an additional track shared by two directions without interruption from the mainline	$T_s^B{}_A = (1/3(T_s^B{}_{A1})) + (2/3(T_s^B{}_{A2}))$
Type III - Similar layout to that of Type II but where use of the shared track would encounter interruption from the mainline	$T_s^B{}_A = (3/4(T_s^B{}_{A1})) + (1/4(T_s^B{}_{A2}))$
Type IV - Only one track for each direction (stations only)	$T_s^B{}_A = T_s^B{}_{A1}$

TABLE 9 DETERMINING THE CRITICAL SIGNAL HEADWAY ($T_s^B{}_A$)

$T_s^B{}_{D1}$, $T_s^B{}_{D2}$, $T_s^B{}_{A1}$ and $T_s^B{}_{A2}$ are calculated using: Equation 1, Equation 2, Equation 3, Equation 4, Equation 5, Equation 6, Equation 7, Equation 8, Equation 9, Equation 10, Equation 11, Equation 12, Equation 13, Equation 14, Equation 15, Equation 16, Equation 17, Equation 18 and Equation 19. The parameter definitions are found below in Table 10:

Parameter	Description	unit
a_i	Acceleration speed of train i	ms^{-2}
$a_i (G_o)$	Acceleration speed of train i on gradient G	ms^{-2}
B_1	Length of the first block section before arrival station	m
B_2	Length of the second block section before arrival station	m
b_j	Deceleration speed of train j	ms^{-2}
$b_j (G_i)$	Deceleration speed of train j on gradient G	ms^{-2}
B_n	Length of the first block section after departing from station	m
B_{n-1}	Length of the second block section after departing from station	m
B_s	Length of the station block	m
G_i	Gradient before arriving at station	‰
G_o	Gradient after departing from station	‰
i	Index of preceding train (the train in front)	
j	Index of following train (the train behind)	
K_a	Acceleration efficiency	
K_b	Braking safety factor	
L	Length of train (m)	m
S_e	Distance between the tail of train to turnout	m
s_x	Distance between the head of train to starting signal	m
$T^A{}_{s,D}$	Average departure signal headway at departure station	s

$T^B_{s,A}$	Average arrival signal headway at arriving station	s
t_d	Dwell time	s
t_o	Time for clearing the signal	s
t_p	Total operating time for switching turnout and changing signal	s
t_r	Reaction time for driver and braking system	s
T_s	Critical signal headway at the most bottleneck place	s
$T_{s,A}$	Average arrival signal headway	s
$T_{s,A1}$	Arrival signal headway at the same track in station	s
$T_{s,A2}$	Arrival signal headway at different tracks in station	s
$T_{s,D}$	Average departure signal headway	s
$T_{s,D1}$	Departure signal headway from the same track in station	s
$T_{s,D2}$	Departure signal headway from different tracks in station	s
v	Cruising speed	ms^{-1}
v_y	Speed limit for yellow signal	ms^{-1}

<div align="center">TABLE 10 PARAMETER DEFINITIONS</div>

The appropriate equations must be used for each service pair. Table 11 defines which equation to use. The choice of equation is determined Signalling system and whether the lead train reaches its maximum speed before it leaves the node.

Type of Headway	Reaching speed limit at departing station	Signalling System	Equation to use
$T_s^B{}_{A1}$	N/A	3-aspect signalling	Equation 1
		4-aspect signalling	Equation 2
		ETCS level 2	Equation 3
		ETCS level 3	Equation 4
$T_s^B{}_{A2}$	N/A	3-aspect signalling	Equation 5
		4-aspect signalling	Equation 6
		ETCS level 2	Equation 7
		ETCS level 3	Equation 8
$T_s^B{}_{D1}$	$(L_i + s_x + B_n) > ((v_i{}^{\wedge 2})/(2K_a * a_i(G_o))$	3-aspect signalling	Equation 9
		4-aspect signalling	Equation 10
		ETCS level 2	Equation 11
		ETCS level 3	Equation 12
	$(L_i + s_x + B_n) \leq ((v_i{}^{\wedge 2})/(2K_a * a_i(G_o))$	3-aspect signalling	Equation 13
		4-aspect signalling	Equation 14
		ETCS level 2	Equation 15
		ETCS level 3	Equation 16
$T_s^B{}_{D2}$	N/A	3-aspect signalling	Equation 17
		4-aspect signalling	Equation 18
		ETCS level 2	Equation 19
		ETCS level 3	

<div align="center">TABLE 11 DETERMINING WHICH EQUATION TO USE FOR TSBA1, TSBA2, TSBD1 AND TSBD2</div>

$$T_S^B A1 = \sqrt{\frac{2(L_i + s_x)}{a_i(G_o)}} + \frac{v_j}{b_j(G_i)} - \frac{{v_y}^2}{2b_j(G_i)v_j} + \frac{B_1 + B_s - s_x}{v_j} + t_o + t_r + t_{di}$$

EQUATION 1 DETERMINING $T_S{}^B{}_{A1}$ WHEN 3-ASPECT SIGNALLING IS USED OVER THE SECTION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B, A1 = \sqrt{\frac{2(L_i + s_x)}{a_i(G_o)}} + \frac{v_j}{b_j(G_i)} - \frac{{v_{ry}}^2}{2b_j(G_i)v_j} + \frac{(v_y - v_{ry})^2}{2b_j(G_i)v_j} + \frac{B_1 + B_s - s_x}{v_j} + t_o + t_r + t_{di}$$

EQUATION 2 DETERMINING $T_S{}^B{}_{A1}$ WHEN 4-ASPECT SIGNALLING IS USED OVER THE SECTION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B, A1 = \sqrt{\frac{2(L_i + s_x)}{a_i(G_o)}} + \frac{v_j}{2b_j(G_i)} + \frac{B_1 + B_s - s_x}{v_j} + t_o + t_r + t_{di}$$

