In2Rail

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Deliverable D3.4

Guideline for the Evaluation and Selection of Innovative Track Solutions

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Executive Summary

This report seeks to develop a guideline for the evaluation and selection of innovative track systems. To this end a range of assessment criteria and developmental track systems were identified, guidelines for evaluation produced and an example holistic analysis undertaken.

The main findings from the exercise are covered in chapters 5-8.

Chapter 5 identified a range of key performance indicators developed in D3.3 and described how they could be broken down and used as assessment criteria.

Chapter 6 identified a range of developmental innovative track systems. Each system was assessed with the strengths and weaknesses being discussed and a method for system categorisation demonstrated.

Chapter 7 provides guidelines for the evaluation and selection of innovative track systems. It covers system methodology, requirements, competence, assessment criteria, value and option analysis.

Chapter 8 demonstrates an example review of a short list of track systems consisting of new and existing trackforms.

The deliverable concludes that the evaluation and assessment of innovative track systems is a complex process that benefits from using a guideline process to ensure that the assessment is carried out in a manner that is transparent and free from bias.

Based on the exercise undertaken as a part of this deliverable the following systems were found to score highly and should be put forward for further investigation/development in the wider Shift2Rail project:

1. BB Embedded Rail
2. Japanese slab track
3. GETRACK Sleepers on asphalt

It must however be noted that the evaluation was limited in some respects for the purpose of the deliverable. The degree of information available for the systems varied depending on how advanced they were in their technical development. It cannot be guaranteed that should the same analysis be undertaken for a more defined scenario with detailed supporting data then the results would be the same.

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Abbreviations and acronyms

Abbreviation / Acronyms	Description
CAPEX	Capital expenditure
KPI	Key performance indicator
LCC	Life cycle cost
OPEX	Operational expenditure
RAMS	Reliability, Availability, Maintainability and Safety
SD	Standard Deviation
SFT	Stress free temperature
TRC	Track Recording Car

1 Background

This document "Guideline for the Evaluation and Selection of Innovative Track Solutions" D3.4 will describe and demonstrate a process by which innovative track systems can be evaluated.

The European rail networks have seen sustained levels of growth that is projected to rise for the foreseeable future. This increased in demand has also put pressure on a network that is, in places, near its capacity.

This success has not come without drawbacks. The cost of maintaining and upgrading the infrastructure to meet the existing demands has grown substantially and step changes need to be made to the way we operate our rail networks.

Some of the challenges the railway faces going forward are:

- **Political**: providing fit for purpose infrastructure systems that allow businesses to develop and grow;
- **Economic**: the need to provide maximum value for money, business models for future growth;
- **Social:** moving passengers and freight away from road congestion and encouraging business customers to reduce their carbon emissions;
- **Technical**: constructing an infrastructure capable of handling increased speeds, higher loads, that's safer for all users with limited, track access time for maintenance.

In order for the railway to continue to grow and meet these challenges it needs to consider how it approaches the design and construction of infrastructure and seek to incorporate and benefit from the use of new technology.

2 Objective / aim

In2rail is a lighthouse project for Shift2rail, whose overall objectives are to:

- enhance the existing CAPACITY fulfilling user demand of the European rail system;
- increase the RELIABILITY delivering better and consistent quality of service of the European rail system;
- reducing the LIFE CYCLE COST (LCC) and increasing competitiveness of the European rail system and European rail supply industry.

The work reported in the current deliverable belongs to the In2Rail group Smart Infrastructure – Innovative Track Solutions.

The current Deliverable, D3.4 together with Deliverable D3.3, relates to the two In2Rail tasks T3.4 "Hybrid track systems" and T3.2 "Optimized ballast track system". Objectives of these tasks as indicated in the In2Rail Description of Work are:

1. establish the current technical status of potential track form enhancements;
2. identification of relevant key performance indicators (KPIs) and potential to influence key KPIs by innovative solutions;
3. evaluation of selected modifications including simulations and physical testing towards an optimized track system;
4. logistics and production considerations and LCC estimates of short and long-term benefits;
5. selection of track elements (including transition zones) for further consideration;
6. holistic assessment of enhanced solutions;
7. establishment of evaluation framework and recommendations for solutions/concepts to be further investigated in Shift2Rail.

Here, Deliverable D3.4 targets mainly items 6 and 7 and more specifically aims to provide the reader with:

- the definition of a "Hybrid or Innovative" track system;
- a range of potential innovative track systems;
- guidance on the identification and use of key performance indicators;
- guidance on the evaluation and selection of innovative track systems;
- a worked example, demonstrating the evaluation process and subsequent recommendations for systems/concepts to be developed in Shift2Rail.

3 Introduction

The construction and renewal of track is an expensive and disruptive process and one that is often considered after all other methods of extracting performance from the system have been considered.

Ballast track has to a large extent been optimised as far as it can go. The returns on investment are reducing and it's becoming increasingly necessary to consider a step change in the way we construct track systems and incorporate innovative technology.

Whilst the benefits of installing slab track and other types of innovative track form are broadly recognised they are often overshadowed by the increased initial capital expenditure and the need for a quick return on the investment.

Moving away from the constraints of ballast track is always going to be difficult. Hundreds of years of experience have focused the rail business on the installation optimisation and maintenance of ballast track systems. However with the increasing demands being placed on the rail infrastructure it's absolutely necessary consideration be given to alternative technologies.

Therefore given the wide range of existing and developmental systems available, there is a need for the development of an objective, robust and transparent guideline for the selection and evaluation of innovative track systems if maximum value is to be obtained.

We have therefore attempted in this deliverable to describe a process by which innovative track systems can be objectively and transparently evaluated.

3.1 The Need for Innovation

Railway track systems are complex and constructed from a range of components and engineering materials.

As the rail network has evolved the constituent components used to construct track systems have been improved and optimised. For example, the modern rail pad has evolved from felt to rubber, rubber to bonded cork and more recently to the advanced closed cell micro cellular polyurethanes in use today.

The evolution of these products is recognised as the product life cycle and is illustrated in Figure 3.1.

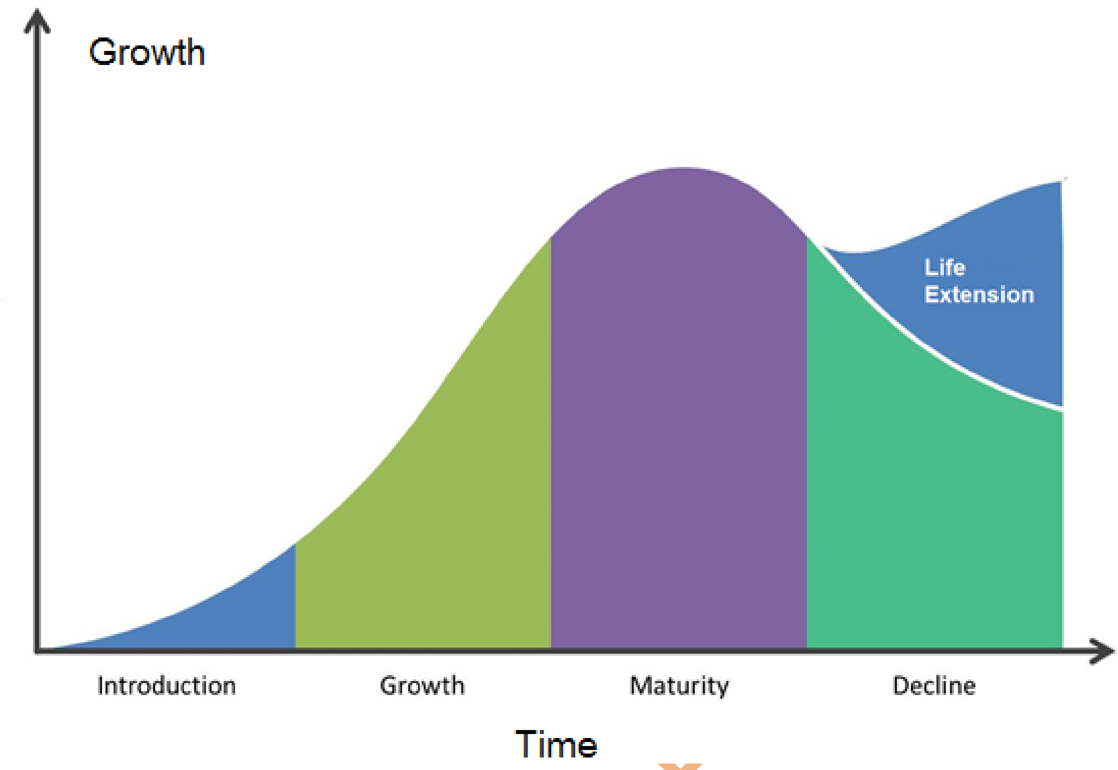


Figure 3.1: Product Life Cycle

There are four key stages in the product life cycle, namely:

- **the Introductory stage** which is expensive and the market for the product may be small. A key aspect of this stage is research and development;
- **the Growth stage** is where the sales and profits begin to increase as the product confidence grows and becomes integrated into the system;
- **the Maturity stage** is where the product is established and is the most competitive time for the product;
- **the Decline stage** is where the market for the product decreases due to customers having already bought the product, switching to a different product, component or system;
- **life extension** is where interventions are made to prolong the decline stage of the life cycle.

It can be convincingly argued that Ballasted Track and its component products have been continuously enhanced for over 200 years and further improvements now require greater effort for smaller returns.

In an attempt to avoid increasing ballasted track life cycle costs many ideas have been tried. These ideas have included adoptions from non-ballasted track, the automotive industry and highways. High profile adoptions include booted sleepers, asphalt, under sleeper pads, polymer reinforced ballast, and concepts such as glued ballast, injected foam, and aerodynamic sleepers.

In tandem with the above ideas, several maintenance practices and equipment have been developed such as stone blowers, high output track renewal trains, ballast shoulder cleaners and railhead profilers.

These individual product enhancements are life extensions, designed to not only optimise performance but to extend the final decline stage of the ballast track system. These enhancements have tended to increase the cost to the point where the main asset of ballasted track i.e. its low first installed cost, has become eroded.

As the demands placed on ballast track grow and the cost of maintaining and extending the life of the asset increases, the argument to move to Hybrid or Innovative track systems (Herein after referred to as "innovative track systems") becomes more economically viable.

3.2 Track System Definitions

For the purpose of Task 3.2 and 3.4 a clear distinction is made between what is classed as an "Optimised ballast track" system and what is classed as a "Hybrid or Innovative" track system. Therefore, the following definitions have been applied.

3.2.1 Optimised Ballast Track

"Optimised" ballasted track can be considered as traditional ballasted track with minor enhancements or changes.

That is, existing ballast track systems that incorporate technology at the construction/renewal stage or retrofitted for the purpose of reducing maintenance.

A range of optimisation technologies were described in In2Rail D3.3 and categorised on whether they were primarily intended to reduce differential rail head alignment or increase lateral stability (although some aspects may be applied in either context and so feature in both lists).

Examples of Optimised track systems/solutions could include:

- Under Sleeper Pads (USP);
- Lateral Resistance Plate (LRP);
- Ballast Mat;
- Geogrid reinforcement;
- Shaping the sleeper and ballast profiles.

3.2.2 Hybrid Track

"Hybrid" or "Innovative" track systems/solutions shall be considered those systems or concepts that introduce a step change from traditional ballast track.

Generally speaking "Hybrid" or "Innovative" track systems/solutions are those that incorporate new or radical technologies at the point of construction or renewal. The introduction of technology is often used to manage a specific performance barrier or to unlock otherwise hidden benefits.

Examples of Hybrid or Innovative track systems/solutions could include:

- Grouted ballast;
- Asphalt track;
- Types of novel slab track;
- Embedded Rail;
- Ballast & Polymer Geo-composites.

4 Relationship to In2Rail Deliverable D3.3

This section will provide an overview of the work in Deliverable D3.3 together with a summary of the main results. Details are provided in the full report.

The main objective of D3.3 was to investigate how ballast track systems can be optimised. The report set out with an overview of recent development in track design. Thirteen high-profile problem areas for railway tracks are then assessed in an overview manner with focus on influence of track type / track design. Five areas were then selected for in-depth investigations. These areas were:

- Differential track settlement – where in particular track modifications to reduce differential vertical settlements are assessed;
- Lateral track stability and lateral track resistance – where numerical simulations are carried out to assess the influence of track characteristics on the risk of track buckling;
- Ballast flight – where different solutions were analysed;
- Transition zones – where a recent superstructure innovation was investigated;
- Rail corrugation – where numerical simulations were used to investigate the influence of track design parameters on corrugation growth in a small radius curve.

The investigations included logistics and production considerations and outlined relevant Key Performance Indicators (KPI). The report concluded with an outline of a method for LCC and RAMS analysis with limited input data. This included qualitative assessments of two innovation categories.

4.1 Relationship between approaches In2Rail D3.3 and D3.4

The technical focus in D3.3 is to identify key areas and evaluate these with in-depth analyses. The result is an enhanced knowledge, definition of key performance indicators, and conclusions for development and assessment of track structures.

The focus in D3.4 is to summarize in guidelines the findings in D3.3, and to establish a methodology for a wider overview assessment where a wide range of aspects are investigated.

Features and pros and cons of the two approaches are discussed in chapter 7. It is emphasized that these two assessment approaches interact in that the overview assessment can be complemented by detailed analyses, where key aspects are investigated more in detail to improve the assessment and/or identify means to improve track characteristics.

4.2 Key performance indicators proposed in In2Rail D3.3

An important part of the in-depth investigations in Deliverable D3.3 was the identification of key performance indicators (KPIs). For the different areas the identified KPIs were:

KPI	Aspects covered include	Note
Differential Track Settlement	The evolution of measured track geometry considering variabilities in stiffness along the track and the rail support stiffness along the length of track, the ease of using traditional maintenance method, the adverse implication on other track components and sustainability.	The chapter includes a qualitative assessment of potential modifications towards these KPIs
Lateral Track Stability	Number of track buckles (normalised per time, per track length) and considering overall lateral track resistance; track irregularities or local reduction in track resistance; difference between actual SFT and prescribed SFT and quality of maintenance. Ease of maintenance by traditional methods, adverse implications on other track components and sustainability.	The chapter includes a qualitative assessment of potential modifications towards these KPIs
Ballast Flight	Probability of ballast flight at operating speed and conditions, installation time, average maintenance time, LCC/Initial cost per km, aggregated LCA indicator and aggregated (health and safety) risk assessment.	
Transition Zones	Global Track stiffness, track stiffness variations and gradients, (evolution of) measured track geometry quality, vehicle base response, Track observations and dynamics response.	

Table 4.1: KPIs identified for thedifferent areas

4.3 Conclusion Summary from D3.3

In summary the main conclusions from D3.3 are:

- technical, LCC and RAMS characteristics of a variety of existing slab track systems show the complex picture in comparing systems;
- under sleeper pads, modified sleeper shape, fibre reinforced ballast and the re-use of "life expired" ballast are shown to have some potential benefits in terms of the key performance indicators regarding differential settlements;
- a method for using continuous track stiffness measurements to establish root causes for track geometry degradation was developed;
- a method to use numerical simulations to analyse the influence of various parameters on the risk of track buckling and translate the influence to equivalent temperature increases has been developed;

- a first study of ballast flight prevention solutions has been carried out and further studies in Shift2Rail are proposed;
- a method for transition zone mitigation was investigated and it was shown that stiffness gradients were not prevented, but that the loading of sleepers in the transition zone was low;
- for corrugation in sharp curves, properties of the rail pad, vehicle speed, transverse rail geometry and friction levels were found to be important;
- Relevant LCC and RAMS parameters have been quantified and a model for estimations has been performed.

5 Key Performance Indicators (KPI's)

Key performance indicators (KPIs) are measurable values commonly used on the railway to gauge the success of a function and are generally linked to strategic goals. It therefore makes sense to use KPI's as high level criteria in the evaluation and selection of innovative track systems.

In2Rail Deliverable 3.3 has focused on categories of performance known through experience to be critical to the success of a track system and has identified KPI's relevant to the assessment of optimising trackform concepts. As part of D3.4 we have summarised the relevant parts of that work and expanded where possible, given our limited resources.

The work carried out for the wider In2rail project considers future developments in performance monitoring, which would be achievable through some level of technological development. However, at least initially, the (Global) KPIs used to assess track systems considers aspects of performance monitoring for which measuring systems and data already exist.

Where possible "Global" performance measures have been broken down into "Contributing" performance measures for which there are known values and measurement methods. It is also the case that for some contributory performance measures the deployment of technology has allowed for improved data capture. For example it is not generally the case that track stiffness is measured on a network wide basis, but because this is at least starting to be measured on some networks (e.g. Sweden) and local trackside measurements have been carried out we are able to include KPIs related to measurement of track stiffness.

To help develop the guidelines for the identification of assessment criteria used in the evaluation of track systems, the definitions shown in Table 5.1 have been applied to demonstrate the approach taken to KPI's.

Term	Definition
Category	An aspect of the track system that is critical to its overall success e.g. Differential Settlement, Whole Life Cost or Deliverability.
Global KPI	A high level quantitative or qualitative indicator of performance already routinely implemented and used to plan maintenance activities e.g. Track quality.
Contributing KPI	A part of the track system that can be directly measured and may be targeted for a specific maintenance intervention.

Table 5.1: KPI Definitions

The following KPI's were identified and detailed in In2Track D3.3 and can be considered relevant to the potential success of an innovative track system:

- differential settlement;
- lateral track stability;
- transition zones;

- rail head defects;
- LCC & RAMS.

In addition to the KPI's identified in D3.3 and based on the skills of the Task3.4 workgroup we have also considered the following categories:

- noise and vibration;
- construction and deliverability;
- system compatibility.

Table 5.2 demonstrates how those KPI's can be tabulated. This list is in no way conclusive and simply provides an overview of the complexity of defining KPI's.

Category	Global KPI	Contributory KPI
Differential Settlement	Track quality.	Track stiffness
		Propensity to settle
Lateral Track Stability	Resistance to lateral load/misalignment of the trackform.	Difference between target and actual stress free temperatures
		Incidence of speed restrictions or other controls being applied
		Lateral track resistance
Transition Zones	Rate of change of stiffness (and/or resulting rate of change of measured/calculated rail deflection).	Length of transition as a function of traffic speed and end stiffness difference
		Maintaining peak pressure at any sleeper connection within TZ below that of adjacent plain line.
		Maintaining sleeper vertical acceleration below a reasonably low value (<5g).
		Maintain ballast confining pressure to a high consistent value.
Performance – Wheel/Rail Interface	Rail Head defects	Propensity to develop Corrugation and surface initiated rolling contact fatigue.
Value	RAMS	Reliability
		Availability
		Maintainability
		Safety
	Life Cycle Cost	Capital cost
		Operating costs
		Maintenance costs
		Renewal/termination costs
Noise & Vibration	Acoustic radiation	Decibel value
	Vibration transmitted to the ground	Settlement
Construction & Deliverability	Feasibility	Availability of materials
		Timescales
		Availability of resource

Category	Global KPI	Contributory KPI
Compatibility	Compatibility with existing equipment	Fastening systems
		Expansion switches
		Insulated bonded joint
		Switches and crossings
	Compatibility with future equipment	Accessibility to track components
		Space available for installation
	Compatibility with infrastructure	Compatibility with embankments
		Compatibility with civil strictures

Table 5.2: KPI Breakdown

Annex A of this document provides further information relating to the KPI's listed on Table 5.2.

6 Innovative Track System Review

To ensure that value for money is achieved it is necessary for the evaluation group undertaking the assessment to familiarise themselves with all available options, so that systems/solutions are not unduly discounted.

The option shortlist should include tried and tested systems so that a value base line can be established and indicate potential improvements coming from the use of newer and less developed systems.

As with any high value project that involves public or stakeholder investment transparency must be maintained, so there can be no accusation of bias or impropriety.

An important point to remember is that all systems, either existing or developmental must be able to satisfy a number of high level key functions, namely:

- ensure the safe passage of railway vehicles;
- provide lateral guidance to railway vehicles;
- provide support to railway vehicles and to distribute the loading through the trackform and into its supporting ground or structure;
- maintain stability under loading and exceptional environmental conditions;
- provide a high standard of ride comfort;
- ensure an acceptable minimum design life.

6.3 Developmental Innovative Track systems

As part of the deliverable we have identified a range of innovative track systems that are currently under development, including systems proposed within the Capacity4rail project. Supporting information for these systems is limited and therefore we have where necessary, used our experience as experienced railway engineers and academics to provide a brief system overview. The following track systems were identified and considered suitable for inclusion in this document:

- direct fixing to asphalt;
- grouted Ballast;
- Precast and Pre stressed Slab with Elastomer and Self levelling Mortar;
- Embedded Rail Track (ERT);
- Multi Modular Multi Block track (3MB);
- Systra Beam track;
- Tata Steel track;
- Asphalt under Ballast.