EQUATION 3 DETERMINING $T_S{}^B{}_{A1}$ WHEN ETCS LEVEL 2 SIGNALLING IS USED OVER THE SECTION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B, A1 = \sqrt{\frac{2(L_i + s_x)}{a_i(G_o)}} + \frac{v_j}{2b_j(G_i)} + \frac{B_s - s_x}{v_j} + t_o + t_r + t_{di}$$

EQUATION 4 DETERMINING $T_S{}^B{}_{A1}$ WHEN ETCS LEVEL 3 SIGNALLING IS USED OVER THE SECTION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B A2 = \frac{v_j}{b_j(G_i)} - \sqrt{\frac{2(s_e)}{a_i(G_o)}} + \frac{{v_y}^2}{2b_j(G_i)v_j} + \frac{B_1 + B_2 + B_s - s_x}{v_j} + t_o + t_r + t_{di}$$

EQUATION 5 DETERMINING $T_S{}^B{}_{A2}$ WHEN 3-ASPECT SIGNALLING IS USED OVER THE SECTION AND WHEN ADJACENT TRAINS USE THE DIFFERENT TRACKS

$$T_S^B A2 = \frac{v_j}{b_j(G_i)} - \sqrt{\frac{2(s_e)}{a_i(G_o)}} + \frac{{v_{ry}}^2}{2b_j(G_i)v_j} + \frac{(v_y - v_{ry})^2}{2b_j(G_i)v_j} + \frac{B_1 + B_2 + B_s - s_x}{v_j} + t_o + t_r + t_{di}$$

EQUATION 6 DETERMINING $T_S{}^B{}_{A2}$ WHEN 4-ASPECT SIGNALLING IS USED OVER THE SECTION AND WHEN ADJACENT TRAINS USE THE DIFFERENT TRACKS

$$T_S^B A2 = \frac{v_j}{2b_j(G_i)} - \sqrt{\frac{2(s_e)}{a_i(G_o)}} + \frac{B_1 + B_2 + B_s - s_x}{v_j} + t_o + t_r + t_{di}$$

EQUATION 7 DETERMINING $T_S{}^B{}_{A2}$ WHEN ETCS LEVEL 2 SIGNALLING IS USED OVER THE SECTION AND WHEN ADJACENT TRAINS USE THE DIFFERENT TRACKS

$$T_S^B A2 = \frac{v_j}{2b_j(G_i)} - \sqrt{\frac{2(s_e)}{a_i(G_o)}} + \frac{B_s - s_x}{v_j} + t_o + t_r + t_{di}$$

EQUATION 8 DETERMINING $T_S{}^B{}_{A2}$ WHEN ETCS LEVEL 3 SIGNALLING IS USED OVER THE SECTION AND WHEN ADJACENT TRAINS USE THE DIFFERENT TRACKS

$$T_S^B D1 = \frac{v_j}{2b_j(G_i)} - \frac{v_j}{b_j(G_i)} + \frac{v_y{}^2}{2b_j(G_i)v_y} + \frac{L_i + s_x + B_n}{v_i} + \frac{B_s - s_x}{v_j} + t_p + t_r$$

EQUATION 9 DETERMINING $T_S{}^B{}_{D1}$ WHEN 3-ASPECT SIGNALLING IS USED OVER THE SECTION IF THE TRAIN DOES NOT REACH THE SPEED LIMIT BEFORE LEAVING THE STATION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B D1 = \frac{v_j}{2b_j(G_i)} - \frac{v_j}{b_j(G_i)} + \frac{v_y{}^2}{2b_j(G_i)v_y} - \frac{(v_y - v_{ry})^2}{2b_j(G_i)v_y} + \frac{L_i + s_x + B_n + B_{n-1}}{v_i} + \frac{B_s - s_x}{v_j} + t_p + t_r$$

EQUATION 10 DETERMINING $T_S{}^B{}_{D1}$ WHEN 4-ASPECT SIGNALLING IS USED OVER THE SECTION IF THE TRAIN DOES NOT REACH THE SPEED LIMIT BEFORE LEAVING THE STATION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B D1 = \frac{v_j}{2b_j(G_i)} - \frac{v_j}{2b_j(G_i)} + + \frac{L_i + s_x}{v_i} + \frac{B_s - s_x}{v_j} + t_p + t_r$$

EQUATION 11 DETERMINING $T_S{}^B{}_{D1}$ WHEN ETCS LEVEL 2 SIGNALLING IS USED OVER THE SECTION IF THE TRAIN DOES NOT REACH THE SPEED LIMIT BEFORE LEAVING THE STATION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B D1 = \frac{v_j}{2b_j(G_i)} - \frac{v_j}{2b_j(G_i)} + + \frac{L_i + s_x}{v_i} + t_p + t_r$$

EQUATION 12 DETERMINING $T_S{}^B{}_{D1}$ WHEN ETCS LEVEL 3 SIGNALLING IS USED OVER THE SECTION IF THE TRAIN DOES NOT REACH THE SPEED LIMIT BEFORE LEAVING THE STATION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B D1 = \sqrt{\frac{2(L_i + s_x + B_n)}{a_i(G_o)}} - \frac{v_j}{b_j(G_i)} + \frac{v_y{}^2}{2b_j(G_i)v_j} + \frac{B_s - s_x}{v_j} + t_o + t_r + t_{di}$$

EQUATION 13 DETERMINING $T_s{}^B{}_{D1}$ WHEN 3-ASPECT SIGNALLING IS USED OVER THE SECTION IF THE TRAIN REACHES THE SPEED LIMIT BEFORE LEAVING THE STATION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B D1 = \sqrt{\frac{2(L_i + s_x + B_n)}{a_i(G_o)}} - \frac{v_j}{b_j(G_i)} + \frac{v_y{}^2}{2b_j(G_i)v_j} - \frac{(v_y - v_{ry})^2}{2b_j(G_i)v_j} + \frac{B_{n-1}}{v_i} + \frac{B_s - s_x}{v_j} + t_o + t_r + t_{di}$$

EQUATION 14 DETERMINING $T_s{}^B{}_{D1}$ WHEN 4-ASPECT SIGNALLING IS USED OVER THE SECTION IF THE TRAIN REACHES THE SPEED LIMIT BEFORE LEAVING THE STATION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B D1 = \sqrt{\frac{2(L_i + s_x)}{a_i(G_o)}} - \frac{v_j}{2b_j(G_i)} + \frac{B_s - s_x}{v_j} + t_o + t_r + t_{di}$$

EQUATION 15 DETERMINING $T_s{}^B{}_{D1}$ WHEN ETCS LEVEL 2 SIGNALLING IS USED OVER THE SECTION IF THE TRAIN REACHES THE SPEED LIMIT BEFORE LEAVING THE STATION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B D1 = \sqrt{\frac{2(L_i + s_x + B_n)}{a_i(G_o)}} - \frac{v_j}{2b_j(G_i)} + t_o + t_r + t_{di}$$

EQUATION 16 DETERMINING $T_s{}^B{}_{D1}$ WHEN ETCS LEVEL 3 SIGNALLING IS USED OVER THE SECTION IF THE TRAIN REACHES THE SPEED LIMIT BEFORE LEAVING THE STATION AND WHEN ADJACENT TRAINS USE THE SAME TRACK

$$T_S^B D2 = \frac{v_i}{a_i(G_o)} + \frac{L_i + s_x + B_n + B_{n-1}}{v_i} + t_o + t_r$$

EQUATION 17 DETERMINING $T_s{}^B{}_{D2}$ WHEN 3-ASPECT OR 4-ASPECT SIGNALLING IS USED OVER THE SECTION AND ADJACENT TRAINS USE DIFFERENT TRACK

$$T_S^B D2 = \frac{v_i}{a_i(G_o)} + \frac{L_i + s_x + B_n}{v_i} + t_o + t_r$$

EQUATION 18 DETERMINING $T_s{}^B{}_{D2}$ WHEN ETCS LEVEL 2 SIGNALLING IS USED OVER THE SECTION AND ADJACENT TRAINS USE DIFFERENT TRACK

$$T_S^B D2 = \frac{v_i}{a_i(G_o)} + \frac{L_i + s_x}{v_i} + t_o + t_r$$

EQUATION 19 DETERMINING $T_s{}^B{}_{D2}$ WHEN ETCS LEVEL 3 SIGNALLING IS USED OVER THE SECTION AND ADJACENT TRAINS USE DIFFERENT TRACK

A.2 COMPUTING LOST TIME

The lost time due to the expected overtaking time (*Tl*) is defined in Equation 20. Briefly the t_l equals half the absolute value of the difference between the time taken for the preceding train (t_i) and the following train (t_j) to travel between the start and end nodes.

$$t_l = \frac{1}{2}\left|t_i - t_j\right|$$

EQUATION 20 DETERMINING THE LOST TIME (T_L)

A.3 COMPUTING OPERATING MARGINS

The operating margins (t_m) are defined in Equation 21. Briefly the t_m equals the sum of the critical signal headway at the most bottleneck place (T_s) and the lost time(t_l), multiplied by the factor of operating margins (β), defaulted to 0.35 in accordance with the TRA model (Lai, et al., 2010).

$$t_m = \beta(T_s + t_l)$$

EQUATION 21 DETERMINING THE OPERATING MARGINS (T_M)

A.4 COMPUTING THE OPERATIONAL HEADWAY

The average operational headway (*h*) for each service pair (the headway between two train categories; see Table 6 all possible service pairs) is defined as a function of the critical signal headway at the most bottleneck place (T_s), the lost time due to the expected overtaking time (t_l) and the operating margins (t_m). The operational headway (*h*) is determined by Equation 22.

$$h = T_s + t_l + t_m$$

EQUATION 22 DETERMINING THE OPERATIONAL HEADWAY (H)

A.5 AVERAGE OPERATIONAL HEADWAY

The next step is to calculate the average operation headway ($\bar{h}$) over the section. This is calculated using a ratio of all the combinations of train service pairs defined by the user. The ratio of various combinations of trains is decided according to the number of trains of each category shown in Equation 23.

$$(\bar{h}) = \frac{1}{n^2}\sum_{i.j}((h_{ij}) * (n_i) * (n_j))$$

EQUATION 23 DETERMINING AVERAGE OPERATION HEADWAY (H^-)

Where:

h_{ij} = operation headway between type *i* and type *j* trains (in seconds)
n_i = number of *i* type of trains
n_j = number of *j* type of trains
n = total number trains

A.6 Computing Track Capacity

The next step is to determine the average trains per hour (TPH) for each track in a section. This is calculated by dividing 3600 by the average headway ($\bar{h}$) as defined in Equation 24:

$$Trains\ per\ hour = \frac{3600}{\bar{h}}$$

EQUATION 24 DETERMINE THE AVERAGE TRAINS PER HOUR (TPH)

A.7 Computing Section Capacity

If multiple tracks in one direction exist within a section, the TPH values of these are summed to give an overall capacity value along a section for each direction. These are defined in Equation 25 and Equation 26:

$$Section\ Capacity\ (TPH\ in\ the\ up\ direction) = TPH_{UP1} + TPH_{UP2} + TPH_{UP3} + TPH_{UPn}$$

EQUATION 25 DETERMINING SECTION CAPACITY IN THE UP DIRECT

$$Section\ Capacity\ (TPH\ in\ the\ down\ direction) = TPH_{DOWN1} + TPH_{DOWN2} + TPH_{DOWN3} + TPH_{DOWNn}$$