6.1.1 Direct Fixing to Asphalt

6.3.1.1 Diagram

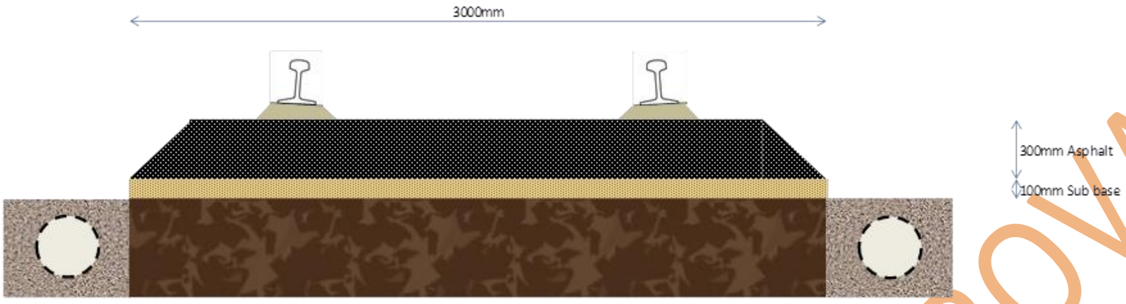


Figure 6.1: Direct Fixing to Asphalt

6.3.1.2 Direct Fixing to Asphalt - Description

Direct fixing of the rail to an asphalt slab removes the need for ballast and associated ballast maintenance activities and renewals. The asphalt slab evenly distributes the load from the rail to the subgrade, reducing localised areas of settlement and maintaining track quality longer.

The slab is 3000mm wide, 300mm deep and laid over a 100mm compacted layer of granular sub base material. The rail geometry is set using a top down approach and the fastening is grouted into place.

The production of the asphalt mix takes place in either mobile or static mixing plants. After production the hot asphalt mix is transported to the site in insulated trucks. On site, application takes place using pavers that place and partially compact the material to the required thickness and width, following which final compaction is achieved using rollers.

Hot mix asphalt is a combination of mineral aggregate and bitumen. By varying the composition of the mixture, the ratio of the various constituents and the particle size distribution of the aggregate, the properties of the eventual mixture can be adapted to suit the specific requirements of the construction. The asphalt mixture may be either stiff and of high stability or, on the other hand, very flexible.

The use of special additives or of polymer-modified bitumen offers the possibilities of complying with specific requirements (e.g. heavy duty, lower temperatures and noise/vibration reduction) for the mixture or the construction.

Due to its specific material properties, asphalt can be suitable for slab track structures. The asphalt mixtures may require modification compared to the mixtures used for roads, as road construction requires specific surface properties i.e. high friction-resistance and resistance to wear and tear. In the case of ballastless superstructures, the asphalts resistance to deformation and stability are the priority.

6.3.1.3 Direct Fixing to Asphalt - Assessment

The use of asphalt in railway construction provides a positive contribution to the bearing capacity of the structure. It improves both the stability and the durability of the structure, which contributes to the reduction in the need for maintenance. In addition, the use of asphalt also contributes to the reducing in noise and vibration.

One of the most important requirements for this type of construction is to ensure that there a perfectly flat and level surface in order to comply with the narrow tolerances that are required for the rail level (+/- 2 mm). Whilst grout is used between the fastening and the asphalt it is not designed to make up large gaps. Modern asphalt laying machines are more than capable of achieving this requirement as they able to make use of the most sophisticated levelling equipment.

As this system eliminates the use of ballast it has the great advantage of lowering the track base. This is import when considering application to tunnels and bridges and also fits with the need to be more environmentally friendly and reduce our carbon footprint.

6.3.1.4 Direct Fixing to Asphalt - Strengths

- asphalt can be paved without joints due to its viscoelastic characteristics;
- asphalt can be paved at a precise tolerance (± 2 mm);
- asphalt does not require hardening and can be subjected to loading immediately after cooling, so high construction productivity can be achieved;
- corrections in the position that may be needed (e.g. due to settlement of the embankment) can be quickly and easily made either by milling off or by putting on another layer of asphalt;
- the lifetime of the asphalt railway trackbed has been estimated to be approximately 60 years;
- as the system eliminates the need for ballast it has the advantage of lowering the track base, which is of importance in the case of tunnels and bridges. This lowering of the track base additionally reduces the quantity of materials required and transport which I turn reduces the overall cost;
- the asphalt slab is impermeable and water can be controlled and directed away from the sub base to a suitable drainage system;
- the construction of this type of system makes use of existing construction technology (paving machines) that are well known in road construction and doesn't require further plant development.

6.3.1.5 Direct Fixing to Asphalt - Weaknesses

- asphalt rigidity in changing temperatures and in service and under both lateral and vertical loading. The ability to retain the track / rail head geometry is critical to the safe operation of the traffic;

- the method of anchoring the rail to the asphalt (element in charge of restraining transverse movement of the track and in charge of joining the asphalt with the rail track) is not yet fully developed;
- the asphalt installation process is sensitive (range of temperature after mix, temperature minimum after truck unloading, temperature minimum of the mix before compaction, etc) to the temperature requirements of the asphalt material and requires strict control;
- the costs coming from the renewal of the material and from the punctual settlement (or any critical defect) is higher in comparison to the costs in comparison to standard ballast track construction;
- the carbon footprint: The asphalt composition has 5% bitumen content which is composed by a highly percentage of carbon, around 82%;
- there is a risk that the asphalt could creep due to it's a thermally reactive material.

6.3.2 Grouted Ballast

6.3.2.1 Grouted Ballast – Diagram

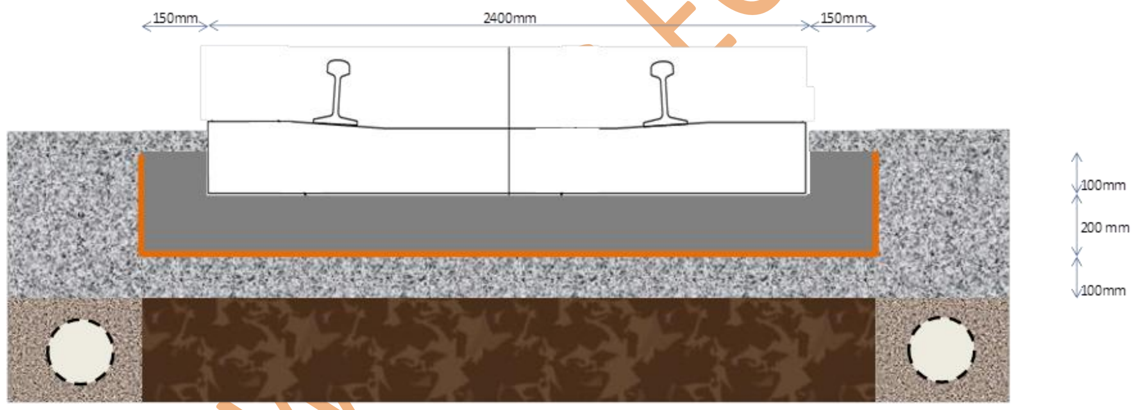


Figure 6.2: Grouted Ballast

6.3.2.2 Grouted ballast - Description

Grouted ballast track combines a cementitious grout with a standard ballast track construction.

The cementitious grout is applied to the upper layer of ballast from the top down. Due to the grouts viscosity it's able to flood the voids between ballast particles. When the grout has cured it locks the ballast particles in place and prevents friction induced degradation of the ballast particles, thereby maintaining the designed track geometry better and distributing wheel loads to the subgrade more uniformly.

The grouted ballast track system is constructed using the following steps:

1. The subgrade is prepared in a manner typical for ballast track.
2. A ballast sublayer is laid and compacted.
3. A containment membrane is laid 200mm below the sleeper.

4. A second layer of ballast is laid and the sleepers are set out.
5. Tamping of the ballast is undertaken to set the correct track geometry.
6. The track is opened to traffic for a period of one month to allow for consolidation of the ballast.
7. Tamping is carried out to achieve final track geometry.
8. Grout is applied to ballast.

6.3.2.3 Grouted ballast - Assessment

The application of cementitious grout to an in situ ballast track system provides the benefit and performance gains of a slab track system but at a greatly reduced cost. The key benefits come through the system's ability to retain accurate track geometry and the improved distribution of load to the sub structure.

The planning and application of routine track maintenance is typically driven by the degradation in track quality. That is as the track geometry becomes less accurate there is an increased need to intervene with some form of maintenance, typically tamping and ballast cleaning. These actions in themselves reduce the life of the ballast and require the frequency of maintenance to be increased until the asset is renewed.

As traffic passes over the ballast the angular contact patches between the ballast particles are subject to friction. Over time these contact points wear away, becoming rounded and allowing the ballast to move more. This in turn leads to the generation of ballast dust which settles at the bottom of the ballast layer and as it gets wet, reduces the draining capability of the ballast.

The application of a grout secures the ballast in place and prevents movement. This reduces the rate at which the geometry degrades and lessens the need for maintenance interventions.

The grouted ballast layer is impermeable water and can be optimised to remove rainfall from the track system efficiently assuming there is a sufficient drainage system. In areas subject to heave and shrinkage the ability to manage the amount of groundwater is a positive benefit.

Repair and removal of such systems can often be a blocker to their wider use. However there are many established techniques for in situ grout repair and for controlled jacking to level areas of settlement

Unlike standard heavy duty slab track systems when the time comes to remove the track, either for renewal or repair, it's relatively straightforward and can be undertaken using standard plant equipment.

6.3.2.4 Grouted ballast - Strengths

- uniformly distributes wheel loads to subgrade and reduces overall stress on formation;
- reduced track geometry degradation leading to reduced need for maintenance;
- impermeable layer allows for better water management from rain and stabilises ground water levels;
- the system is simple to construct and uses existing plant;
- the grout secures the sleeper in place and increases leave of lateral stability;
- reduced levels of flying ballast;
- able to achieve and maintain high levels of track geometry;
- easy to remove in comparison to concrete slab track;
- requires minimal earthwork preparations;
- provides bridging against minor vertical alignment changes;
- makes use of existing sleepers and fasteners.

6.3.2.5 Grouted ballast - Weaknesses

- the grout lacks reinforcement and could crack if subject to high impact loads;
- there is an increased carbon footprint;
- minimal increase to contraction time and cost;
- repairs to grout are time consuming;
- major adjustments to track geometry are costly and time consuming;
- requires suitable drainage works to prevent voiding.

6.3.2.6 Grouted ballast Opportunities

- offset increased carbon footprint by recycling ballast and sleepers on site;
- offset construction cost through reduced need for ballast maintenance such as cleaning and tamping;
- development of different grouts for specific conditions;
- use of dynamic stabilising could remove the need for follow up tamping and allow for opening at line speed.

6.3.3 Precast and Pre stressed Slab with Elastomer and Self levelling Mortar

6.3.3.1 Precast and Pre stressed Slab with Elastomer and Self levelling Mortar - Diagram

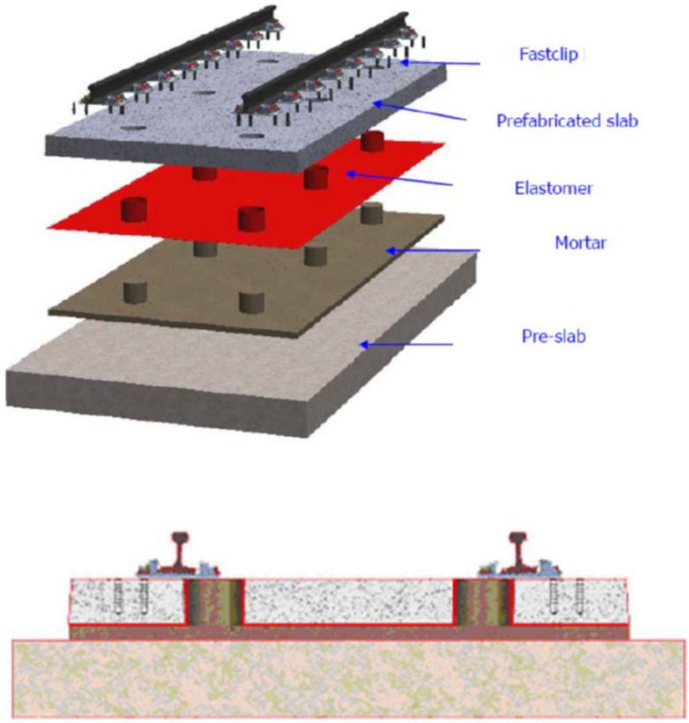


Figure 6.3 - Precast and Pre stressed Slab with Elastomer and Self Levelling Mortar

6.3.3.2 Precast and Pre stressed Slab with Elastomer and Self levelling Mortar - Description

This trackform consists of a precast slab which is pre-stressed both longitudinal and transversally, a layer of self-levelling mortar and an elastomer layer affixed to the underneath the precast slab. The mortar keys into the precast slab to prevent movement.

The purpose of the elastic layer is to reduce the vertical rigidity of the assembly formed by the track, the fastening of the track slab and the substrate compared to the traditional track with sleepers and ballast. Additionally it reduces the wear due to friction of the contact surface existing between the substrate, when it is made of concrete, and the precast concrete slab. Said wear is due to the transmission of forces to the substrate due to braking, longitudinal and centrifugal accelerations.

The process for installing the track system comprises of the following steps:

1. Precast the structural concrete slabs, including inserts on the upper surface for fixing the rails, cylindrical boreholes with their elastomer lining or sleeve, an elastomer layer weakly and/or provisionally fixed at a series of specific points to the lower surface of the slab, but not fully adhered or bonded. The elastomer layer is placed on the lower surface of the slab once the concrete has cured;
2. After transporting the slab to its location, the onsite positioning and vertical and horizontal plotting of the slabs in relation to the substrate is carried out. Metal frames or other provisional elements with hydraulic and mechanical elements can be used for this operation, which will allow the geometric adjustment of the slab;

3. Subsequently injecting the self-compacting bonding mortar, levelling and filling, carried out without vibration and which mortar is distributed though the preferably cylindrical boreholes or holes existing in the slab and evenly distributed in the base for allowing complete filling with said self-compacting mortar of the space existing between the slab and the substrate;
4. The final step of the installation process consists of the setting of the mortar, removal of the provisional fixings or pedestals and making the final geometric adjustments of the rail to be installed on the slab.

This system has been tested on the Madrid to Valencia line in Spain and has been installed on a four hundred metre test section inside the Horcajada tunnel,

6.3.3.3 Precast and Pre stressed Slab with Elastomer and Self levelling Mortar - Assessment

Using this trackform provides usual benefits of slab tracks such us a long cycle of life with low maintenance requirements, constant stiffness along the track, reduced weight suitable for tracks over bridges, reduced height appropriate for tunnels and the elimination of ballast flight risk.

This specific design brings further distinctive benefits:-

The slabs show good behaviour against fatigue and cracking thanks to the pre-stress in both directions applied during the manufacture process. **Error! Reference source not found.** Due o the fact that the track is built with individual slabs, fixing a broken slab is easier than with longer continuous slab systems although, this geometry might require a joint between slabs, deferred strains of each slab are decoupled with invert concrete pre-slab so that no joint between slabs is needed. The whole system benefits from the simplicity of the geometry of the slab and can be easily adapted to bridges with no need to split the slabs.

The construction process also shows several advantages as a high standardization, an easy vertical adjustment that can be readjusted in case of reasonable settlement.and the elimination of the concreting process in situ.

Stoppers filled with mortar and covered with elastomer provide good behaviour against horizontal loads in the rail areas with thermal variation **Error! Reference source not found.**. hereas the elastomeric mat allows adjustment to the stiffness of the system through altering its thickness, the fastening system also gives some elasticity to the system having therefore a double level of elasticity.

6.3.3.4 Precast and Pre stressed Slab with Elastomer and Self levelling Mortar - Strengths

- good behaviour against fatigue and cracking due the longitudinal and transversal pre-stressing;
- no joint between slabs is needed. Deferred strains of each slab are decoupled with invert concrete pre-slab;
- easier to repair damage if necessary (compared to continuous slabs systems).

- high standardization of construction process
- stoppers provide good behaviour against horizontal load. There is a double level of elasticity: A higher level provided by the fixation and a lower level, under the pre cast slab, which remains as a mass elastically linked to the substrate through the elastomers**Error! Reference source not found.**. Therefore, stiffness can be adjusted hrough the thickness of the elastomer and the fastening system.

6.3.3.5 Precast and Pre stressed Slab with Elastomer and Self levelling Mortar - Weaknesses

- high level of initial capital outlay;
- there can be increased levels of air borne noise compared to standard ballast track;
- repair of medium or major defects is time consuming and expensive;
- the speed of construction is low due to the fulfilment of strict tolerances;
- the rail either has to have post drilled fixings or each slab has to be made for and transported to a specific location;
- if the slabs should move the rail will be placed under increased strain/stress/fatigue;
- the mortar needs to be able to resist the longitudinal loads imposed by braking and temperature changes affecting constituent components.

6.3.4Embedded Rail Track (ERT)

6.3.4.1 Embedded Rail Track (ERT) - Diagram

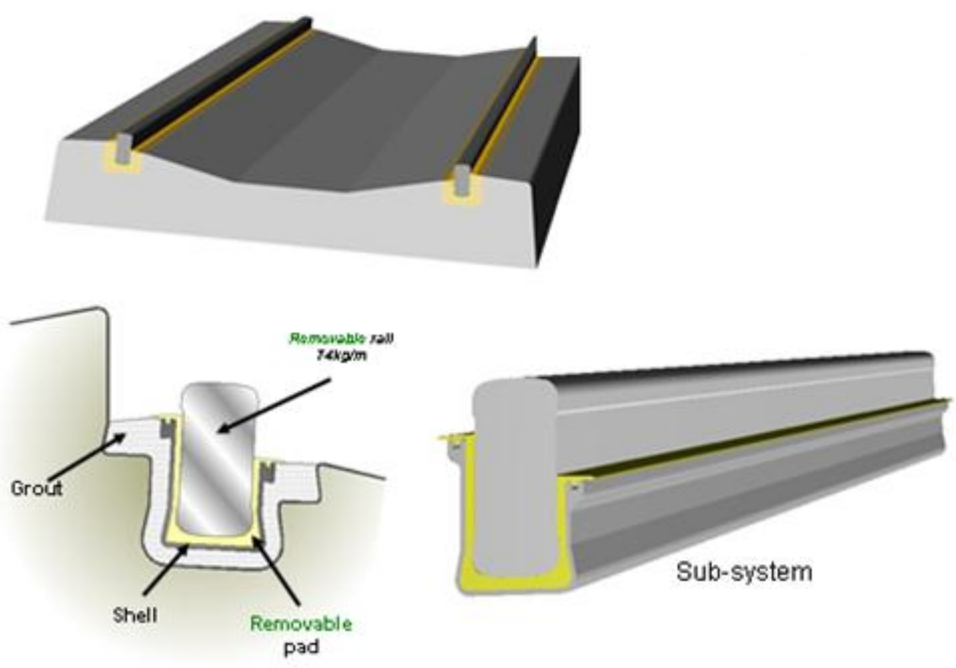


Figure 6.4 – The Embedded Rail System

6.3.4.2 Embedded Rail Track (ERT) - Description

The ERT system is comprised of three main components:

- Rail: the rail is a rolled rectangular profile with a head surface profile identical to that of the CEN 60 rail. Uniquely, the entire rail section can be ultrasonically tested from the railhead. The rail height provides up to 100% increase in allowable headwear. The solid web reduces the noise and provides reduced risk of rail breaks. A dummy GRP rail is used to enable top down construction without supporting a heavy rail;
- Pad: by varying the stiffness of the high quality micro cellular polyurethane, the stiffness of the rail system can be varied over a wide range. Due to the continuous length the pad is not fatigued and is designed to last the life of the rail. It features an integrated seal to prevent ingress of air, moisture, and contaminants. The rare lateral control of the railhead enables a softer / less stiff system to be provided without the usual risk to gauge widening;
- Shell: the main function of the GRP shell is to form a dimensionally accurate slot, to constrain the rail and to ensure the correct performance of the elastomer rail supports. At the same time it provides good electrical insulation. . The rigidly held rail enables a dual resilient performance with only a single resilient pad;
- Installation: after the provision of a support slab with two wide slots in it the shell with a light dummy rail head is inserted, aligned and grouted. The dummy head section is removed, the pad fixed and finally the rail is installed.