EQUATION 26 DETERMINING SECTION CAPACITY IN THE DOWN DIRECT

Appendix B.   Investment Option 1

B.1   INVESTMENT OPTION 1: HIGH LEVEL GOALS CAPABILITIES OUTCOMES

B.2   INVESTMENT OPTION 1: AFFORDABILITY OUTCOMES

B.3   INVESTMENT OPTION 1: AUTOMATION OUTCOMES

B.4   INVESTMENT OPTION 1: RESILIENCE OUTCOMES

B.5   INVESTMENT OPTION 1: ADAPTABILITY OUTCOMES

Appendix C.   Investment Options 2

C.1   INVESTMENT OPTION 2: HIGH LEVEL GOALS CAPABILITIES OUTCOMES

C.2 INVESTMENT OPTION 2: AFFORDABILITY OUTCOMES

C.3 INVESTMENT OPTION 2: AUTOMATION OUTCOMES

C.4   INVESTMENT OPTION 2: RESILIENCE OUTCOMES

C.5   Investment Option 2: Adaptability Outcomes

Appendix D. Investment Options 3

D.1   INVESTMENT OPTION 3: HIGH LEVEL GOALS CAPABILITIES PERFORMANCE OUTCOMES

D.2   INVESTMENT OPTION 3: AFFORDABILITY OUTCOMES

D.3 INVESTMENT OPTION 3: AUTOMATION OUTCOMES

D.4 INVESTMENT OPTION 3: RESILIENCE OUTCOMES

D.5   INVESTMENT OPTION 3: ADAPTABILITY OUTCOMES

Appendix E.   User Guide

Contents

1   Overview of the tool

1.1   PRINCIPLES

The Capacity Trade-Offs Analysis Tool (CTA) supports strategic investment decisions on infrastructure enhancements, operational strategies and technology deployment

The purpose of the tool is to allow railway operators and managers to investigate the impacts of introducing different strategies or innovations on a route (or network).

The tool enables a high level assessment of alternative options to improve capacity. Impacts are assessed considering a "whole-system" approach which looks at trade-offs among different capabilities.

For example:

Determine best way to …	… by doing …	… by comparing …
Get 50000 people an hour through Route A	Capability design trade-offs	High performance low capacity trains vs low performance high capacity trains
Get 300 people off the train every 3 minutes	System design trade-offs	Acceleration/braking vs number/size of doors

The use of such a tool is expected to bring significant savings to complex long term planning processes.

1.2 DESIGN OF TOOL

The CTA Tool features:

- Inputs
    - Defining the current and future route configuration
    - Defining the current and future capabilities through the answering of structured questions
- Calculations
    - The Tool estimates the line capacity based on the inputs
- Outputs
    - Visualisation of Outcome Measures

The main features of the Tool are shown in Figure 21.
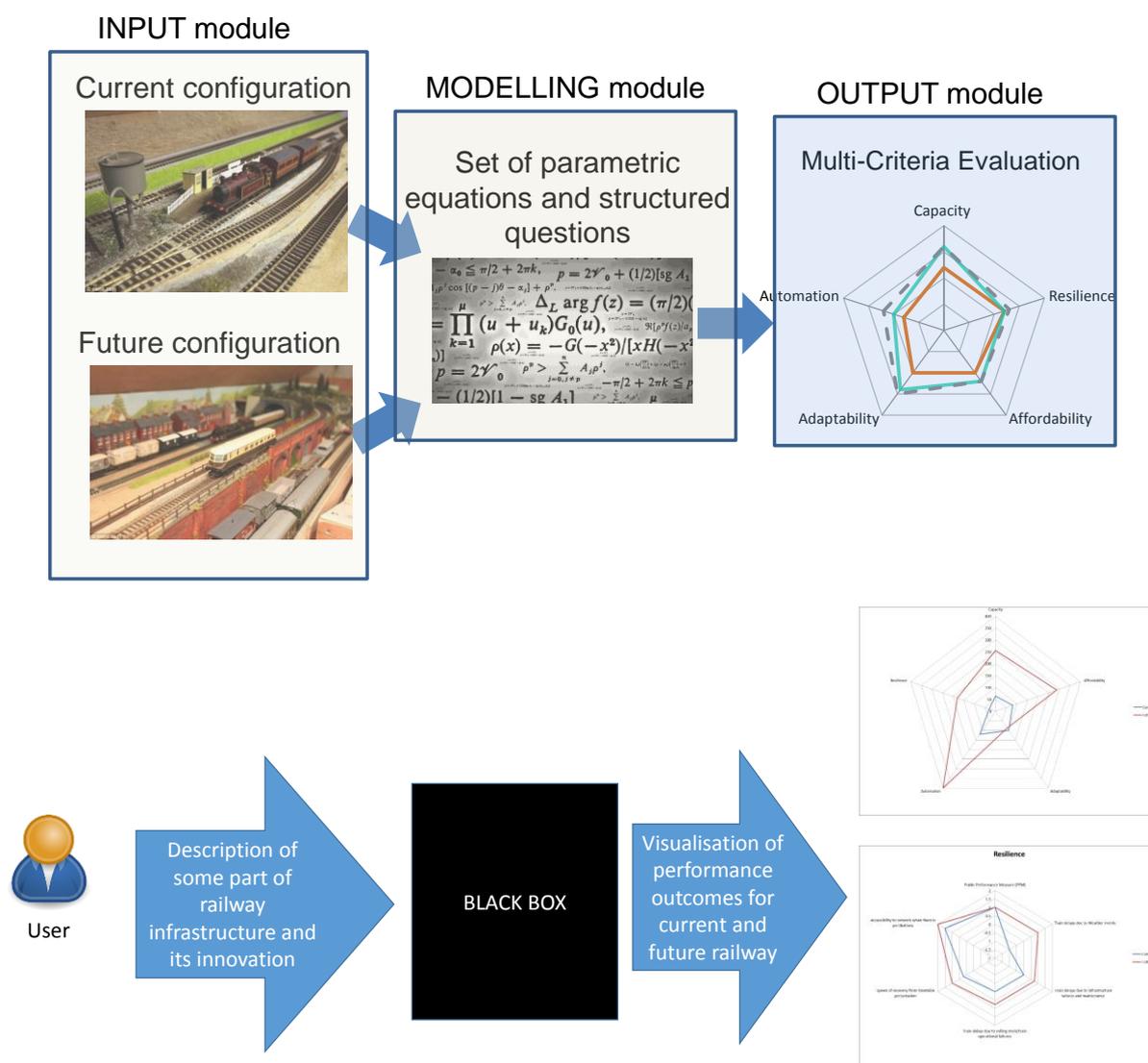
FIGURE 21. FEATURES OF THE TOOL

1.3 TYPICAL ANALYSIS WORKFLOW

The User defines certain improvements, or Innovations, for a route and enters information on the capabilities before and after the improvement is made. The tool carries out analysis of the data and provides a visual representation of the impact of the innovation.

Each analysis is carried out for a route divided into sections, with each section containing a link (one or more tracks) and two adjacent nodes (stations or junctions).

An overview of the process for creating and running an analysis is shown below in Figure 22 and is summarised as:

- The User defines the analysis section (Steps 1 to 3)
- The User inputs the current capabilities of the system (Step 4)
  - Infrastructure
  - Rolling stock
  - Operations
- The User inputs the future capabilities for each proposed improvement option (Steps 5 and 6)
- The User inputs information on the wider capabilities of the route before and after improvement (Step 7)
- The Tool reports (Step 8) on:
  - Impact on the Capacity of the section
  - Affordability of the 'option'
  - Relative costs/Life cycle costs
  - Changes in the Resilience and Adaptability of the section
  - Changes to Automation levels within the system
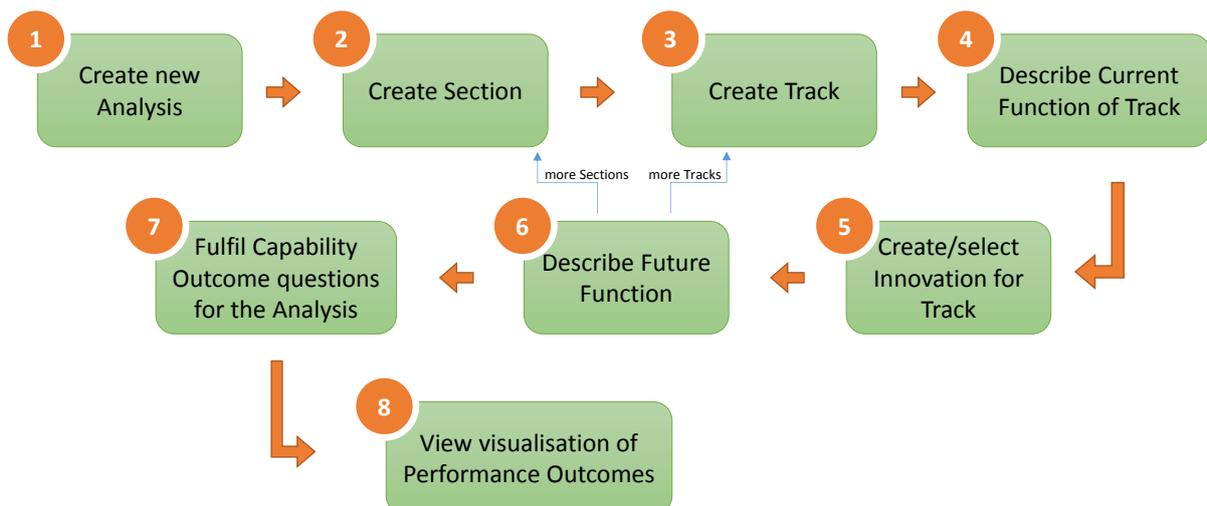
FIGURE 22. TYPICAL ANALYSIS WORKFLOW

2   Step by Step Guide
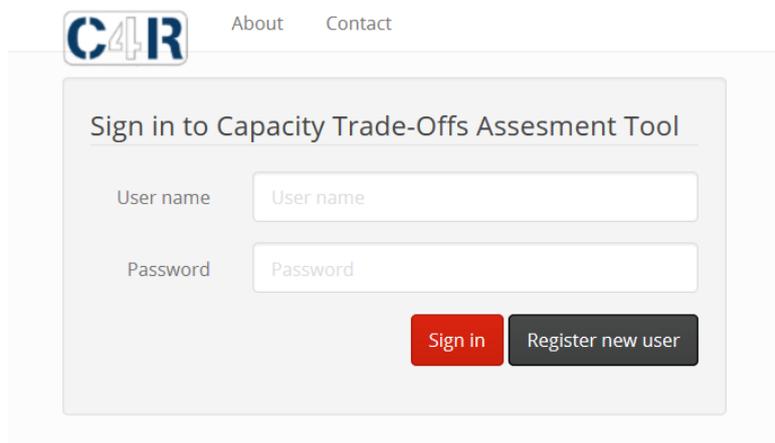
2.1   SIGN IN

FIGURE 23. SIGN IN SCREEN

2.2   CREATE NEW ANALYSIS/EDIT EXISTING ANALYSIS

1. On homepage, click on 'Create new analysis' or 'View Detail' for existing analysis
2. On 'New Analysis' page, shown in Figure 24, enter name and description of the route to be analysed
3. Provide target for capacity increase (%) on the route