Figure 6.5: Slip forming the concrete base for Embedded Rail

Figure 6.6: Precast concrete base for Embedded Rail

6.3.4.3 Embedded Rail Track (ERT) - Assessment

The concept eliminates traditional rail fastening requirements. The advantage of a continuously embedded rail trackform is that the support can be designed as an efficient simply supported beam on an elastic foundation. This can be pre-cast or slip-formed or cast in-situ, whether in slab or ladder configuration. The beam or ladder track can also be placed on piles to minimize the influence of poor formation. As identified in the INNOTRACK project the required formation strength required to support the system is low making civil preparation work quicker and more economic.

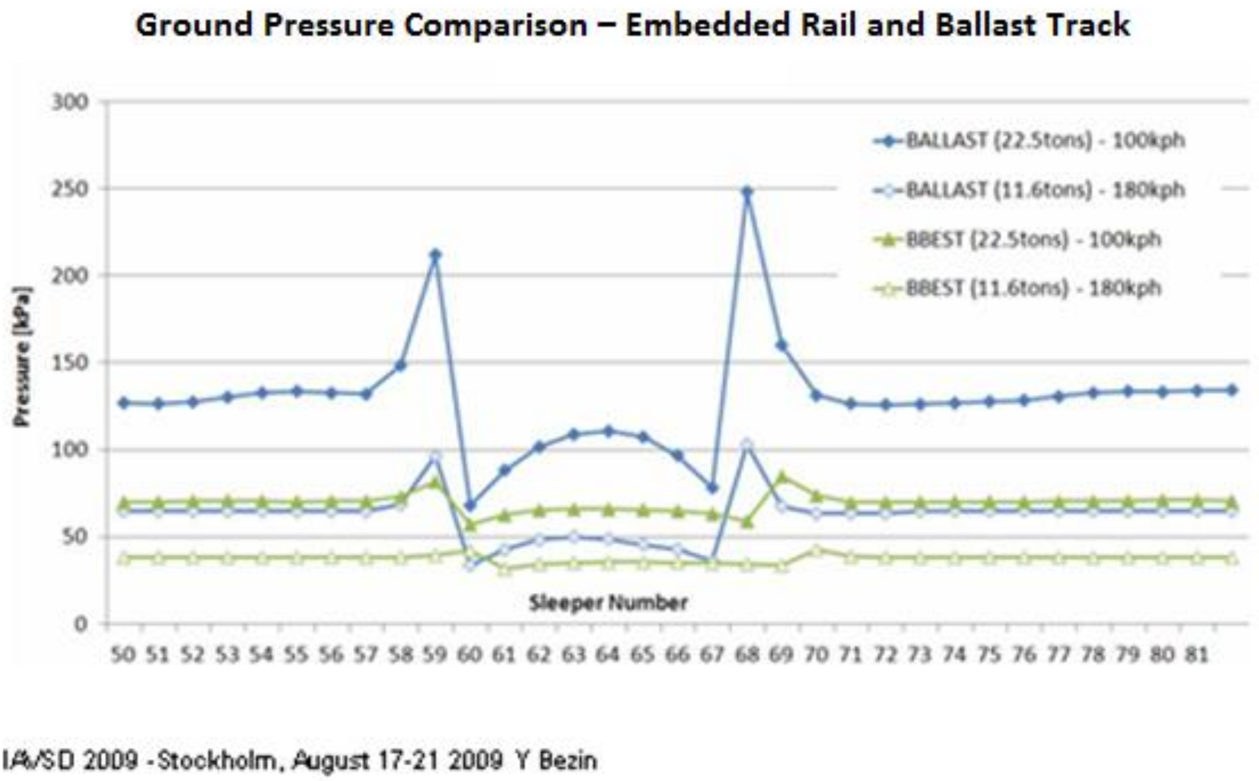


Figure 6.7: Ground pressure comparison

As up to 50% of traditional rail-breaks initiate from ultrasonically undetectable defects, i.e. in the rail foot, the system is significantly safer than flat bottom rail sections. (Ref B. Whitney PWI presentation, 24th May 2017 London)

The embedded rail system lends itself to high levels of mechanisation. The construction process is designed to use established and proven civil engineering techniques, plant, tools equipment and skills to reduce the installed cost.

Settlement adjustment can be made in the pad, the grout or if very large in raising of the slab.

6.3.4.4 Embedded Rail Track (ERT) - Strengths

- with no rail fastenings in the way derailment protection is easy;
- no fastenings are required for the system. The shell is set in grout accurately (+/-1mm) and when the pad and rail are installed this provides a designed restraint to the rail;
- it permits a very low stiffness without the risk of head deflection;
- pre-casting, pre-stressing, asphalt support and under slab resilient pads can be incorporated where the benefit is valid and outweighs the additional cost;
- the disconnection of the concreting, alignment and railing activities has removed the normal onerous programme activity constraints which are often simultaneous;

- a dual pad performance is achieved with a single pad. It overcomes the incompatible requirements of providing rail head stability at the same time as low track resilience: a problem commonly faced by Surface mounted rail alternatives which leads to two or more layers of resilience;
- the rectangular rail shape and its embedment are effective in controlling noise and reducing the risk of rail break;
- the typical height of embedded rail track is much less than alternative options. The embedded rail system can be half of that needed for ballasted track. The leads to potential savings in civil structures such as viaducts, tunnels, cuttings etc.;
- the track geometry retention properties of embedded rail are excellent. The continuous vertical and lateral support ensures the rail rotation and deflection is consistent and minimised. The pad is not highly stressed and retains its designed stiffness for the normal life of the rail;
- as the track quality does not vary maintenance is greatly reduced. The frequency of rail grinding is less as the rail is less likely to corrugate due to the continuous support;
- the embedded rail system is very reliable, primarily because components, and their failure modes, have been designed out of the system. Traffic can pass over a rail break (in the unlikely event that one occurs) as the rail is deemed to be permanently clamped. Thus safety is maximized and disruption to traffic is minimised;
- the independent alignment and profile of the ERT rail as experienced by each wheel is infinitely adjustable to optimize the interface performance;
- rail buckling is reduced to a negligible level by the grip on the rail. Consequently rail tensioning is only needed in extreme conditions;
- of particular importance is the disconnection of the otherwise dependent construction activities such as concreting, aligning or railing. Each can be done without the risk of a delay in the other. This approach has the potential to significantly reduce the cost of track installation compared to ballasted track or other slab trackforms;
- minor settlement can be overcome by introducing a thicker pad or spacer. Major settlement is addressed by raising the slab a process common to other slabs;
- pre-casting, pre-stressing, asphalt and under slab resilient pads can be incorporated into the systems to alter track support conditions;
- track quality performance is improved;
- no fastenings are required for the system;
- the capital cost of the embedded rail system should be less than any equivalent slab trackform. The reason for this are fewer components are required and site activities are minimised. The use of inexpensive and readily available standard civil engineering plant and processes also reduces specialist railway costs. It will also present savings on construction time and thus minimise disruption to operations as the required

formation stiffness is significantly lower than that for ballasted track. In given circumstances the construction cost will be less than ballasted track.

6.3.4.5 Embedded Rail Track (ERT) - Weaknesses

- the adoption of this track requires a cultural change; currently rail engineers are reluctant to move out of their comfort zone of ballasted track and begin to accept its shortcomings of increasing cost and unsuitability for the traffic of the future;
- the lowered likelihood of settlement and the mitigation strategy appropriate to this system needs to be fully understood;
- this solution requires a change in objectively addressing risk. The potential reduction of both the consequences and likelihood of financial and technical failure using this system needs to be appreciated.

6.3.5 Multi-Modular Multi Block Track (3MB)

6.3.5.1 Multi-Modular Multi Block Track (3MB) - Diagram

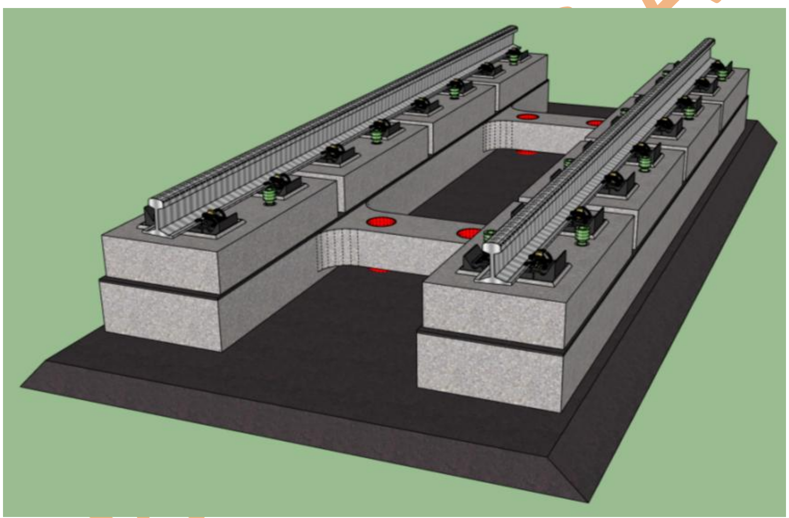


Figure 6.8: 3MB final design general view

6.3.5.2 Multi-Modular Multi Block Track (3MB) - Description

This “Moulded Modular Multi-blocks Slab-Track” (3MB) is a RAMS oriented slab track design produced by the project Capacity4Rail project.

3MB is based on the concept of multiple-level modularity and aims to provide fast and easy maintainability, through the use of easily replaceable, precast components.

The reinforced precast slab designed for both mixed traffic and high speed traffic and is a hollowed “ladder track” design in order to be lighter compared to other precast slab-track systems. The slab is prevented from moving under traffic by securing it to the base layer with stopper pins.

With this system it’s possible to achieve specific stiffness values by adjusting one more component properties in the following ways:

- varying the design of the asphalt sublayer;

- varying the properties of the elastomeric strip used between the precast concrete elements;
- adjusting the fastener components.

The system modules are broken down into 4,80m long sections, with each section containing the following elements:

1. a precast base in the form of two longitudinal reinforced concrete beams connected by two transversal beams. The transversal beams have cylindrical holes for in-situ connection with the bituminous sub-base where needed;

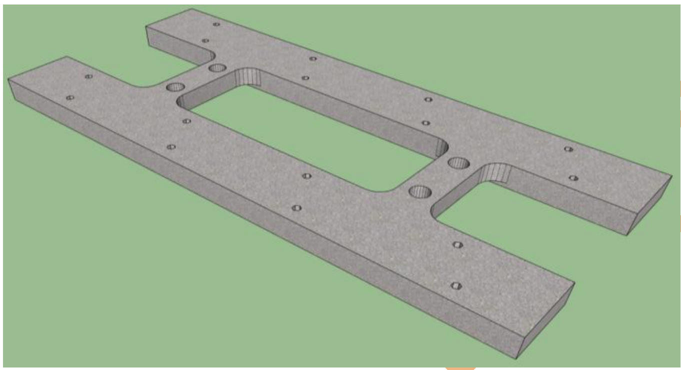


Figure 6.9: **3MB Base slab**

2. TPV+EVA elastomeric strips on the upper surface of the slab, providing extra vibration attenuation for the system and preventing the hammering of the moulded blocks against the base slab. The mats present cylindrical through holes to allow the passage of steel connecting pins;

Figure 6.10: Elastomeric strip

3. eight precast moulded concrete blocks, four on each longitudinal beam of the base slab, provide support for the fastening system and rail. The blocks upper surface contains two cavities used for the levelling adjustment and installation of fasteners, as well as two cylindrical through holes to accommodate the steel connecting pins;

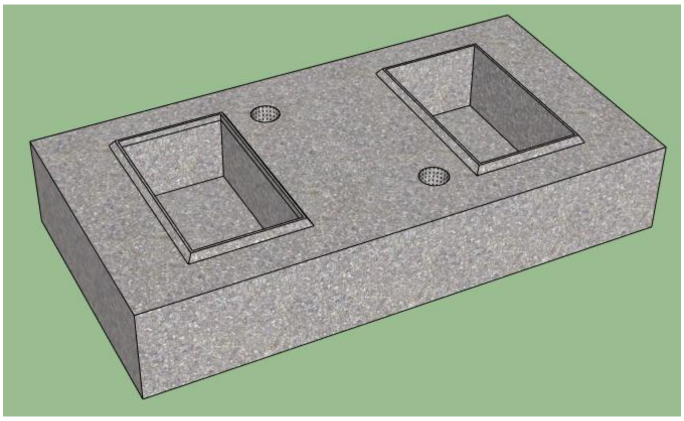


Figure 6.11: Moulded precast blocks

4. In order to restrain the moulded blocks horizontally while allowing unrestrained vertical movement, a double steel piston system (steel pins) has been devised. The system is devised so that the piston is fixed to the base slab while the cylinder is fixed to the through holes in the block, thus allowing the block to move parallel to the piston axis but constraining all other movement. Each block is restrained by two non-coaxial steel connectors, thus preventing unwanted rotation around the piston axis;

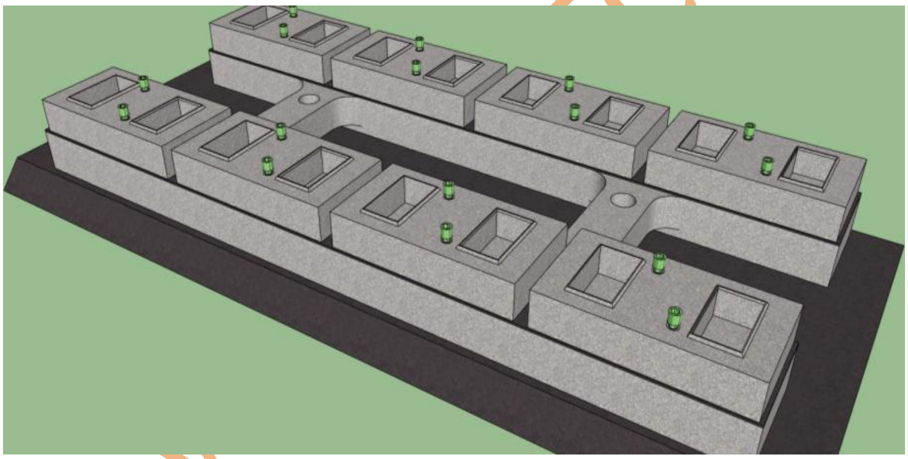


Figure 6.12: Steel pin connectors

5. this slab trackform uses the DFF21 rail fastening system from Vossloh, connected to the moulded blocks through plastic dowels embedded in mortar, poured in situ in the rectangular block cavities;

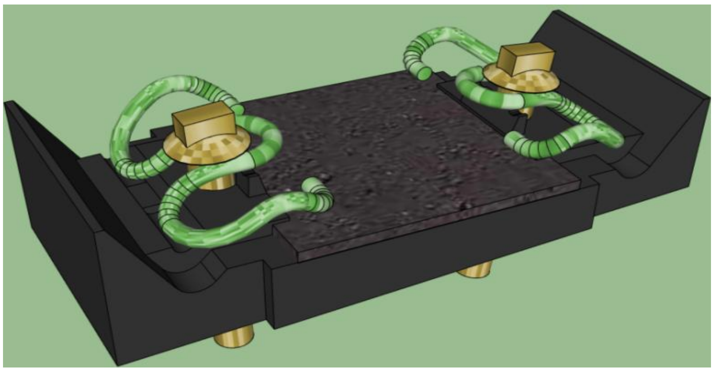


Figure 6.13: DFF21 Fastening system

6.3.5.3 Multi-Modular Multi Block Track (3MB) - Assessment

The 3MB system is based on the concept of multiple-level modularity and strives to achieve fast and easy maintainability through the use of easily replaceable, precast components.

The design of this system is completely modular thanks to standard easily replaceable elements.

Blocks are designed to act as a "fuse", guaranteeing that, in case of structural damage, it shall concentrate on the most easily replaced elements. Thanks to the removable pin system, blocks can replaced with minor to no elevation of the rail.

Each of the systems components has a specific role in ensuring optimal system performance.

- the bituminous subgrade provides adaptability to terrain settlements disperses the loads transferred by the base slab and, where needed, allows the in-situ anchoring of the base slab;
- the base slab supports the moulded blocks, clamps the steel pins and disperses the loads transferred vertically by the blocks and horizontally by the pins. Where needed, it holds the in situ stoppers that connect the system to the sub-base;
- the elastomeric strips provide vibration attenuation and prevent the hammering between base slab and blocks;
- the steel pins restrain the blocks horizontally while allowing the free vertical movement the elastomeric strip requires for dissipating vibrations;
- the moulded blocks provide support (both vertical and horizontal) for the fastening system by means of the in situ mortar poured on the fastener-holding cavities;
- the fastener mortar provides geometric adaptability, allowing for top-down alignment, and once hardened guarantees track gauge and alignment.

6.3.5.4 Multi-Modular Multi Block Track (3MB) - Strengths

- as the system is constructed using a top-down alignment process, the degree of subbase accuracy to be achieved during construction is reduced, simplifying and speeding up the overall construction process;
- the main elements are precast off-site, allowing for mass production, providing enhanced quality control and drastically shortening on site construction time;
- design is completely modular thanks to standard easily replaceable elements;
- the elastic level under the blocks provides vibration attenuation and energy dissipation;
- blocks are designed to act as a "fuse", guaranteeing that, in case of structural damage, it shall concentrate on the most easily replaced elements;
- bituminous sub-base and base slab are designed to adapt to terrain settlements without compromising structural integrity;

- track realignment after a soil settlement episode is easy and does not require base slab replacement;
- thanks to the removable pin system, blocks can be replaced with minor to no elevation of the rail;
- maintenance and replacement of any element except for the slab panel does not require the use of heavy lifting machinery;
- the rail has a good longitudinal and lateral restraint. The behaviour against heat expansion, braking and buckling is fair;
- system stiffness can be tailored through the adjustment of one or more components.
- the system is able to retain the designed alignment better.

6.3.5.5 Multi-Modular Multi Block Track (3MB) - Weaknesses

- there must be a high initial investment on slab production factories;
- while the mortar poured between the fastener and the block cavity is hardening , thermal stress on the rail have to be taken into account to avoid rail movements owing to the light heavy of the system composed of rail and fasteners;
- the installation system requires auxiliary elements (false sleepers), in order to place the rail at its right geometric position;
- owing to the fact that this system has not been installed in real construction-site, there is an uncertainty in terms of installation time and real cost;
- the fixity of the plastic dowels to the mortar is currently uncertain. Their long length increases the overall height of the system;
- several types of machinery are needed for first installation: (asphalt extension, heavy lifting for slabs tracks);
- it’s difficult to include check rail and ground based electrification systems.

6.3.6Systra Beam Track

6.3.6.1 Systra Beam Track - Diagram

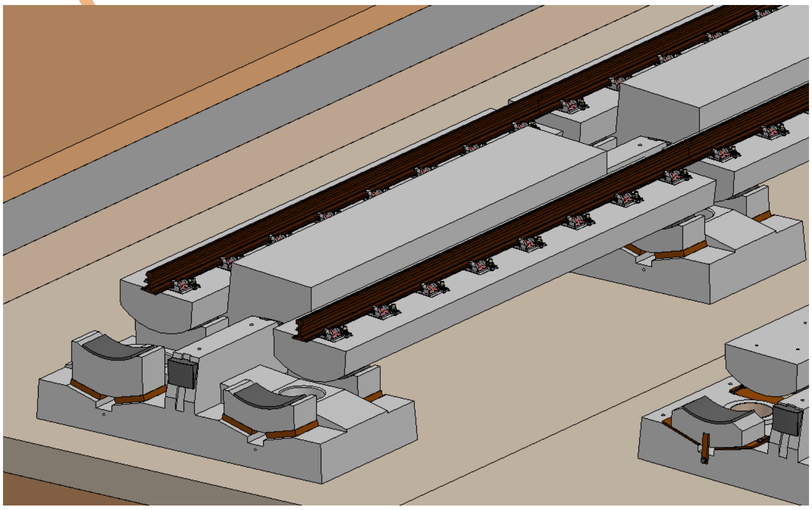


Figure 6.14: Concrete track beams

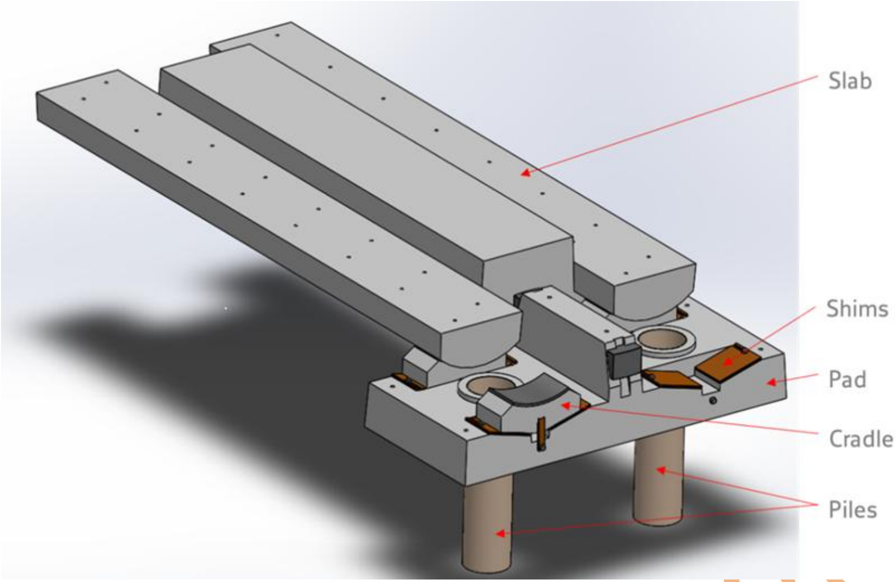


Figure 6.15: Beam Supports

6.3.6.2 Systra Beam Track - Description

The SYSTRA beam track system is constructed by placing five meter long precast reinforced concrete beams on supports. Each support consists of four adjustable bearing devices allowing for beam alignment.