FIGURE 24. NEW ANALYSIS SCREEN

4. When complete click OK, the analysis is added to the list on the homepage as shown in Figure 25.

FIGURE 25. LIST OF CREATED ANALYSES

5. To view information and edit an analysis, on Homepage click on 'View Detail' for the created analysis
6. Details, including target capacity increase and the State of the analysis (Incomplete, Complete etc) are shown under Analysis Detail in the top half of the screen, shown in Figure 26 .
7. Information on the Sections added are shown under **Sections**
8. Information on the Innovations (proposed improvements options) for each analysis are shown under **Innovation definitions**

FIGURE 26. ANALYSIS DETAILS SCREEN

2.3   CREATE NEW SECTIONS AND TRACKS

Key Information

- Each analysis is for a route comprising one or more sections, with each section comprising one or more tracks
- Stations and junctions are termed nodes
- Each track between the nodes is a link
- Every section contains a link and the two adjacent nodes at each of its ends
- Section names should include identification of the start and end nodes
- Track names should identify key information such as the speed and direction of line

1. On Homepage, click on 'View Detail' for the created analysis

Adding Sections:

2. Under **Sections**, click 'Add new section' and provide Section name. Section names should include identification of the start and end nodes
3. Click 'OK', and the section will be added to the list shown under **Sections**
4. Multiple sections may be required to be added for each analysis. Repeat the same process for each section required.

Adding tracks to each section:

5. Under **Sections**, click 'View Detail' on the required section from the list
6. Under **Tracks**, shown in Figure 27, click on 'Add new Track' and provide Track name. Track names should identify key information such as the speed and direction of line
7. Click 'OK', and the Track name will be added to the list shown under **Tracks**
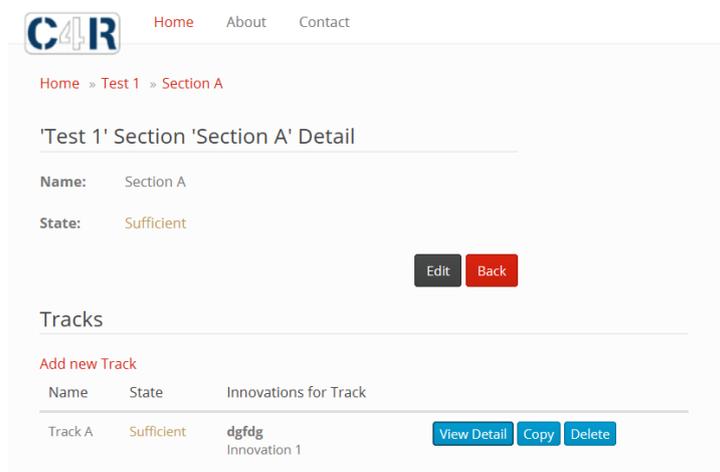
FIGURE 27. SECTION DETAILS SCREEN

2.4   DESCRIBE CURRENT FUNCTION OF TRACK
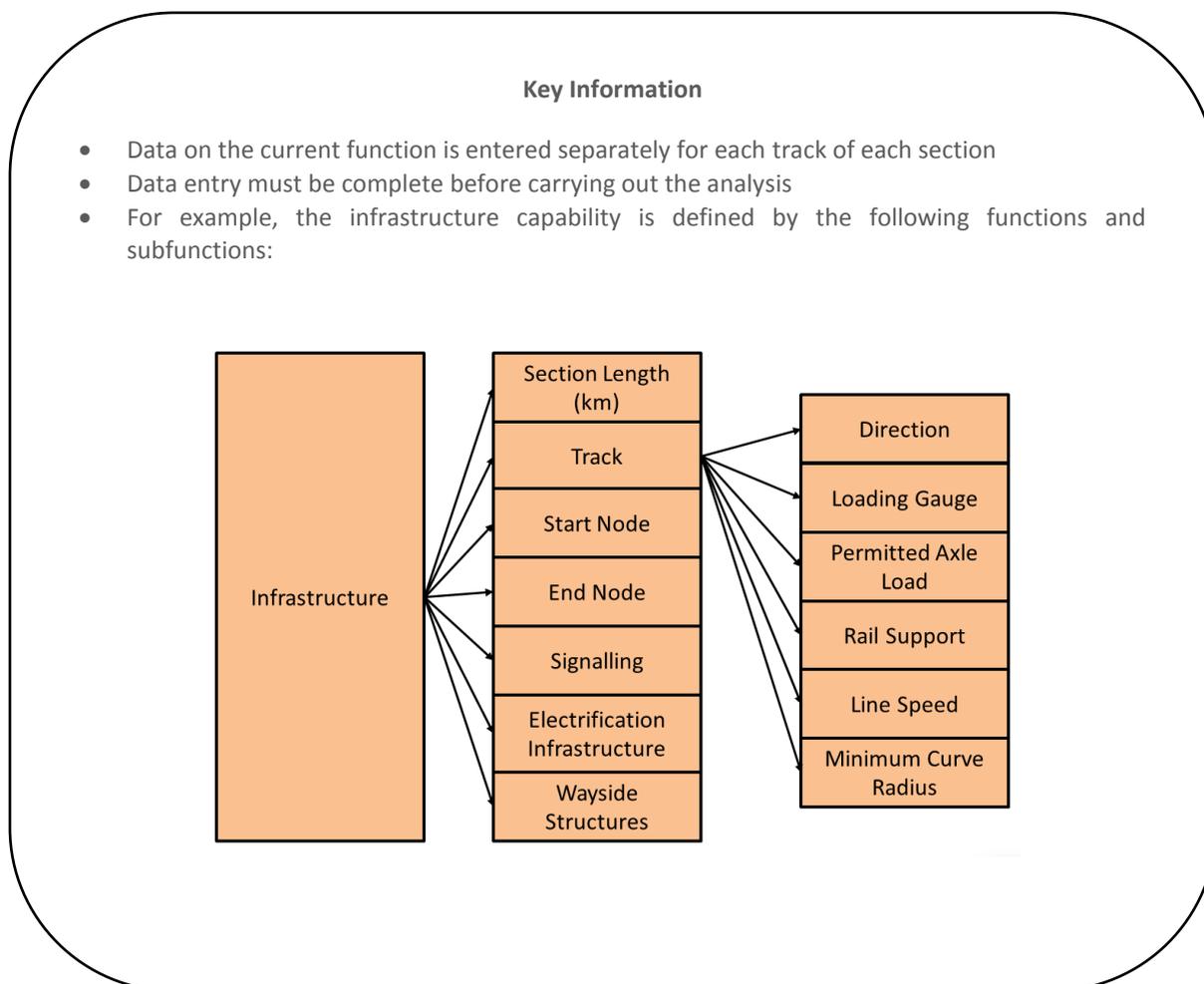
1. Under **Sections**, click 'View Detail' on the required section from the list
2. Under **Tracks,** click 'View Detail' on the required Track from the list
3. Click on 'Current Function'
4. The Current Functions input screen is shown in Figure 28. Enter data for each of:
    *   Infrastructure
    *   Scheduling
    *   Train category characteristics
5. Click 'Save & Next' after entering each Function data – any errors or missing will be highlighted in red
6. The status of the data entry is indicated as New/Sufficient/Incomplete/Complete
7. Repeat for each Track in analysis