The bearing devices can be adjusted vertically and laterally and in combination, allowing for three degrees of freedom: vertically, laterally and rotationally. Adjustments are made by altering the size and the position of the shims.

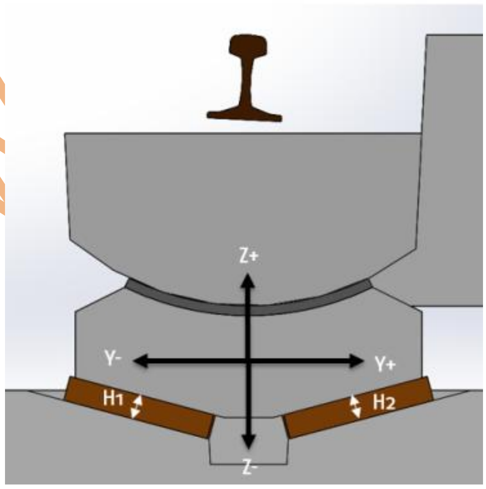


Figure 6.16: Adjustment of the track alignment

The beam supports are anchored to a hydraulically bonded layer by piles. This approach allows for track construction in areas with poor soil conditions and reduces the need for extensive earthwork remediation.

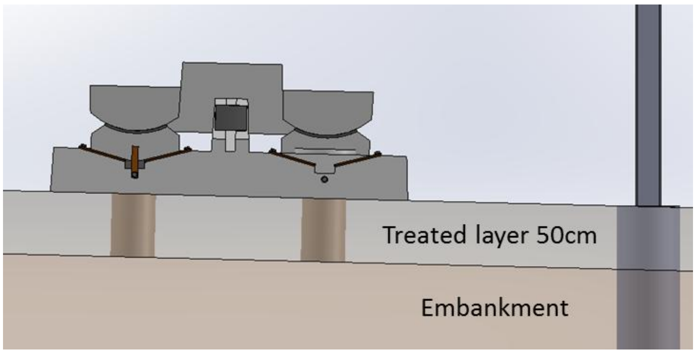


Figure 6.17: Subgrade

Cant can be set and adjusted by using different sized and shaped cradles under the beams.

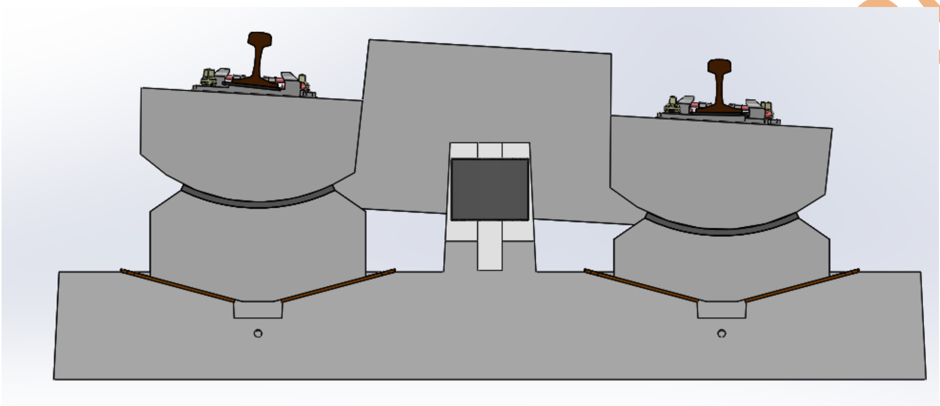


Figure 6.18: Cant adjustment of the track beams

The track laying process was studied in detail via a thorough analysis of the laying process (although using available on the shelf machinery), and a quotation of the time and resources needed for each singular operation, along with the associated cost. This resulted in a laying performance up to 500m/day. This performance is due to the full modularity of the system using pre manufactured elements which are just assembled on the site. Indeed there should be no cement or bitumen poured on side, so no concrete curing time nor bitumen cooling. The tools used for laying the track are state of the art tools (gantry cranes).

The life of the system is estimated to be 100 years and is suitable for a wide range of traffic types and operational scenarios.

6.3.6.3 Systra Beam Track - Assessment

SYSTRA's slab track is designed to have the performance and benefits of slab track whilst retaining the flexibility and cost of traditional ballast track and is suitable for a wide variety of applications and traffic. Using precast elements reduces the time required for onsite construction and makes repair of the track simple.

SYSTRA's slab track requires a light subgrade substructure and is therefore compatible with soils with low bearing capacity. The construction is fast due to the use of precast elements and existing machines (gantry cranes) can be used for the installation.

As the beams carrying the track are decoupled from the ground there is a high degree of resilient to natural weather events such as flood, sand and snow.

6.3.6.4 Systra Beam Track - Strengths

- modular design makes the construction and maintenance operations easier;
- high degree of resilience to natural weather events;
- precast elements increase the construction speed on site;
- easy track geometry adjustment to compensate for unavoidable subgrade settlement or heave;
- reduced maintenance requirements;
- suitable for a wide range of ground conditions and reduces the need for costly and time consuming earth works.

6.3.7 Systra Beam Track - Weaknesses TATA steel track

6.3.7.1 TATA steel track - Diagram

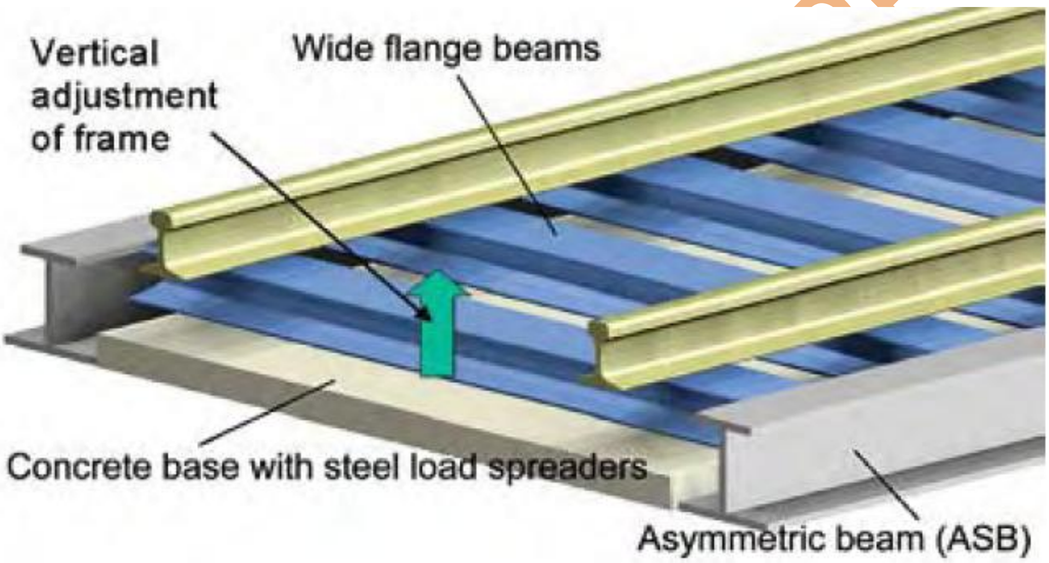


Figure 6.19: Steel track construction

Figure 6.20: Steel track test installation

6.3.7.2 TATA steel track - Description

The system was initially developed for plain line application and was installed in a stretch of industrial track in the UK as a demonstrator within the INNOTRACK project.

The design consists of a two-layer system. The base slab of concrete-encased steel beams rests on the natural ground layer while a steel frame with enhanced longitudinal stiff members as well as transverse beams forms the second layer. The base slab allows the upper frame to be jacked and track alignment corrected as well the effectively distributing load into the ground.

The steel frame is supported on the base slab with layers of shock absorbing material, which cushion wheel loads and ensure that the cross members are uniformly supported from below.

6.3.7.3 TATA steel track - Assessment

Pressure on the formation is reduced by use of a stiff frame supported on a load spreading platform.

The system is designed to be pre-assembled in panels and transported by rail to site with the advantage of speeding up the installation process.

The upper steel frame on which the rails are mounted can transmit loads directly to the formation independently of the base during the period of concrete curing. This offers the advantage of opening the track to traffic with little delay and undertaking concreting at a more convenient stoppage.

The steel frame and base can be adjusted relative to each other both at installation and following unforeseen changes of the formation due to settlement or severe flooding

For higher speed trains, additional noise expected from slab track can be attenuated by the behaviour of heavy baseplates, acting as tuned absorbers for parts of the frequency spectrum. Further aspects of the design permit the inclusion of damping and noise absorbing materials, if required

The developed system can be adapted for S&C layouts and although installation costs are estimated to be 10-15% higher, these are fully compensated if costs of train delays and cost savings from handover at line speed and are accounted for.

6.3.7.4 TATA steel track - Strengths

- the inherent bridging capability of the steel frame structure enables the system to tolerate major problems of the formation should they occur;
- the consistency of support integral to the system offers significant savings in future maintenance costs;
- considerable reduction in ground vibration (10 to 25 dB) between 10 Hz and nearly 200 Hz has been measured on the demonstration track installation;

- the system can preassembled reducing construction time on site;
- less formation pressure and preparation work. Greater resistance to formation weakness.

6.3.7.5 TATA steel track - Weaknesses

- for reasons of cost effectiveness, the system is not recommended for conventional full track renewal of life expired plain line ballasted track nor is it recommended as an alternative for full specification concrete slab track for green field applications;
- in the medium to long term durability of the steel will need to be managed especially where physical or chemical damage occurs;
- carbon footprint.

6.3.8Asphalt under Ballast

6.3.8.1 Asphalt under Ballast - Diagram

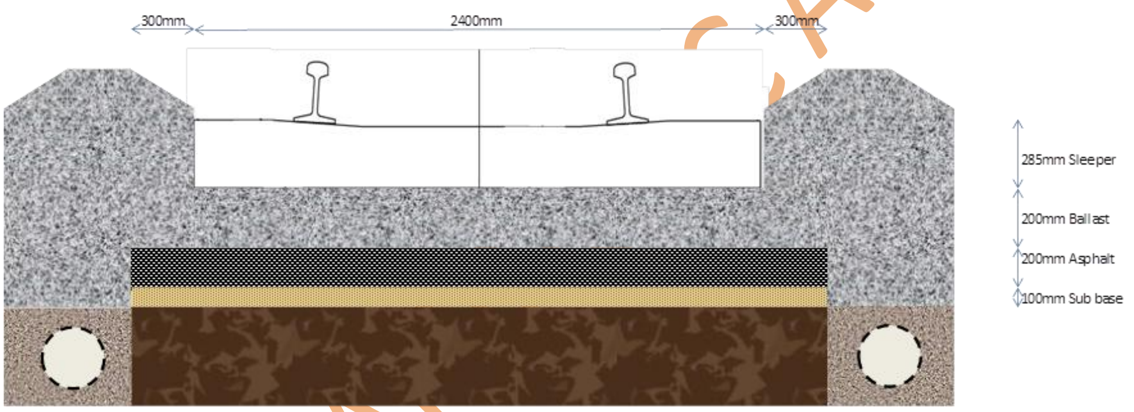


Figure 6.21: Asphalt under ballast

6.3.8.2 Asphalt under Ballast - Description

The asphalt under ballast track system combines standard ballast track design with a hot rolled asphalt slab.

The asphalt slab evenly distributes the load from the rail to the subgrade, reducing localised areas of settlement and maintaining track quality longer.

Construction requires a continuous asphalt slab 3000mm wide and 200mm deep, to be laid over 100mm of compacted granular sub base material. 200mm of ballast is then laid over the asphalt and the track and sleepers set out using standard methods. The ballast is topped up to the final level and shoulders constructed, follow up tamping is used to achieve final track layout.

6.3.8.3 Asphalt under Ballast - Assessment

In the last decade, the surge in rail traffic loads and volumes has increased the rate at which conventional ballast track systems deteriorate. This increased load cycling generates fatigue cracking of the ballast, embankment settling, and consequently, the deterioration of the rail geometric. Due to this fact the maintenance works are costly and more frequent.

In order to maintain the rail geometry, as well as avoid the deterioration of the structure due to the traffic loads, an asphalt layer is used as sub-ballast, interposing a special semi-rigid layer in the area between the ballast and the subgrade.

The thickness of the asphalt layer depends on the quality of the subgrade support and traffic loadings. 120mm to 150mm of asphalt is used in normal conditions. However, under poor subgrade support conditions and areas of high impact, a minimum thickness of 200 mm would be considered.

The addition of an asphalt layer to a ballast track system benefits the overall performance of the track system in the following ways:

- **Resistance to vertical deformation:** the relatively high stiffness of the asphalt layer compared to granular material leads to less permanent vertical deformation by trainloads. The vertical loading conditions and the relatively short loading time are relatively small, so there will be no permanent deformation in the asphalt layer;
- **Drainage and weather effects:** the impermeable asphalt sub-ballast layer can resist water coming down through ballast layer as well as coming up through mud and fines pumping. This allows for better management of ground water, a key factor in the systems deterioration mechanism;
- At the same time, weather effects such as temperature changes, Ultra Violet radiation, and exposure to oxygen are reduced by the ballast cover and in consequence, the durability of the asphalt layer is increased;
- **Durability:** The asphalt sub-ballast layer increases the foundation modulus. Providing a more rigid foundation reduces the tension and shearing stresses inside the ballast material and leads to less degradation and wear of the individual aggregate particles.

6.3.8.4 Asphalt under Ballast - Strengths

- the asphalt layer distributes the load from the ballast to the subgrade evenly, reducing localised areas of settlement and maintaining track quality (geometry) longer;
- this system is tolerant of poor quality ground conditions and reduces the need for time consuming and expensive preparatory earthworks;
- the depth of the ballast over the asphalt is reduced, lowering the overall height of the track system and reducing the system weight, an important consideration for use in tunnels and on structures;
- the impermeable asphalt sub-ballast layer allows for better water management of the substructure and reduces the formation of voids through pumping;

- as the asphalt is covered by ballast weather effects (temperature changes, Ultra Violet radiation and oxygen) will not affect the asphalt and in consequence, the durability of the asphalt layer is increased;
- the technology required for laying asphalt is well known in road construction;
- the asphalt surface, which can be extended without joints, can be used as an auxiliary path during the construction process
- reduced infrastructure life-cycle cost from reduction in subgrade fatigue and associated maintenance activities.

6.3.8.5 Asphalt under Ballast - Weaknesses

- there is an increased amount of construction machinery required as two types of materials are used, ballast and asphalt;
- the carbon footprint: the asphalt composition has 5% bitumen content which is composed by a highly percentage of carbon, around 82%;
- the asphalt installation phase is temperature sensitive and requires careful planning and logistics support.

6.3.8.6 Asphalt under Ballast - Opportunities

- development for use as standard installation under S&C and level crossings.
- the overall depth of construction may preclude it from situations where system height is limited;
- noise is emitted;
- the consequences of derailment could be multiplied.

6.4 Classification of track systems

Depending on the situation the evaluation process may favour systems with specific design characteristics. Given the wide range of systems available it may therefore be beneficial to simplify the process by grouping together track systems based on generic type's e.g.

- Rail;
- Fastening;
- Structural interface;
- Superstructure;
- Sub-structure.

Figure 6.22, Figure 6.23, Figure 6.24 and Figure 6.25 demonstrate a simplified breakdown. Superstructure is sufficiently similar to structural interface to warrant not reproducing the same chart.