FIGURE 28. CURRENT FUNCTION INPUT SCREEN

2.5 CREATE/SELECT FUTURE INNOVATION FOR TRACK

Key Information

- Improvement options, or Innovations, are created that are applicable to one or more of the Functions for each track:
  - o Infrastructure
  - o Scheduling
  - o Train category characteristics
- The created Innovations are assigned to one or more tracks for each analysis

Create innovation:

1. Under **Innovation definitions**, click 'Add new Innovation' and provide Innovation name and description.
2. Click 'OK', and the Innovation name will be added to the list shown under **Innovation definitions**
3. Under **Innovation definitions**, click 'View Detail' on the required Innovation from the list
4. Select the Function to which the Innovation applies, shown in Figure 29, by ticking the box for one or more of:
   - Infrastructure
   - Scheduling
   - Train category characteristics
5. For each Function, click '+' to view and select sub functions.
6. When selection is complete, click 'Save Functions'
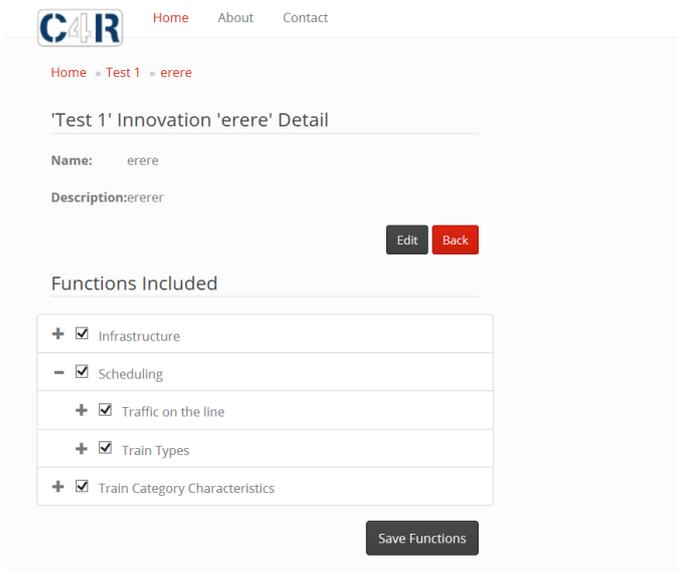
FIGURE 29. INNOVATION FUNCTION INPUT SCREEN

Assigning innovations for each Track

1. Under **Sections**, click 'View Detail' on the required section from the list
2. Under **Tracks**, click 'View Detail' on the required Track from the list
3. Under **Assigned Innovations**, as shown Figure 30, select the required innovation from the drop down menu and click **'Assign Innovation'**
4. The innovations assigned to each Section are listed on the screen under **Assigned Innovations**
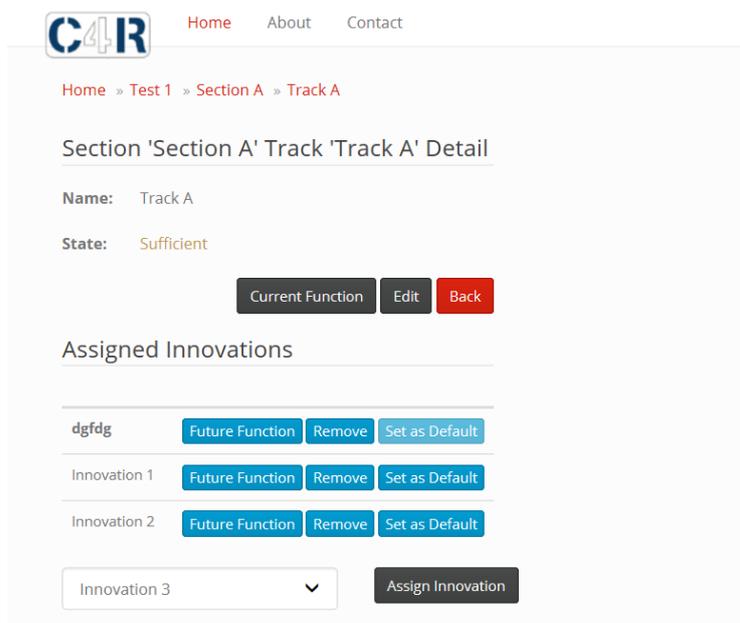

FIGURE 30. ASSIGNED INNOVATIONS TO SECTION

2.6   DESCRIBE FUTURE FUNCTION

Key Information

- For each Track to which Innovations are applied, the User defines the Future Functions after applying the Innovation.
- New values are inputted for the Functions to which the Innovation applies (selected when creating the Function).