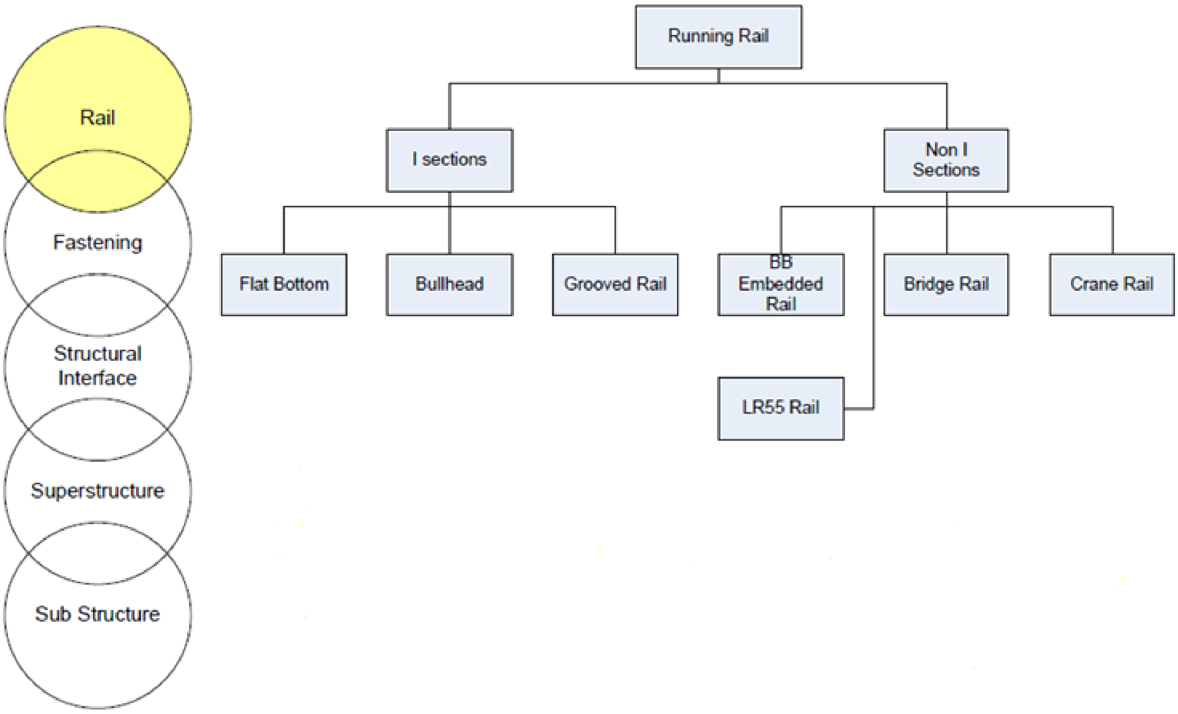


Figure 6.22: Categorising systems according to rail type

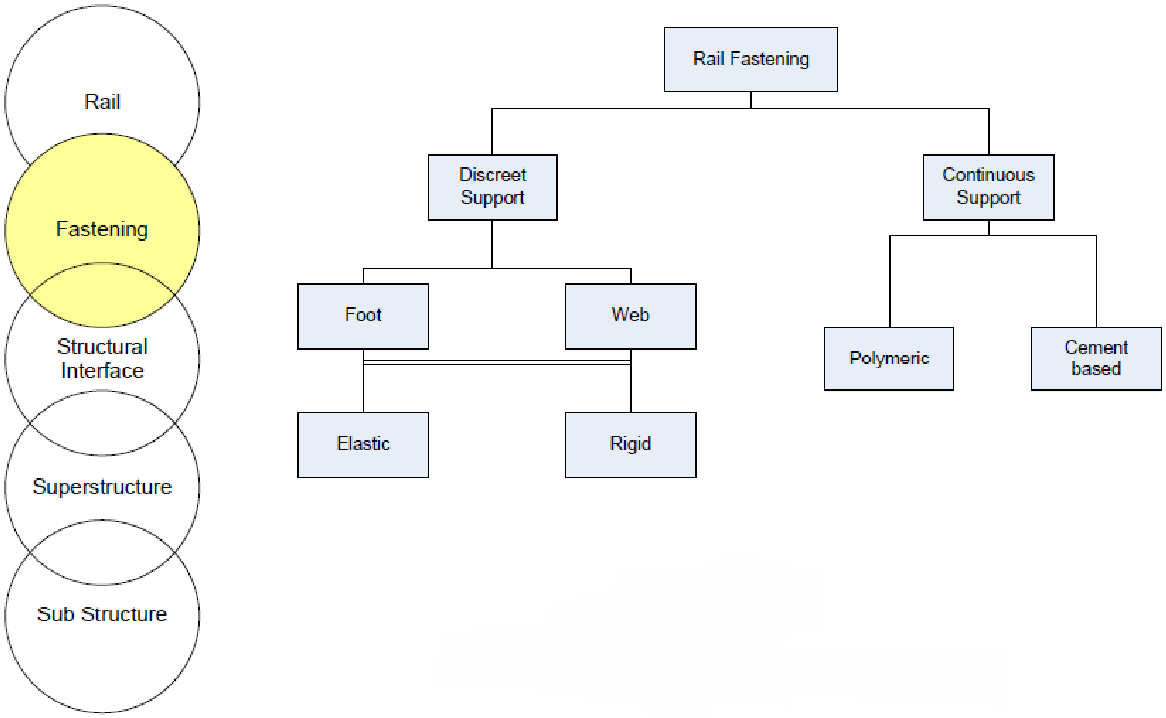


Figure 6.23: Categorising systems according to fastening type

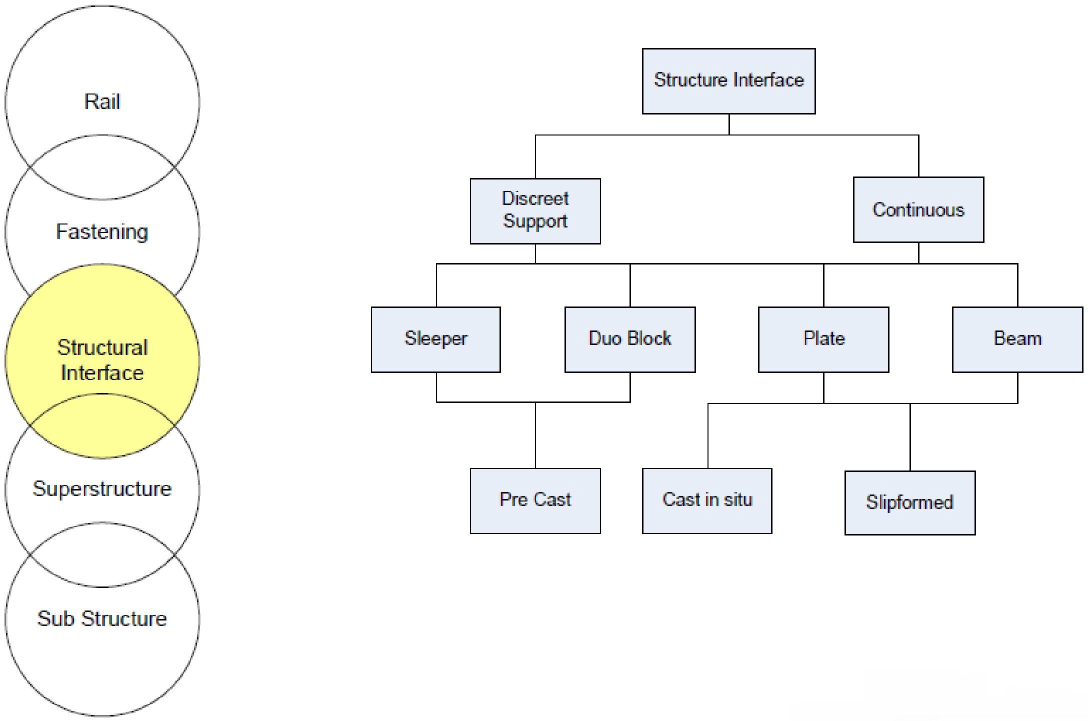


Figure 6.24: Categorising systems according to structural interface

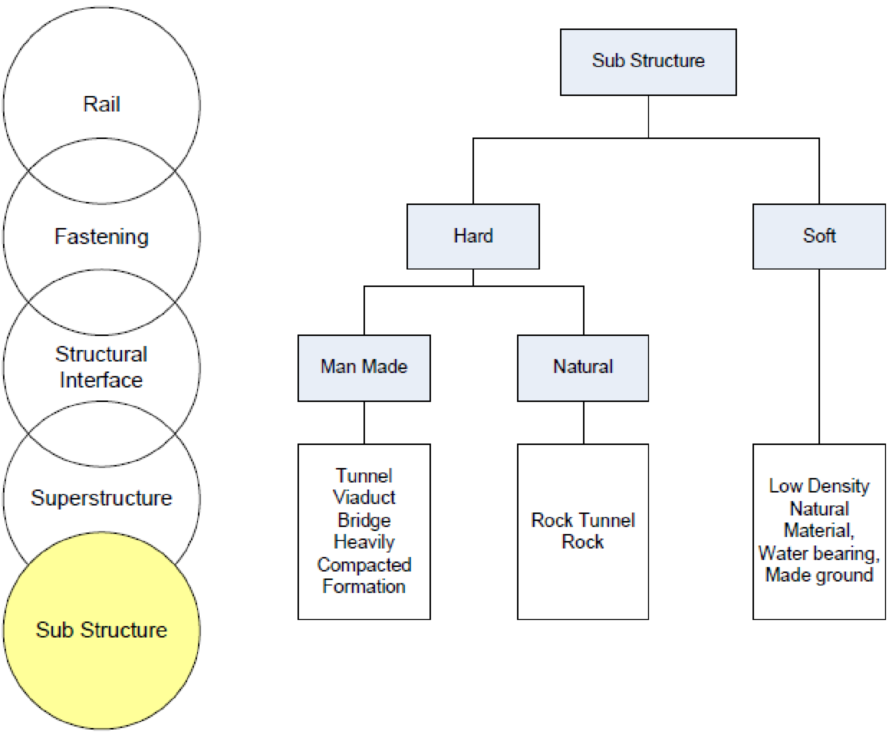


Figure 6.25: Categorising systems according to sub structure

7 Guidelines for the Evaluation and Selection of Innovative Track Solutions

The selection of track systems is a difficult and complex process that requires many factors to be considered. It is therefore important that the evaluation and selection process be as systematic, objective and transparent as possible.

7.1 Assessment methodology

There are a wide variety of methods that can be employed for the evaluation and section of track systems. These methods can be generalised as coming from either an overview "top down" approach which considers a range of systems from the outset, or an in depth technical "bottom up" approach that focusses on a specific technical issue. The in depth method is preferable when undertaking sensitivity analysis for a specific parameter.

7.1.1 Overview assessment method

The typical approach to undertaking an overview technical assessment consists of the following steps:

- selection of the assessment criteria;
- assign weightings to the assessment criteria;
- evaluation of the system against the assessment criteria.

The overall technical ranking is then essentially obtained as a summation of the weighted scores for the different criteria.

A major benefit with the approach is that it can be carried out in a very early stage of the decision process. However if the assessment is carried out in an overly general fashion it is possible to discriminate against solutions at an early stage. This introduces the risk that some useful solutions may be discarded in the initial process. Hence, the knowledge and experience of the staff carrying out the assessment is very important.

A second benefit is that the evaluation results in a structured list of evaluation criteria. The main challenge is of course to obtain a complete and non-overlapping list of criteria. Also, as is well known (Pirsig, 1974), it is possible to construct such lists from different aspects (e.g. technical systems and subsystems vs. functional requirements).

There are a number of potential pitfalls in any decision process. The most obvious is of course being that the outputs are only as good as the competence of the evaluation group. It is important that the group that performs the evaluation is as fully informed and unbiased as possible.

As with any assessment, care must be taken to minimize potential issues (see Table 7.1).

Potential issue	Description
Double counting of features	It is very hard, not to say impossible, to create a list of criteria where all features are included in only one item. To take a simple example, a list of evaluation criteria for track solutions should feature the lateral track resistance. It should also feature the risk of track buckling. In this case the lateral track resistance is included in both criteria. Since track buckling relates not only to lateral track resistance, but also to factors such as track geometry distortion, restricted longitudinal rail displacement etc. the criterion cannot simply be excluded. The complication does not mainly stem from the fact that some features can be included in several criteria, but more from the difficulty in identifying in which criteria the different features are included. This is especially the case for more general criteria such as environmental impact, buildability etc. Here "environmental impact" may include e.g. noise pollution, which may also be a separate criterion. A failure in this identification may result in incorrect weighting of the different features leading to over representation in the final scoring.
Clarity of criteria	Another potential pitfall is that "overall" assessment criteria such as environmental impact may be interpreted in different manners. As an example, we may take "environmental impact", which by some evaluators may be biased towards greenhouse gas emissions, by another towards noise emissions and by a third towards worker's health. This can to some extent be mitigated by a common agreement in the evaluation group; however the ambiguity may appear again when the evaluation is interpreted by decision makers.
Non-linear weighting	The difficulty of assigning correct weights also relates to the fact that these factors in general are non-linear. As an example, we can continue with the risk of track buckling. If that risk is significant for the track system, this factor is crucial. For track systems where the risk decreases, the importance decreases. However, at a certain level the risk becomes negligible. At this level any further improvement does not add any additional benefit. As another case we can take the time required to repair the track structure: If the repair process is "long" a moderate improvement is not very important. However, when the repair times decrease so that repair might be carried out e.g. during a single night shift, the repair time becomes crucial. Further decreases (e.g. half a night shift) are positive but do generally not yield the same benefits.
Small difference in crucial factors	Factors such as deterioration rates of different parts of the track structures are crucial for the overall performance of the track. Since this is well known, most track systems are the results of significant efforts in addressing these topics. Consequently, the differences between systems are small and very difficult to quantify in an overview assessment. For this reason, it is likely that most solutions end up at similar ratings. Thus, even if the weight factor is high, there will be little distinction between the solutions even if they will result in significantly different operational lives and maintenance needs.

Table 7.1: Potential issues in the assessment process

7.1.2 In-depth assessment method

In-depth assessments of track design typically rely on numerical simulations and/or (laboratory or field) experiments. These provide a detailed analysis of specific aspects of the track structure. A benefit related to these types of analyses is that they can consider "what-if" scenarios; what will the consequence be if the axle load is increased. This is especially the case for numerical simulations. This is important in tackling one of the major challenges for in-depth assessment which is that they require large amounts of input data that are commonly not available. Through evaluation of "what-if" scenarios (or more correctly: through sensitivity analyses) it is often possible to estimate boundaries for the response of the track structure even if input data is lacking. As for overview assessments, the outcome of in-depth analyses is highly sensitive to the competence of the persons carrying out the analyses: Incorrect modelling assumptions or test simplifications may lead to completely misleading conclusions. As for the discussion on overview assessments, the discussion below of potential pitfalls of the methodology presumes that evaluation is performed by competent, fully informed and unbiased evaluators. Some remaining potential pitfalls that relate solely to the evaluation methodology are described in Table 7.2.

Potential pitfalls	Description
Translation of assessment results to operational consequences	The evaluations will result in measures such as stress levels, deformations, carbon emissions etc. These can be compared to e.g. material strength, currently allowable deformations and targets for emissions. However, the issue still remains of whether the levels are acceptable and – if so – how the benefit of increased/decreased values should be quantified. Note however that in detailed assessments it is easier to handle "non-linear" assessments in the sense that limit magnitudes and non-linear benefits can be prescribed.
Full-system analysis	It is an inherent feature of detailed analyses that the entire system cannot be analysed: A numerical model can of course include both train and track, but some aspects (e.g. the detailed ballast response) then need to be simplified or omitted. The nature of these simplifications will depend on the focus of the investigations. Restraints in time, resources and knowledge (evaluation of some aspects is still beyond the current research front) inevitably requires some aspects to be omitted. If these aspects turn out to be crucial, this is problematic.
Weighting of criteria	Detailed analyses are generally objective in the sense that they will result in a quantification of some variable that relates to some operational performance of the track. The magnitude of the evaluated variable can then be compared to limit values and criteria. Several in-depth analyses will provide a more detailed picture. However, what the detailed analyses cannot provide is a weighting of the different criteria towards each other. This strongly relates to the issue of proper weighting for the overall assessment. It should however be noted that the situation of weighting setting out from detailed analyses is more beneficial: It is easier (although far from straight-forward) to compare a decreased noise emission of 5dB to a decrease in surface pressure of 5 MPa than to compare a "less noisy" solution to a "lighter" solution.

Table 7.2: Potential pitfalls related solely to the evaluation methodology

7.1.3 Assessment Method Considerations

From the discussion above, it is clear that overview assessments and detailed assessments complement each other in a good way. In an ideal assessment scheme they should be combined such that:

- a first overview assessment is carried out to structure the assessment criteria and identify the most important issues;
- detailed analyses are carried out to compare the different solutions with respect to these criteria;
- more information of the exact situation for the project at hand is collected. The list of criteria is revised and limit values and weight factors for the different criteria are selected to represent the evaluation scenario;
- the results for the detailed analysis are evaluated with respect to limit values and evaluation criteria. Additional simulations are carried out if needed;
- the results from the detailed analyses are employed in a final evaluation of the different solutions based on weighted criteria.

Time and resources often prohibit such thorough evaluations from being carried out. Still, most evaluations of potential solutions already today follow (implicitly or explicitly) the broad outline of what has been described.

The aim of the current Deliverable is to make this procedure more stringent and demonstrate the overview assessment procedure for an example case as presented in Chapter 8.

References

In2Rail Deliverable D3.3: Evaluation of optimised track systems, 304 pp, 2017.

Pirsig, R. M. (1974). Zen and the art of motorcycle maintenance: An inquiry into values. New York: Morrow.

7.2 System requirements

Requirements can be considered as “a set of prioritised needs elicited from all stakeholders that together cover the functionality and performance required for the system or service to be developed or deployed”

The defining of requirements is an iterative process that gives the stakeholders the opportunity to explore, discuss, clarify and agree upon what the desired railway system will look like. The likelihood of a project satisfying the needs of the stakeholders is greatly increased when the stakeholders collaborate and agree on a shared vision bought about by insight into each other’s perspectives and needs.

Ambiguous requirements can lead to issues and tension between the stakeholders during the project and in the worst case scenario; it may lead to the selection of a system that is not fit for its desired purpose.

It is important to remember that; just as it would be unrealistic to embark on any project without a set of requirements, it would be equally as unrealistic to assume that once identified that the requirements would be a fixed target until the project is delivered. The requirements will change as issues arise and the project develops during its development lifecycle.

Reference

Network Rail, Requirements Engineering Fundamentals, NR/PSE/GUD/0231, Issue 03, December 2015.

7.3 Assessment group

As discussed in chapter 7.1.1 and 7.1.2 there are a number of ways errors can be introduced to an assessment and their accumulated effect could lead to the section of an unsuitable system.

To reduce the likelihood of error being introduced into the evaluation the assessment group where possible should:

- be experienced and component in their respective fields;
- provide representation from a diverse range of disciplines;
- be free from any conflicts of interest or affiliations;
- use independent subject matter experts where necessary to provide key research/data;
- include enough people to ensure a balanced output.

7.4 Selection and weighting of assessment criteria

7.4.1 Criteria selection

Selection of the correct criteria is fundamental and underpins the whole evaluation process. Whilst many of the assessment criteria are applicable to wide range of scenarios, there will always be a need to review and adjust depending on the location or operational requirements. Chapter 5 explained how known key performance indicators (KPI's) can be used for high level assessment criteria as they often reflect the strategic aim of a project.

7.4.2 Criteria Weighting

Weighting of the criteria allows for specific aspects of the assessment to be considered with differing degrees of importance and can be used to address specific project requirements, such as speed, axle loads or resilience to adverse conditions.

For example if the assessment were being done for a specific region such as Sweden, the system's ability to manage snow would be of higher importance and therefore weighted accordingly. If the assessment were being done for the UK the weighting for tolerance to seismic activity would be less than that of Italy.

7.5 Life Cycle Cost Analysis

Life Cycle Cost (LCC) analysis is an economic based assessment tool used as part of the decision making process and requires the calculation of the total cost of a system over its entire lifespan including development, investment, and maintenance and recycling.

This type of economic assessment on its own will not provide a guaranteed indicator of success, but when combined with additional methods of assessment such as RAMS and Value Analysis it significantly increases the chances of the best solution being identified.

Deliverable 6.5.4 of the INNOTRACK project provides a detailed Guideline for LCC and RAMS analysis.

Reference

INNOTRACK, Guideline for LCC and RAMS Analysis, D6.5.4, TIP5-CT-2006-0314

7.6 Option and Value Analysis

The weighted sum model (WSM) is one of the most popular and simple tools used for multi-criteria decision analysis (MCDA). MCDA allows for a number of options to be assessed against a set of decision criteria with given weights. However the decision criteria must be of the same unit, typically it will be a benefit score.

To demonstrate the WSM method:

- we have three systems, A,B and C.
- we have four criteria, C1, C2, C3, and C4.
- weightings have been determined as:

  - C1= 0.2, C2=0.15, C3=0.4 and C4=0.25

- benefit scores have been given in the table below,

Criteria	C1	C2	C3	C4
Weighting	0.2	0.15	0.4	0.25
Option A	25	20	15	30
Option B	10	30	25	30
Option C	30	10	30	10

Table 7.3: Weighted sum matrix

We therefore score the options in the following manner:

Option A score = (25 x 0.2) + (20 x 0.15) + (15 x 0.4) + (30 x 0.25) = 21.50

Option B score = (10 x 0.2) + (30 x 0.15) + (25 x 0.4) + (30 x 0.25) = 24

Option C score = (30 x 0.2) + (10 x 0.15) + (30 x 0.4) + (10 x 0.25) = 22

In this case the best option is the one with the highest score. That is option B.

7.6.1 Best Value Analysis

Best value analysis builds on the option analysis by incorporating the life cycle cost information with the option scores. This gives a more rounded and complete view of the systems value and allows for the best value option to be identified.

The Best Value analysis method is detailed further in the INNOTRACK document "Selection of a Railway Track System by Best Value Analysis".

Reference

INNOTRACK, Selection of a Railway Track System by Best value Analysis, TIP5-CT-2006-031415.

Triantaphyllou, E. (2000). *Multi-Criteria Decision Making: A Comparative Study*. Dordrecht, The Netherlands: Kluwer Academic Publishers (now Springer). p. 320. ISBN 0-7923-6607-7.

8 Example Track System Evaluation

The following process was undertaken to demonstrate an approach to the evaluation and selection of innovative track systems. The evaluation was undertaken as rigorously and as independently possible given what the project time and resources would permit.

For this exercise a range of systems are considered against a generic scenario using the "Best Value Analysis" method of evaluation.

The process requires the following steps to be carried out:

1. track classification;
2. stakeholder identification;
3. determination of importance criteria;
4. benefit evaluation;
5. option evaluation;
6. option analysis;
7. costing;
8. Value Analysis;
9. monetary equivalent of value savings (omitted from this exercise).

8.1 Track Classification

For the purpose of the example evaluation a simplified generic profile has been assumed that is broadly speaking, similar and relevant to all European countries.

Traffic – Mixed traffic including passenger and freight.

Speed – 0 to 200km/h

Axle load - 22.5 tonne

Gauge - No exceptional gauge constraints, standard rail gauge of 1435mm and suitable for containers.

Access - Typical night possessions and longer weekend possessions.

Formation – No additional consideration given for areas of high or low stiffness, average level of ground water with acceptable drainage.

Structures – No additional consideration given for tunnels, bridges, viaducts or embankments.

8.2 Stakeholder identification

The following members of Task 3.4 were considered to be the stakeholders and undertook the evaluation:

- Network Rail;
- Acciona;
- Chalmers University of Technology;
- Embedded Rail Technlogy;
- FCC Servicios Ciudadanos;
- Lulea Tekniska Univsitet;
- Systra;
- University of Huddersfield;
- University of Southampton

8.3 Assessment Criteria

To ascertain the criteria for the evaluation the stakeholder group identified in Chapter 8.3 undertook a workshop session to discuss and agree on the range of criteria to be included and how the criteria were to be defined.

The criteria selected focussed on the following key areas:

- design performance;
- buildability;
- safety;
- environment;
- maintenance.

Annex B of this document lists all of the criteria that were used during the evaluation and provides a brief description of how they were interpreted by the group.

8.4 Benefit evaluation

Each of the assessment criteria were weighted in order of their importance. This was carried out during the same workshop that was used to determine the criteria and descriptions in Chapter 8.4.

During the workshop each of the criteria was explained to the group by the chair person. When a broad agreement was achieved, each person of the assessment group identified by use of a flip pad their weighted score. If the scores were found to be broadly similar then an average was used. In situations where a score was considerably stretched further discussion took place to clarify and reach an accepted level of understanding.

The agreed weighting system used was based on 10 being Excellent, 7 Good, 4 Fair and 1 as Poor.

8.5 Option evaluation

Given the wide range of systems available on the market and those currently under development it is not possible within the confines of this project to evaluate them all.

For the purpose of this exercise a short list of 13 representative trackforms was drawn up for assessment by the group. The shortlist includes some well-studied current systems against which to compare the potential of the new systems so that any improvement can be identified. The short list includes two track concepts developed as part of the Capacity4Rail project.

Of the tracks commonly found in the rail network the following were taken to be representative of their generic group:

1. PoRR slab trackform;
2. Sleepers on asphalt GETRAC®;
3. Rhomberg IVES track;
4. Slab track with Booted Sleepers;
5. 'Moulded Modular Multi-blocks Track' (3MB);
6. Ballast track with an asphalt layer;
7. Systra Beam Track.

Grouping of track systems is discussed in Chapter 6.

These were added to tracks systems that have previously been identified and studied in an Independent study commissioned by the UK Department for Transport:

8. Ballast track (BLT);
9. Japanese slab track (JST);
10. German slab track (GST);
11. Prefabricated slabs on asphalt base (PSA);
12. Rheda2000 (Rh2)
13. Balfour Beatty embedded rail system (BBERS)

Of these 13 systems, 6 are in extensive use, 2 are proven in traffic and 3 represent new concepts.

8.6 Option analysis

Each member of the assessment group individually assessed the track system options against the weighted criteria.

The scoring used was 10 being Excellent, 7 Good, 4 Fair and 1 as Poor.

The group were able to make use of an online collaboration tool developed for the In2Rail project. The application allows members to work in a shared online space and input scores as they determine them. This hand off approach is valuable when it's difficult to arrange for all members to be in the same place at the same time.

The assessment is controlled by one person and until each stage is fully completed progress to the next stage is not permitted. Where scoring conflicts arise the system allows for an online discussion to take place by the people scoring at the extremities so that a resolution can be made.

To reduce bias ERT did not score the embedded rail system during the analysis stage.

Annex C of this document provides the scoring data collected from the online collaboration assessment exercise.

8.7 Life Cycle Cost

For the purpose of the evaluation, the LCC model developed for a slab track research project (ref RO1012, April 2010) commissioned by the Department for Transport (UK Government) and carried out by Booz & Company has been used.

Additionally this deliverable has taken the opportunity to update the original findings of the Booz report with a selection of innovative, hybrid, and potentially high value systems. These were identified as options 1-7 in Chapter 8.6.

The updated report and cost information can be found in its entirety in the Addendum document – Slab Track Research Project Addendum 2017/2018, ref R17031-04 and was carried out independently of Task 3.4 by Rebel Group.

The LCC model enables calculations with an all but endless number of parameter settings to match the actual route characteristics. To demonstrate how the LCC can vary given the variance in input data, four different scenarios have been defined for comparison:

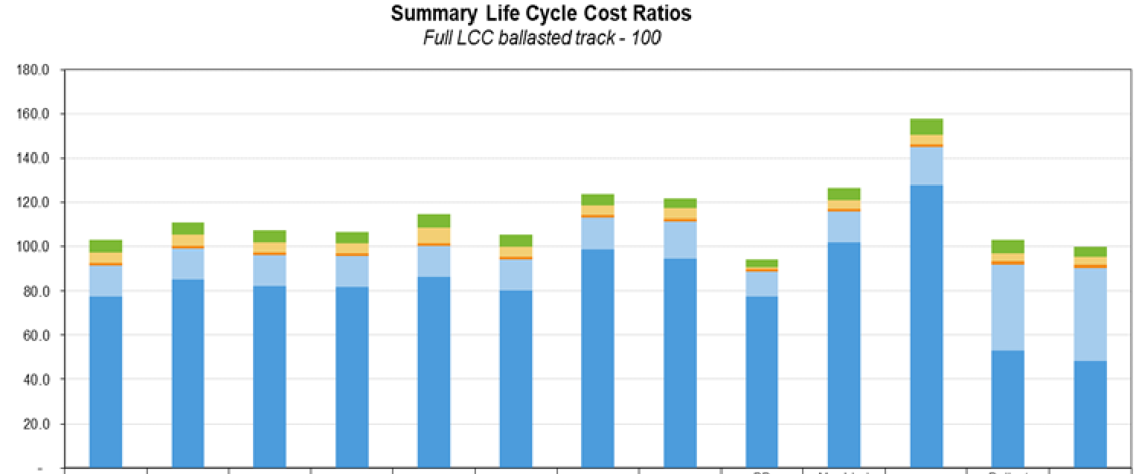
- **Base Case:** model parameters match a typical UK route; track possession duration is 'full weekend';
- **Extended Working:** the duration of the track possession is set to 'full week', all other parameters are conform base case;
- **Better Subsoil:** higher percentage of the route on good soils, all other parameters conform to base case;
- **Less Trains**: annual tonnage 50% of base case, all other parameters is conform base case.

Additionally, two sensitivity analyses have been conducted to provide an insight into the impact of the parameters below on the overall LCC:

- **Possession time:** comparing the impact of track possession times on LCC;
- **Annual tonnage:** comparing the impact of higher and lower annual tonnage on LCC.

8.7.1 Scenario 1 - Weekend only working (52 hours) - Base Case

The Base Case scenario has been selected as it represents a typical section of a route in the UK.



	Japanese Slab Track	Bögl Slab Track	PORR Slab Track	Prefab Slabs on Asphalt	Rheda 2000	Sleepers on Asphalt	Rhomberg	Booted Sleeper	BB Embedded Rail System	Moulded Modular Multi-Blocks	Systra Slab Track	Ballast Track on Asphalt layer	Ballast Track
Disruption *)	5.7	5.7	5.7	5.3	5.7	5.3	5.3	4.5	3.7	5.7	7.2	5.8	4.5
Risk	4.8	4.9	4.3	4.3	7.3	4.5	4.5	4.5	0.6	4.2	4.1	3.7	3.7
Maintenance	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.1	1.2	1.2	1.5	1.6
Renewals	14.1	14.1	14.1	14.1	14.1	14.1	14.1	17.1	11.3	14.1	17.1	38.9	41.9
Initial Construction	77.4	85.1	82.1	81.9	86.3	80.3	98.8	94.5	77.4	101.6	127.9	53.0	48.4

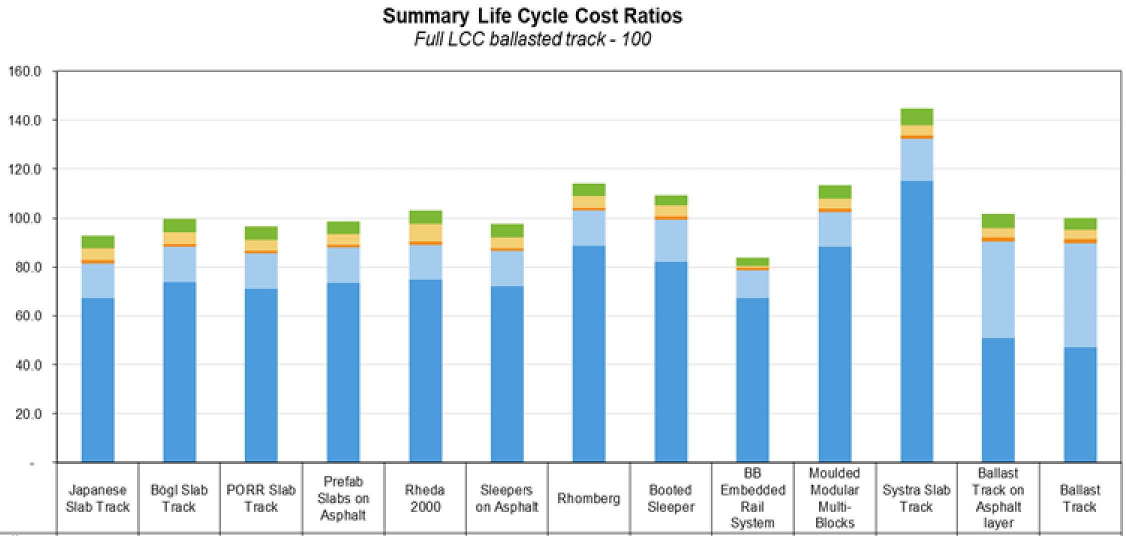
Figure 8.1: Summary LCC Ratios- Weekend only working (52 hours) - Base Case

Ballast track (with and without asphalt layer) and the BB embedded rail have the lowest life cycle cost of the considered track structures. The initial construction cost for BB embedded rail is higher compared to ballast track but the renewal need over the life-cycle is lower, resulting in comparable LCC values.

All other ballastless track structures are more expensive, which is predominantly due to the initial construction cost.

8.7.2 Scenario 2 - Weekday "Extended working"

The 'extended working' scenario uses the base case input parameters with the exception of the possession duration, which has been changed to 'full week' to show the impact of longer working times.



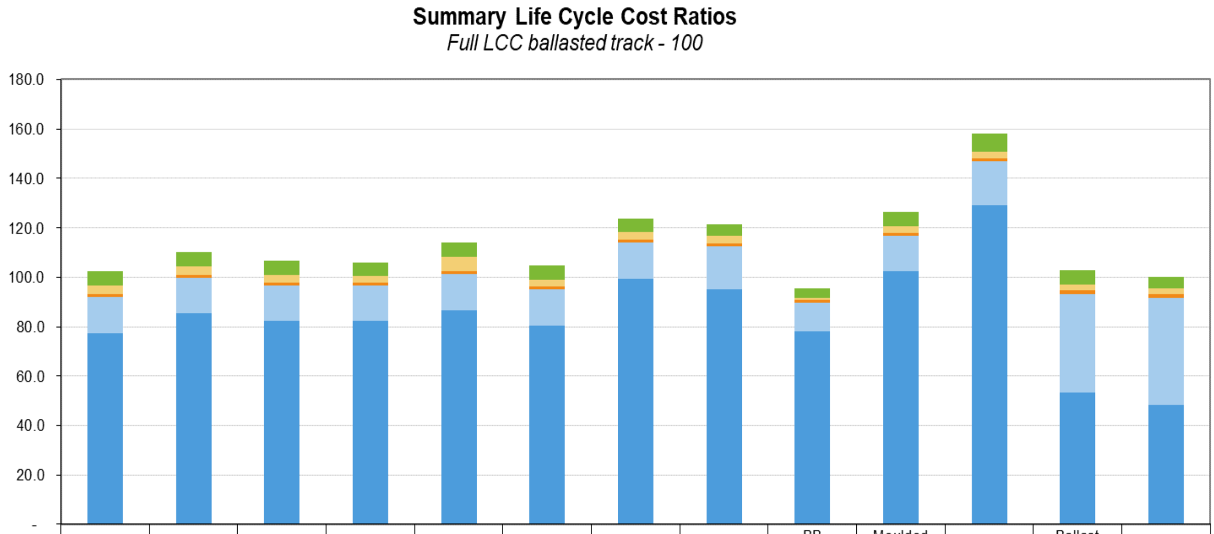
	Japanese Slab Track	Bögl Slab Track	PORR Slab Track	Prefab Slabs on Asphalt	Rheda 2000	Sleepers on Asphalt	Rhomberg	Booted Sleeper	BB Embedded Rail System	Moulded Modular Multi-Blocks	Systra Slab Track	Ballast Track on Asphalt layer	Ballast Track
Disruption *)	5.3	5.3	5.3	5.3	5.3	5.3	5.3	4.2	3.4	5.3	6.8	5.9	4.8
Risk	4.9	5.0	4.4	4.3	7.4	4.5	4.6	4.6	0.7	4.3	4.2	3.7	3.7
Maintenance	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.1	1.2	1.2	1.6	1.6
Renewals	14.3	14.3	14.3	14.3	14.3	14.3	14.3	17.4	11.5	14.3	17.4	39.6	42.8
Initial Construction	67.2	73.9	71.2	73.6	74.9	72.2	88.8	82.0	67.2	88.2	115.0	50.8	47.1

Figure 8.2: Summary LCC Ratios - Scenario 2 - Weekday "Extended working"

Over the whole range of ballastless tracks, the life cycle cost is significantly reduced by the lower cost for initial construction as a result of greater efficiency. The BB embedded rail, prefab slabs on asphalt, sleepers on asphalt, PORR slab track and Japanese slab track are now under the cost level of the two ballast track systems.

8.7.3 Scenario 3 - Better subsoil

The 'better subsoil' scenario uses the base case input parameters with the exception that the soil conditions have been changed to show the impact that better soil conditions has on the overall LCC.



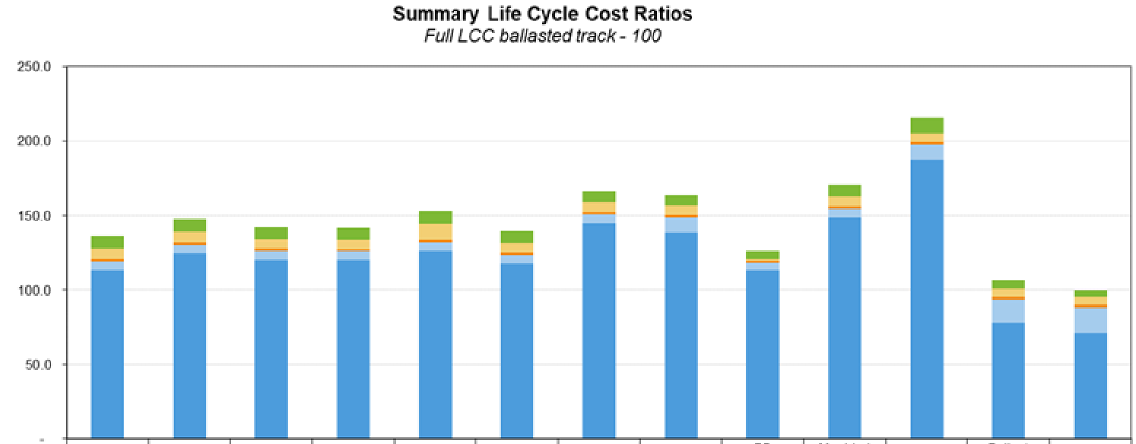
	Japanese Slab Track	Bögl Slab Track	PORR Slab Track	Prefab Slabs on Asphalt	Rheda 2000	Sleepers on Asphalt	Rhomberg	Booted Sleeper	BB Embedded Rail System	Moulded Modular Multi-Blocks	Systra Slab Track	Ballast Track on Asphalt layer	Ballast Track
Disruption *)	5.8	5.8	5.8	5.5	5.8	5.5	5.5	4.6	3.8	5.8	7.3	5.9	4.6
Risk	3.4	3.5	2.9	2.8	5.9	3.0	3.1	3.1	0.7	2.8	2.7	2.3	2.3
Maintenance	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.1	1.2	1.2	1.6	1.6
Renewals	14.4	14.4	14.4	14.4	14.4	14.4	14.4	17.5	11.6	14.4	17.5	39.8	43.0
Initial Construction	77.5	85.4	82.3	82.2	86.7	80.5	99.5	95.0	78.1	102.3	129.3	53.2	48.5

Figure 8.3: Summary LCC Ratios - Scenario 3 - Better subsoil

With improved soil conditions, the amount of initial soil improvement works is reduced and the cost for risk related activities is reduced. Due to the discount rates used in the NPV calculation, the impact of the reduced risk related maintenance activities on the total life cycle cost is limited.

8.7.4 Scenario 4 - Less train tonnage

The 'less trains' scenario uses the base case input parameters with the exception of the annual tonnage, which has been changed to show the impact that a lower tonnage has on the over LCC.



	Japanese Slab Track	Bögl Slab Track	PORR Slab Track	Prefab Slabs on Asphalt	Rheda 2000	Sleepers on Asphalt	Rhomberg	Booted Sleeper	BB Embedded Rail System	Moulded Modular Multi-Blocks	Systra Slab Track	Ballast Track on Asphalt layer	Ballast Track
Disruption *)	8.3	8.3	8.3	7.8	8.3	7.8	7.8	6.6	5.5	8.3	10.5	5.8	4.4
Risk	7.0	7.1	6.3	6.3	10.7	6.5	6.6	6.7	0.9	6.2	6.1	5.4	5.4
Maintenance	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.5	1.5	1.9	1.9
Renewals	5.9	5.9	5.9	5.9	5.9	5.9	5.9	10.3	4.8	5.9	10.3	15.9	17.4
Initial Construction	113.5	124.8	120.3	120.1	126.4	117.7	144.8	138.4	113.5	148.9	187.5	77.6	70.9

Figure 8.4: Summary LCC Ratios - Scenario 4 - Less train tonnage

The reduction of annual tonnage has a direct impact on the maintenance activities that are tonnage related and on the number of renewals for ballast track. The latter has a major impact as the renewal cost for ballast track is a major cost factor; with the first renewals being pushed back in time significantly, the impact in NPV is big. The impact on all ballastless track structures is much lower because the renewal component is much smaller compared to the initial investment.

8.8 Sensitivity Analysis

8.8.1 Sensitivity analysis 1 - Possession duration

The input parameters for the sensitivity analysis remain the same as those used for the base case scenario with the exception of the possession duration.

As expected the construction efficiency is greater with longer track possession. This is particularly the case for ballastless tracks that require curing of materials and is one of the reasons why it’s not possible to construct ballastless track systems during nightly possessions.

8.8.2 Sensitivity analysis 2 - Annual tonnage

The input parameters for the sensitivity analysis remain the same as those used for the base case scenario with the exception of the annual tonnage.

It was found that as the annual tonnage increases, ballastless track becomes more cost effective when compared to ballast track, especially when the annual tonnage is around 20MGT and higher.

8.9 Value Analysis

Value analysis is the combination of the option analysis (systems scores) and the total LCC costs.

Annex D of this document provides the value analysis data in full for the four LCC scenarios outlined in Chapter 8.8.

Table 6.2 demonstrates the value analysis using the base case scenario.

Table 6.3 describes the individual criteria used to derive the best value ranking.

A	B	C	Japanese Slab Track	Bögl Slab Track	PORR Slab Track	Prefab Slabs on Asphalt	Rheda 2000	GETRACK Sleepers on Asphalt	Rhomberg	Booted Sleeper	BB Embedded Rail System	Moulded Modular Multi-Blocks	Systra Slab Track	Ballast Track on Asphalt layer	Ballasted Track
Ref			1	2	3	4	5	6	7	8	9	10	11	12	13
	Scenario	Benefits	1877	1889	1943	1804	1915	1913	1973	1925	1989	1821	1762	1780	1751
		Benefits Ranking	8	7	3	10	5	6	2	4	1	9	12	11	13
A	Base case	Installed costs	77.4	85.1	82.1	81.9	86.3	80.3	98.8	94.5	77.4	101.6	127.9	53	48.4
		Post installed costs	25.8	25.9	25.4	24.9	29.3	25.1	25.1	27.3	16.7	25.2	29.6	49.9	51.7
		Total Life Cycle costs	103.2	111	107.5	106.8	115.6	105.4	123.9	121.8	94.1	126.8	157.5	102.9	100.1
		Installed Cost Value rating	24.25	22.20	23.67	22.03	22.19	23.82	19.97	20.37	25.70	17.92	13.78	33.58	36.18
		Installed Cost Value ranking	4	7	6	9	8	5	11	10	3	12	13	2	1
		LCC value Rating	18.19	17.02	18.07	16.89	16.57	18.15	15.92	15.80	21.14	14.36	11.19	17.30	17.49
		% of Best LCC Value	86.0%	80.5%	85.5%	79.9%	78.4%	85.9%	75.3%	74.8%	100.0%	67.9%	52.9%	81.8%	82.8%
		LCC Value ranking	2	7	4	8	9	3	10	11	1	12	13	6	5

Table 8.1: Base case scenario value analysis

Benefits	The total weighted score for a given system.
Benefits ranking	System ranking based on benefits only.
Installed cost	Base construction cost
Post installed cost	Disruption, risk, maintenance and renewal costs combined
Total life cycle cost	Sum of the installation and post installation costs.
Installed cost value rating	Benefits divided by installed costs.
Installed cost value ranking	System ranking based on installation cost.
LCC value rating	Benefits divided by total LCC.
% of best LCC Value	LCC value rating percentage of the highest scoring LCC Value.
LCC Value Ranking	System ranking based on LCC value rating.