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1. Under **Sections**, click 'View Detail' on the required section from the list
2. Under **Tracks**, click 'View Detail' on the required Track from the list
3. Under **Assigned Innovations**, select 'Future Function' on each of the assigned Innovations
4. Input the new values for the Functions, click 'Save & Next' after entering each Function data – any errors or missing will be highlighted in red

2.7   CAPABILITY OUTCOME QUESTIONS FOR THE ANALYSIS

Key Information

- In addition to the Capacity calculation, the Tool enables the inputting of information relating to wider capabilities including:
    - Affordability
    - Adaptability
    - Cost
    - Automation
    - Resilience
- The User completes a series of structured questions for each analysis, defining the current and future capabilities under the above headings

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1. Under **Analysis Detail**, click 'Capability Home'
2. Click on the green button for each of the capabilities and complete the series of questions identifying the future and current capabilities shown in Figure 31.
3. Click OK after completing each set
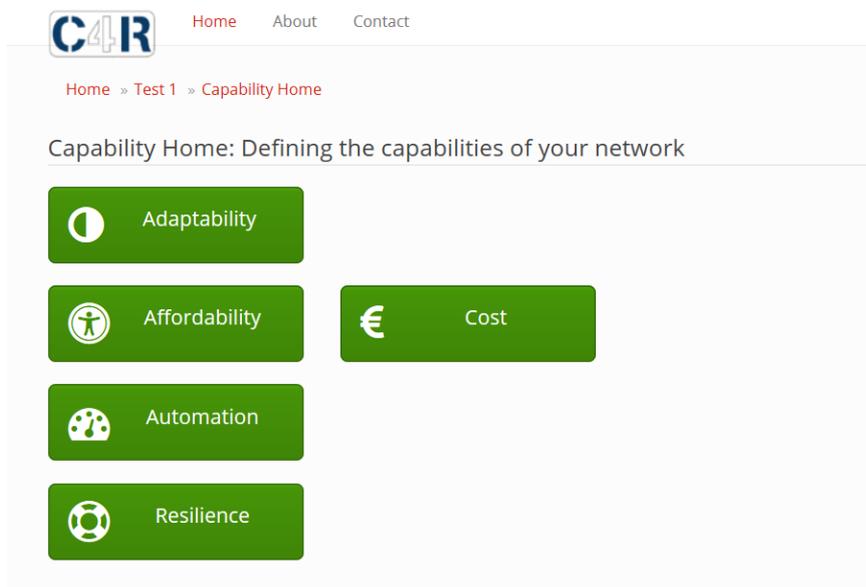
FIGURE 31. INPUT SCREEN FOR DEFINING CAPABILITIES

2.8 REPORTING OF PERFORMANCE OUTCOMES

Key Information

- After completing entry of all required data, the Tool provides a visual output of the impact of improvement options for each of the Capabilities:
  - Capacity
  - Automation
  - Resilience
  - Adaptability
  - Affordability
- The target for capacity increase entered by the User provides a reference point for comparison of the Capacity output.
- The User can choose to view the output for each Capability separately.

To view performance outcomes:

1. Under **Analysis Detail**, click 'Chart'
2. The Current and Future values for the performance outcomes are displayed on a diagram, and the Capacity target indicated by the green circle
3. To view the detailed breakdown of information, click on the blue buttons at the bottom of the screen for each Capability.
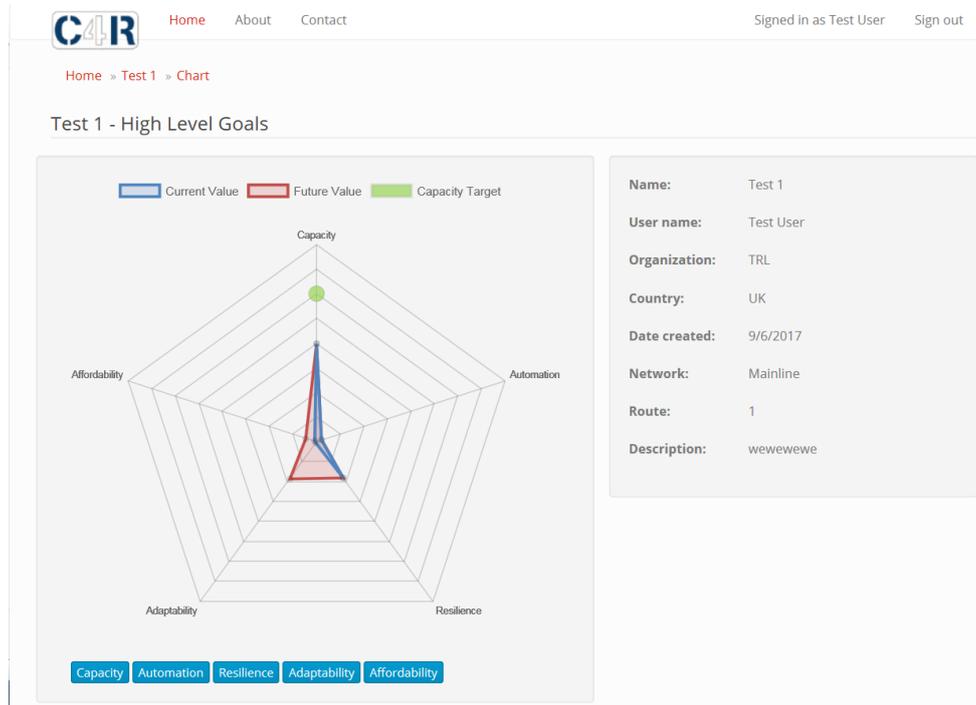
FIGURE 32. VISUALISATION OF PERFORMANCE OUTCOMES