Table 8.2: Criteria definitions

As we can see from the analysis in Table 8.2, the top three ranked systems at each stage are:

Benefits only:

- Embedded Rail
- Rhomberg Sersa
- PORR Slab Track

Installed cost only:

- Ballast Track
- Ballast on Asphalt
- Embedded Rail

LCC & Benefits:

- Embedded Rail
- Japanese Slab track
- Sleepers on Asphalt

9 Summary, Conclusions and Recommendations for further action in Shift2Rail

The evaluation and selection of track systems is a complex and time consuming process. However, given the cost of such installations and the expectations placed upon them it's essential that all suitable options are carefully considered at the project outset.

There is no one size fits all approach to the evaluation of innovative track systems; there are simply too many factors to be taken into consideration. Therefore, the object of this deliverable has been to demonstrate a guideline process that can be applied to a range of situations. The use of a clear and organised approach demonstrates an objective and transparent selection process free from bias and prejudice.

Below are a number of key summary points to be considered when undertaking an evaluation of a range of innovative track systems:

1. sufficient time should be allocated at the design phase of a construction project to allow for a detailed and robust system evaluation to be carried out;
2. when commencing a track system evaluation consideration should be given to available options that have been proven in the market. Only then can you compare a new solution against the existing to identify potential benefit uplift. It is no guarantee that because a system is new it will be better that what previously existed;
3. the competence of the people involved in the evaluation will significantly impact on the scoring process. Having a broad range of skills and experience available will increase the likelihood of the scoring being more accurate. Where necessary the use of independent experts should be considered;
4. the identification of detailed system requirements at the outset of the project provides a foundation for developing an accurate and robust scoring exercise;
5. it is clear that overview assessments and detailed assessments complement each other in a good way. In an ideal assessment scheme they should be combined;
6. LCC can be used to model a range of different scenarios and undertake sensitivity analysis. This additional work my result in alternative solutions being more suitable for a given requirement. The increased accuracy of the input data for LCC modelling will significantly affect the output;
7. value analysis enables the track system selection process to move away from single parameters such as LCC to a more holistic environment. The output from the evaluation shows us that that if one were to only take the LCC costs as the guiding parameter for the selection of a system, it may in reality not be the best option in the long term.

9.3 Assessment findings

Based on the exercise undertaken as a part of this deliverable the following systems were found to score highly and should be put forward for further investigation/development in the wider Shift2Rail project:

1. BB Embedded Rail;
2. Japanese slab track;
3. GETRACK Sleepers on asphalt.

It must however be noted that the evaluation was limited in some respects for the purpose of the deliverable. The degree of information available for the systems varied depending on how advanced they were in their technical development. It cannot be guaranteed that should the same analysis be undertaken for a more defined scenario with detailed supporting data then the results would be the same.

10 Annex A – KPI Assessment Criteria

This information in this annex is intended to support the KPI's identified in Chapter 5 of this document.

10.1 Differential Settlement

Settlement is the vertical movement of the ground under an applied load. This may be uniform settlement (the whole system moves by the same amount) or differential settlement (different parts of the system move by different amounts). Differential settlement is the more troublesome for track and commonly requires replacement or relevelling of the Sub Structure, be it slab or ballast : OR it may be 'minor settlement' which can be accommodated in short possessions or outside service hours usually by modifying the sub system and its fixings. A large settlement may not be significant if it is not differential.

Railway track develops plastic settlement with cumulative tonnage of traffic as a result of the deformation of both the ballast (where present) and the subgrade. Permanent deformation arises from (i) densification (volume reduction) caused by rearrangement of the particles or grains, and possibly particle breakage and wear; and (ii) shear deformation of the ballast and/or the subgrade[1]. For high quality track built to modern construction specifications, the plastic settlement per loading cycle (axle pass) after initial bedding in should be low – perhaps in the order of a nanometre (10^{-9} m). Nonetheless over many millions of load cycles, plastic settlement in the order of centimetres (10^{-2} m) may accumulate[2]. However, this settlement is not uniform along the line such that differential settlement builds up with traffic. Deviation from the design geometry leads to accelerations of vehicles and variations in dynamic increments of load which in turn contribute to varying rates of differential settlement.

10.1.1 Track Quality (Global KPI)

Differential settlement is not routinely measured. However, the non-uniformity of settlement along the track often results in a gradual deterioration in the quality of the track geometry (usually referred to as track quality). Track quality may be measured using dedicated, instrumented Track Recording Cars (TRCs). Wheel/axle acceleration is measured and the resulting data processed & filtered over wavelengths of 35 m, 70 m or 150 m (depending on the speed category of the line) to provide relative level/alignment. A standard deviation (SD) from the design geometry for longitudinal level ("top") and alignment ("line") may be determined and related to the general level of differential

[1] Dahlberg, T. (2006). Track issues. In *Handbook of railway vehicle dynamics* (ed Iwnicki, S.). CRC Press

[2] Shenton, M. J. 1984. Ballast deformation and track deterioration. In *Track Technology* (Proceedings of a conference organised by the Institution of Civil Engineers), 253-265. University of Nottingham, UK

settlement along track sections e.g. in the UK track quality is reported per 1/8 of a mile. Historical records may be used to project forward and plan track maintenance and renewal operations at prescribed trigger levels of SD for track categories which are more onerous for faster and more heavily trafficked/loaded lines.

10.1.1.1 Track stiffness (Contributing KPI)

More recently vehicle based measurements of track stiffness have been developed and are starting to be routinely deployed. For example a new type of TRC (IMV100) used by Trafikverket allows for simultaneous measurement of longitudinal level and track stiffness. Longitudinal level is measured by means of accelerometers mounted on the car body and compensation LVDTs (Linear Variable Differential Transformer) between the wheelset and the car body. Together with a mechanical chord system, these systems form the basis for the EVS (EBER Vertical Stiffness) method of vertical stiffness measurement[3].Trackside systems of track stiffness measurement using accelerometers, geophones and high speed filming systems[4,5]are also becoming common place. However, these would be restricted to the measurement of stiffness and its changes over time at localised sections of track for which specific needs may justify dedicated deployment.

Changes in stiffness and the general variability of support stiffness are thought to be drivers of differential settlement (e.g.[6]) because changes in stiffness give rise to vehicle accelerations and resulting increments of dynamic load. Understanding of how track stiffness measurement could be used to predict track settlement is at an early stage and more data is needed to develop more rigorous relationships.

10.1.1.2 Propensity to settle (Contributing KPI)

The propensity towards settlement of a particular trackform and the natural soil present gives an indication of the potential magnitude of differential settlement. However, equations to predict track settlement able to account for all the potential trackforms and soils present remain at best empirical. Also, while numerical models based on particular settlement models have been developed and provide insights into the development of differential track settlement these remain strongly dependent on the types of settlement

3 E. Berggren, A. Nissen & B.S. Paulsson, Track deflection and stiffness measurements from a track recording car, Proceedings of the Institution of Mechanical Engineers, Part F (*Journal of Rail and Rapid Transit*), 228(6), 570-580, 2014

4 Le Pen, L., Milne, D., Thompson, D. & Powrie, W. 2016. Evaluating railway track support stiffness from trackside measurements in the absence of wheel load data. *Canadian Geotechnical Journal,* 53**,** 1156-1166.

5 Bowness, D., Lock, A. C., Powrie, W., Priest, J. A. & Richards, D. J. 2007. Monitoring the dynamic displacements of railway track. *Proceedings of the Institution of Mechanical Engineers, Part F (Journal of Rail and Rapid Transit),* 221**,** 13-22.

6 Sussman, T., Ebersöhn, W. & Selig, E. 2001. Fundamental Nonlinear Track Load-Deflection Behavior for Condition Evaluation. *Transportation Research Record: Journal of the Transportation Research Board,* 1742**,** 61-67.

equations applied. Research continues into understanding how different trackforms/systems settle but nonetheless assessment of the potential to settle of a particular system can be carried out qualitatively and theoretically provided certain assumptions are made. The critical factor occurs when the 'differential' settlement, rather than the settlement at any particular location, puts the railhead out of its required alignment specification.

10.1.1.3 Summary

The measurement of track quality has certain drawbacks, for example the classification of track sections by arbitrary lengths (e.g. 1/8 mile in the UK) does not provide sufficient granularity to identify particular local drivers of differential settlement, for example the presence of changes in trackform (e.g. at S and C), changes in underlying geology or the presence of substructures (e.g. bridges and buried culverts). Measurement of track stiffness could in principle be used to develop greater understanding of how local track quality is being affected by changes in support conditions along the track. Assessing particular trackforms for their propensity to settle both qualitatively using relative reasoned assessment and theoretically can provide insights into the potential for differential settlement to develop.

As more track stiffness monitoring data becomes available it may be possible to develop preventative maintenance strategies to target the drivers of differential settlement before differential settlement even becomes apparent.

10.2 Lateral Track Stability

10.2.1 Resistance to lateral load/misalignment of the trackform (Global KPI)

Track needs to be able to resist lateral loading in order to maintain acceptable alignment for normal use. Similarly to vertical settlement of the track, differential movement of the lateral alignment can progressively lead to the need to realign the track through planned maintenance interventions. However lateral stability is also required to guard against the occurrence of rail buckles which require immediate closure of routes and emergency remediation. It should be pointed out that in practice 'track buckling' only applies to ballasted track. The lateral restraint provided by concrete slab track is so high that lateral displacement of the track is effectively zero. No additional measures are required as long as the requirements for rail destressing, especially on long structures, are fully complied with.

10.2.1.1 Difference between target and actual stress free temperatures (Contributory KPI)

It is not currently possible to measure the rail SFT using TRCs. The methods for measuring SFT are highly disruptive and either involve rail cutting or removal of clips over lengths of 70m or more.

10.2.1.2 Incidence of speed restrictions or other controls being applied (Contributory KPI)

Incidences of preventative speed restrictions (and/or other buckling prevention controls) due to e.g. high temperatures coupled with known risk factors and track buckling per unit time indicate the performance of the network, although need to be understood in the context of local weather (e.g. all things being equal, a hot summer will produce more track buckles as the rail temperature will exceed SFT).

Track buckles are caused by the compressive stress in the rail exceeding the lateral resistance of the track. This is usually initiated by dynamic loading due to the passage of a train and may occur where there is an existing lateral alignment or gauge defect which may be indicative of increased compressive stress in the rail.

10.2.1.3 Lateral track resistance (Contributing KPI)

As mentioned above, it is difficult to measure the track features that allow track buckles to develop. A simple solution to this is to increase the lateral track resistance. This can be done by adding ballast (especially to the shoulder at the sleeper ends; as extra width up to a certain critical value, then as extra height[7]), compacting (stabilising) the ballast, and assuring the integrity of fastenings. More drastic remedial actions include modifications of the track structure e.g. through modifications to sleepers such as the attachment of centre- or end-plates or use of alternative sleeper designs. This is considered further in In2Rail Work Package 5, which addresses more thoroughly the issue of lateral track stability, in particular, the possibility of enhancing the lateral stability of sleeper tracks on ballast is investigated.

10.2.1.4 Summary

The effects of insufficient track lateral resistance can be easily measured in the form of track buckles. It is possible to detect some possible pre-cursors of track buckles by monitoring the changes in lateral alignment and gauge using Track Recording Coaches as well as monitoring temperature which increases the lateral forces on the track which can lead to buckling.

The most effective measures for preventing the application of speed limits and other measures to reduce the risk of track buckling, while reducing the number of buckling incidents is likely to increase the track lateral resistance, particularly in at-risk areas (e.g. curves with a radius of less than 300 m), using the methods described above.

[7] Le Pen, L., Bhandari, A. R. and Powrie, W. (2014). Sleeper end resistance of ballasted railway tracks. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, April 2014. DOI 10.1061/(ASCE)GT.1943-5606.0001088

10.3 Transition Zones

In general terms, a transition zone is a discontinuity in support conditions between different types of connected track sections. Transitions typically occur where slab track abuts ballasted track, or where any track form (but most usually ballast) crosses a major change in support ground conditions such as a bridge deck or a box culvert.

Transitions are usually characterised by an abrupt variation in track stiffness (i.e. ratio of the load applied to the rail to the vertical rail deflection) resulting from different types of support construction and material characteristics either side of the transition. This leads to non-uniform vertical displacements, hence non-uniform dynamic loading and damage including rail corrugation and wears; fatigue failures in the rail and fastening systems; cracked sleepers; and accelerated settlement of the ballast at different rates along the transition.

Accelerated local settlement is often associated with an increased risk of rail break in and around the transition because of the increased bending stresses imposed. This leads to increased dynamic loads as tonnage accumulates, further accelerating differential track degradation. Frequent maintenance and even renewals are then required to ensure continued safety and passenger comfort, resulting in a loss of route capacity, availability and increased costs.

As explained in In2Rail D3.3 and as demonstrated through reported site measurements, the majority of the vertical settlement occurs in the ballast layer and the 'root cause' for the increase load is a consequence of voided sleeper. Several references in the literature also demonstrate numerically and experimentally the particularly significant effect of loose or hanging sleepers, where under specific conditions certain sleepers might not bear any load or impact on the ballast with greater pressure, leading to localised increase in ballast compaction and horizontal flow.

In the context of an evaluation for hybrid track, there is therefore a lot of scope to reduce issues surrounding transition zone because voided sleepers are a specific problem of conventional ballasted track. There are several implications on the use of hybrid tracks. On one hand they can potentially be used as a solution to known transition problem on ballasted track over structures, by installing a hybrid track form over and approaching structures. This might mean that the transition issue at the ends of the structure is eliminated or drastically reduced, and a smoother transition to standard ballasted track might be achieved further away in a more controlled way (hybrid being potentially close enough in form and shape to a ballasted track). On the second hand where hybrid track might be used over long distances, there might still be remaining transition, away from structures, onto different track forms, slab track or conventional ballasted track. Here again the hybrid concept, might help mitigate this differences if it has features matching the track it transition onto.

In terms of performance and quality of transition zones, there is a wider number of surrounding factors also influencing their behaviour. This includes axle load, train speed, direction of travel, geotechnical characteristics of the natural soil or subgrade and characteristics of the resilient layers and track components (e.g. rail pads, under sleeper pads and ballast mats).

The vehicle parameters (axle load, speed & direction) have an influence on the dynamics of the system, i.e. load amplification factor (peak pressure at any one location) and phase (variation of peak pressure along the track). The geotechnical track parameters have an influence on the overall stiffness behaviour and quality retention of ballast or the hybrid track structure. Other track components parameters influence the track's ability to spread the loads and reduce pressure on ballast so that it elastically recovers from loading.

10.3.1 **Rate of change of stiffness (Global KPI)**

The rate of change of track stiffness is the ideal primary measure of transition zone quality and performance. This is defined as the ratio of the load applied to the rail at any one point to the vertical rail deflection. There are vehicle based measurement techniques being developed in some countries and trackside systems of track stiffness measurement using accelerometers, geophones and high speed filming systems. However, these would be restricted to the measurement of stiffness and its changes over time at localised sections of track for which specific needs may justify dedicated deployment.

The former allows a continuous recording of equivalent track global stiffness over long distance (routes scale) and can also detect variation over structures to a resolution close to the sleeper spacing or equivalent to standard track recording vehicles track geometry resolution, i.e. around $^{1}/_{3}$ or a $^{1}/_{4}$ of meter. This means that transition zone quality and deterioration over time can be detected by running repeated measurements at time intervals and comparing evolution and generate trends. The problem remains that these vehicles are few and mainly used for research purposes at the moment. Also the acquisition method and the signal processing used, does not guarantee an absolute stiffness value, however, since transition zone are mainly characterised by spatial variation in stiffness this is acceptable.

The track based measurement techniques are obviously more intrusive, but they can be deployed effectively over specific site and given a large range of sensors, a detailed survey of a specific site performance under varying traffic can be obtained in a day or two. This can be repeated at wider interval to understand trends over time. This is a useful investigation and research method, but remains limited for a generic network based monitoring technique.

It is envisaged that the combined use of the above two techniques on specific case studies will help reinforce the quality and robustness of the vehicle based techniques and make them more widely available. In particular there are initiative looking at measuring voided sleeper or local support issues based on commercial running trains (cab or axle mounted measurement), these could eventually substitute dedicated measurement vehicles and carry out the same task, with the added advantage that multiple vehicles will run over each transition zone giving a performance report multiple time a day, and independent response based on different vehicles. This would increase the capability to predict and manage risk based maintenance and intervention.

If the above techniques are not available, the best proxy for track stiffness variation remains the rail deflection and in particular the deformed track geometry (rail horizontal level) as measured by track recording cars. Local issues in terms of hanging sleepers, or local support deterioration might be related to local exceedances or other measures such as track twist or cyclic top. However there are multiple reasons for the track horizontal level to vary and relating it to a specific rate of change of stiffness implies a better understanding of necessary treatment of the signal for specific wavelength of interest. This is still an area opened for more research. More detailed criteria are given in the contributing KPI that follow.

10.3.1.1 Length of transition as a function of traffic speed and end stiffness difference (Contributing KPI)

- at design stage, the difference in system stiffness either side of the transition needs to be established and the length designed to ensure sufficiently smooth transition between the two stiffness levels;
- after installation, the quality is ensured using standard horizontal level measurement from TRC's to identify soft spot or large variations [not currently established to look at transition zone, but signal processing could be developed to do so, in combination with other monitoring methods];
- vehicle mounted axle box acceleration measurement on first pass before possession is restored and monitored thereafter at increasing intervals as the transition zone settles [not currently an established method, still experimental].

10.3.1.2 Maintaining peak pressure at any sleeper connection within transistion zone below that of adjacent plain line. (Contributing KPI)

- at design stage through Finite Element or equivalent calculation method to ensure the track structure and mitigation measures lead to smooth transitions;
- after installation it is possible that sensors be embedded in the track structure to monitor load distribution over the length of the transition zone, before and after handover using for example Bragg fibres, strains gauges, compact load cells etc.

10.3.1.3 Maintaining sleeper vertical acceleration below a reasonably low value (<5g). (Contributing KPI)

- as measured by vehicle mounted axle box acceleration measurement [not currently an established method, still experimental but could be calibrated against sleeper acceleration];
- specific track site measurement using accelerometers and geophones or other remote monitoring techniques;
- using embedded sensors (accelerometers, Bragg fibre, etc.).

10.3.1.4 Maintain ballast confining pressure to a high consistent value. (Contributing KPI)

- using embedded sensors to ensure the quality of the ballast consolidation and that no significant ballast migration occurs;
- using remote sensor technologies to detect ballast migration;
- intrusive track site investigations.

10.3.1.5 Summary

Transition zones are unavoidable consequences of railway lines being installed on varying and non-homogenous geology, made of varying constructions types (ballast, ballastless and hybrid) but more importantly traversing structures such as bridges, culvert and tunnels.

Transition zones are a magnet for performance (increased maintenance and inspections) and safety issues (rail break), specifically because of the inherent limitations of ballasted track.

Design and performance of transitions zones are intrinsically linked to the rate of change of track stiffness, however while it is easy to design for it, it remains a challenge to measure it. Alternatively, measuring variation in vertical deflection of the track in transition zones is the most accessible measure, but technology needs to be developed to make this data measured in a more continuous way and with sufficient periodicity, ideally through in service vehicles, to enable risk and performance based maintenance decisions.

Finally, moving away from conventional ballasted track and using hybrid technology should enable an efficient control of transition zone related issues and expenses.

10.4 Value

10.4.1 RAMS (Global KPI)

RAMS characteristics are essential parameters relevant to the assessment of innovative railway solutions for ballasted, slab and other trackforms. Railway RAMS describes the confidence with which a system can guarantee the achievement of a defined level of rail traffic in a given time period, safely [1]. RAMS of a trackform is the qualitative and quantitative indicator of the degree that the system can be relied upon to function as specified and is both available and safe [2]. The selection of the methods, tools and techniques and models for determining RAMS performance should be based on the system complexity, configuration, operational context and data availability service requirement and purpose of analysis [1], [3]. It entails the determination of the following performance indicators: ***reliability, availability, maintainability and safety***.

10.4.1.1 Reliability (contributing KPI)

Reliability is defined as the probability that an item can perform a required function under given conditions for a given time interval, measured in terms of e.g. function probability, failure rate, mean time to failure (MTTF) or mean time between failure (MTBF).

10.4.1.2 Availability (contributing KPI)

Availability is defined as the ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external sources are provided. Availability can be seen as the total number of trains being able to run on a track section in a 24-hours day, while taken into account a time schedule for maintenance and an operational margin for potential train delays.

10.4.1.3 Maintainability (contributing KPI)

Maintainability is defined as the probability that a given active maintenance action, for an item under given conditions of use can be carried out safely and within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources and is measured in terms of e.g. mean time between maintenance (MTBM), mean time to maintain (MTTM) or mean time to restore (MTTR).

For railway tracks, maintenance operations include activities of inspection, maintenance, upgrade, and renewal. In reality inspection requires track possessions and therefore reduces the track availability. In addition to the time to repair and to the failure probability, the track maintainability is therefore increased with an easy access to the track component, its low number of parts, and an easy and fast maintenance activity.

For most tracks, maintenance activities which are the most time consuming and the most expensive, are usually the track geometry maintenance, which counts sometimes for more than 30% of the maintenance activities. The aim is to reduce track geometry irregularities by adjusting the track geometry alignment. This task can be eased by using mechanised equipment for the realignment. For assessing the maintainability of the track geometry, the track possession duration is also regarded, including the duration of works and the travel time for the plant between the maintenance facilities and the work site.

Finally, the requirement for speed restriction has to be taken into account. A speed restriction is set up during the works for operation safety, and can also be set up after the works for the track stabilization. Reduction or elimination of the requirement for maintenance is the best way to provide maintainability.

10.4.1.4 Safety (contributing KPI)

Safety is defined as freedom from unacceptable risk of harm and is measured as e.g. hazard rate, mean time between hazard system failures (MTBHSF) or numbers or severity of accidents.

10.4.1.5 Summary

The RAMS criteria aim at guaranteeing a good equilibrium between operations and maintenance, providing the best availability possible for the trackform. The availability is seen as a consequence of a low failure rate, and an efficient inspection and maintenance policy, while ensuring the system safety. These indicators will be particularly studied for track robustness and the track geometry, as these drive the main track maintenance activity and are critical for the operations safety.

10.5 Cost

10.5.1 **Life Cycle Cost (Global KPI)**

Life cycle cost (LCC) is a methodology for economic assessment of innovative railway solutions at various levels. It can provide basic decision support in the form of: strategic decisions, decisions between different variants, selection of appropriate solutions in terms of products and processes, optimization of existing systems. It can be applied to either the entire life cycle of a trackform or combinations of separate phases.

An important objective in the development of LCC models is to identify costs drivers, i.e. point out those cost elements that may have a major impact on the LCC or may be of special interest for that specific application. An important aspect in LCC analysis is the estimation of the RAMS related costs which is basically stochastic in nature and dependent on so many parameters (e.g. design, operation, environmental, maintenance). RAMS characteristics can be translated into the following cost elements: corrective maintenance cost, preventive maintenance cost, unavailability cost. Figure 8.1 shows the connection between some RAMS parameters and related operation and maintenance costs. These affect and are interactive with the Installed cost.

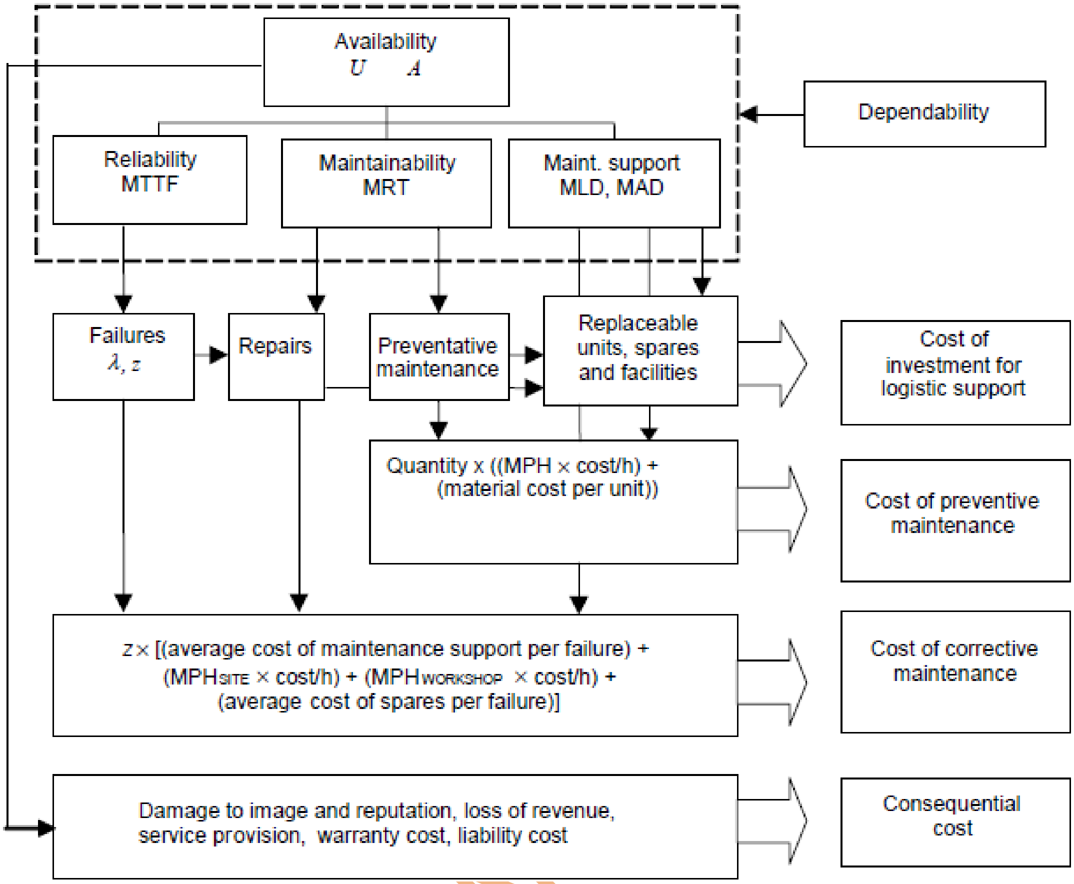


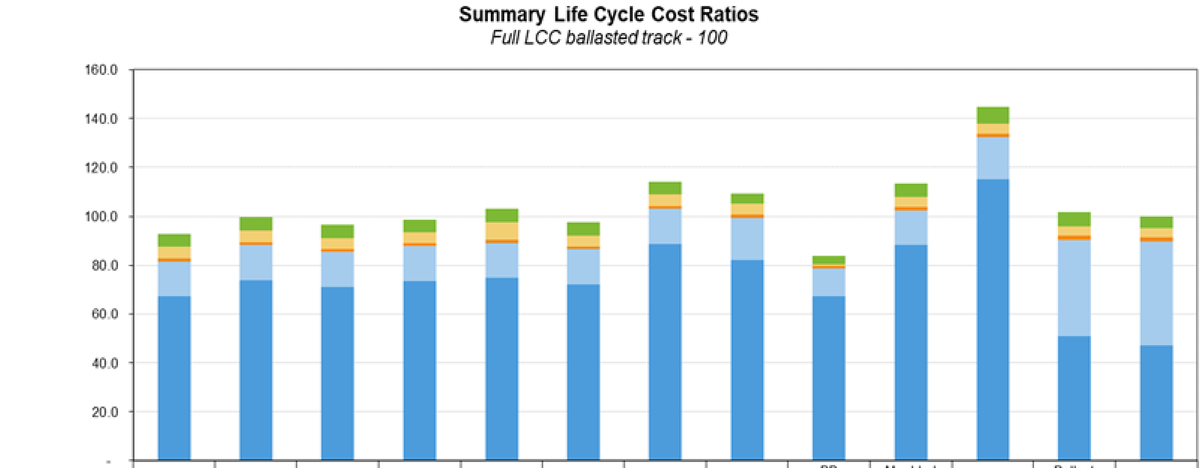
Figure 10.1: Connection between RAMS and LCC model for the operation and maintenance phase of the systems

To facilitate effective decision making or recommendation with LCC outcome, KPIs are required. The choice of the appropriate KPI depends on the use case, LCC requirements, system involved and analysis context. A list of economic KPIs that can be used the assessment of track solutions is given below:

- Corrective maintenance cost / Total maintenance cost;
- Preventive maintenance cost / Total maintenance cost;
- Total Maintenance Cost/ Asset Replacement Value;
- LCC / Total tonnage;
- LCC/ km or item;
- Annuity value or annual worth.

LCC Guidelines

The main building blocks and the constituent steps to guide LCC assessment of innovative railway solutions for ballasted, slab and hybrid trackforms are presented in



	Japanese Slab Track	Bögl Slab Track	PORR Slab Track	Prefab Slabs on Asphalt	Rheda 2000	Sleepers on Asphalt	Rhomberg	Booted Sleeper	BB Embedded Rail System	Moulded Modular Multi-Blocks	Systra Slab Track	Ballast Track on Asphalt layer	Ballast Track
Disruption *)	5.3	5.3	5.3	5.3	5.3	5.3	5.3	4.2	3.4	5.3	6.8	5.9	4.8
Risk	4.9	5.0	4.4	4.3	7.4	4.5	4.6	4.6	0.7	4.3	4.2	3.7	3.7
Maintenance	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.1	1.2	1.2	1.6	1.6
Renewals	14.3	14.3	14.3	14.3	14.3	14.3	14.3	17.4	11.5	14.3	17.4	39.6	42.8
Initial Construction	67.2	73.9	71.2	73.6	74.9	72.2	88.8	82.0	67.2	88.2	115.0	50.8	47.1

Figure 8.2.

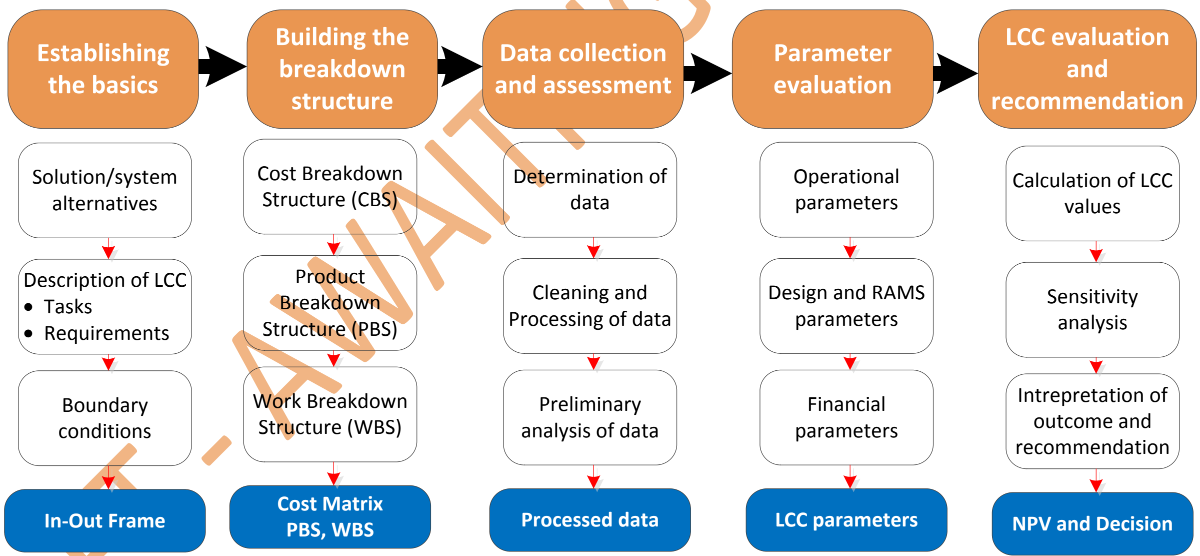


Figure 10.2: Guidelines and building blocks for LCC analysis [6]

This guideline covers different LCC aspects: description of LCC basics, building breakdown structure, collection of required data, evaluation of needed parameters and calculation of LCC values and interpretation of the outcome.

10.5.1.1 Capital costs (contributing KPI)

Capital costs represent the acquisition costs for all the track components.

10.5.1.2 Operational costs (contributing KPI)

Operation costs and unavailability costs are often gathered in one category, because they are all due to train operations. They are considered for the whole lifetime of the trackform.

10.5.1.3 Maintenance costs (contributing KPI)

Like operational costs, maintenance costs are considered for the whole lifetime of the trackform. Therefore it includes the renewal of some track components.

10.5.1.4 Renewal/termination costs (contributing KPI)

Renewal and termination costs are also gathered in the same costs category, since they correspond to the end-of-life costs.

10.5.1.5 Summary

The LCC analysis relies on the notion of the track lifetime, which should be seen as the duration time for which the track is operational and maintainable. In reality, a maintainability threshold is often set, above which the track maintenance and the renewal of some components is too expensive / unsustainable and a track renewal has to be instigated. During the track lifetime, Life cycle costs are split in four categories for the best value analysis: capital costs, operational costs, maintenance costs, and renewal/termination costs. However, since affordability is often the main criteria for the choice of a trackform, the Life of the track may in reality be reduced to 10 or 15 years.

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1. R.F. Stapelberg, *Handbook of reliability, availability, maintainability and safety in engineering design*, Springer, 2008.
2. EN 50126, "Railway applications - the specification and demonstration of reliability, availability, maintainability and safety (RAMS)," *European Standard* 1999.
3. N. Lyngby, P. Hokstad and J. Vatn, "RAMS management of railway tracks," in *Handbook of performability engineering,* K.B. Misra, Ed. London: Springer, 2008, pp. 1123-1145.
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5. EN 60300-3-3, "Dependability management part 3-3: Application guide – life cycle costing (European committee for standardization (CEN))," *European Standard* 2004.
6. INNOTRACK, "Guideline for LCC and RAMS analysis, INNOTRACK, project nr, TIP5-CT-2006-031415, deliverable D6.5.4," 2009.
7. INNOTRACK, “Guideline for Selection of a Railway Trackform by Best Value Analysis” Deliverable 2.3.6 “ 2009

10.6 Noise and Vibration

Noise and vibration criteria are related to the annoyance of the track surroundings. Both criteria come from the same excitation phenomenon.

These excitations are principally due to two mechanisms:

1. the relative displacement between the rail and the wheels: this displacement is induced by the combined roughness of the rail and the wheels. Several models are available for this displacement (TWINS[8], S-RIVE or VibraFer[9]), which consider the following main parameters: stiffness, mass and damping coefficient of the rail (infinite beam), the rail pad and the underlying resilient layer (soil is assumed to be rigid); the sleeper mass; the masses and the stiffness's which represent car bodies, bogies, and wheelsets (un sprung masses) and primary and secondary suspensions;
2. the deformation of the rail between two sleepers: this deformation generates small impacts and contributes to the low frequency vibrations transmitted to the soil. The main parameters are the distance between two sleepers, the train mass, the rail stiffness, and the train speed.

10.6.1 Acoustic radiation (global KPI)

For outdoor tracks, the noise is directly transmitted but can easily be reduced in the surrounding buildings by using adequate mitigation means (e.g. frontage soundproofing). The main phenomenon is the radiation of track and train elements (wheels and rails). This radiation is due to the vibrations generated in these elements by the excitation process.

The wheel/rail radiating noise comes from the stress imposed by the vehicle on the track. It derives from the vibrations and from the radiation of elements such as the wheel, the track and the sleepers. Depending on the type of excitation, we can discriminate three categories of contact noise[10]:

- Impact noise: this noise is related to irregularities of the wheel and to local defects of the track, for instance at the joints and at the switches. Hence, it is spatially and temporally localized by the impulse nature of this excitation;
- Squeal noise: this is one of the most important problems the urban rail transport authorities are faced with. This high frequency squeal noise is due to nonlinear stick slip forces between railway wheel and rail. The lateral sticking and slipping causes vibrations in the wheel to increase until stable amplitude is reached. Damped and resilient wheels are sometimes used to reduce squeal noise;
- Rolling noise: related to the irregularities of the rolling surface, it is the main cause of wheel/track contact noise and can be considered as a wide band noise.

For the frequencies above 400 Hz, the vibration behavior of the wheel can be seen as very close to that of a disk. Up to this frequency, it is more proper to consider the whole axle. From an acoustical point of view, an important part of the energy is radiated by the bending

[8] D.J. Thompson, M.H.A. Janssens, and F.G. de Beer, TWINS theoretical Manual*, third edition*, 1999.
[9] M. Villot *et al*, Vibration emission from railway lines in tunnel characterization and prediction, *International Journal of Rail Transportation,* August 2016.
[10] D.J. Thompson and C.J.C. Jones: A review of the modelling of wheel/rail Noise generation. Journal of Sound and Vibration, 231(3):519–536, 2000.

of the veil (axial vibration). The remaining part of the energy is rather radiated by the flat of the wheel (radial vibration). The magnitude of the induced radiation is minimal up to 500 Hz but becomes more significant above this frequency[11].Noise is measured by microphones situated along the track at different distances from the track, and characterized by its frequency (in Hz) and its level (in dB).

10.6.2 Vibrations transmitted to the ground (global KPI)

The annoyance induced by vibrations is mainly due to the ground borne noise generated inside the buildings. The ground borne noise is the noise emitted by walls and floors of the building when submitted to vibrations. The mechanism of vibrations comprises the excitation process, the transmission from the track to the soil and the propagation through the buildings. Mitigation means are essentially possible on the track to reduce the transmission to the soil.

Unlike the wheel, the vibrations of the track can travel on a long distance. The acoustical radiation of the rail can be, in a first approach, approximated by using the behavior of a pulsating cylinder. However, the modelling of vibrations propagating in a rail is a more complex phenomenon. Indeed, there are many types of vibration waves, such as vertical and lateral bending waves[12]. These waves are composed of a strongly mitigated near field and a long-range propagation wave whose mitigation depends on the frequency and on the resilient medium of the rail support.

Geophones are the most common sensors used to measure the soil vibrations, placed at different distances from the track. Actually, soil vibrations have a quick attenuation with the distance from the track. Frequency spectrums are deduced from the measurements performed by the geophones, giving frequencies and amplitudes of the vibrations.

10.6.3 Resilient materials, mass elements, radiating elements (contributing KPIs)

Those three contributing KPI contribute at the same time to noise and to vibrations, but don't have the same effect on both.

Resilient materials are used to mitigate the vibrations of the track elements, dissipating the transmitted energy. An important benefit of resilient materials is the decoupling of subsystems: rail, sleepers, and slab (or ballast). Actually, resilient materials located between the track components uncouple their own vibrations movement. This decoupling appears for large enough frequencies (typically around 60-80Hz for ballastless tracks and 30-40Hz for ballasted tracks) and reduces the level of vibrations. Under these frequencies, the dissipation due to resilient materials of the track is quasi ineffective and vibrations are

[11] D.J. Thompson and C.J.C. Jones: Sound radiation from a vibrating railway wheel. *Journal of Sound and Vibration, 253(2):401–419*, 2002

[12] B. Faure : Caractérisation du rayonnement acoustique d'un rail à l'aide d'un réseau de microphones. *IFSTTAR, Université de Grenoble*, 2011

difficult to mitigate. Examples of resilient materials are under sleeper pads, rail pads, ballast mats.

In addition, vibrations transmission between two parts is governed by the ratio of their mechanical impedances. The transmission is perfect for a ratio equal to one, and tends to zero when the ratio tends to zero or infinity. Nevertheless, if vibrations are not transmitted to the soil or not dissipated in resilient pads, they are reflected into the track and feed the radiation of the rails and the noise propagation. Hence resilient materials can have a positive impact on the mitigation of vibrations and a negative impact on the reduction of emitted noise.

Mass elements of the track are the rails and the sleepers. In particular, the sleepers are specific components of the track and are designed, among others, for vibrations mitigation. In a first approach, the displacement is a function of the inverse of the mass of the sleeper. An addition of mass drops the decoupling frequency between the track and its support. As explained above, this leads to a better vibrations mitigation for a same resilient material.

Radiating elements are of importance for the noise and vibration propagation, such that noise and vibrations emitted at the wheel/rail contact propagate more widely with radiating elements. For example, smooth surfaces like concrete are more radiating than uneven surfaces. Rails with larger surface areas (Vignole) have higher radiation potential than solid rails (Rectangular embedded).

10.6.4 Summary

The implementation of resilient materials in the track design is crucial to protect sensitive buildings such as hospitals or laboratories including sensitive measure equipment. Another method could be to change the mass of the sleepers in order to modify the mitigation of the waves in the structure. Finally, the quality of the smoothness of the surface of the railway has to be preserved to ensure the regularity of the rolling. To do so, a regular maintenance is required to avoid the defaults between the rail and the wheel. Impact sounds are also generated by the switches and crossings systems even though mobile switches are recommended to alleviate the disturbance of this type of devices. Applying a general solution for all kind of railways and situation seems to be unrealistic. The development or design of mitigation measures have to be specific to be as suitable as possible. Mitigation measures additional to the track design can be installed on the track to reduce noise and vibration propagation. They are for example resilient materials such as rail dampers, mats under the ballast or under the slab. Noise barriers and vibration barriers can also be added to avoid the propagation of noise and vibrations.

10.7 Construction and Deliverability

This section is focused on the parameters that should be taken into account in terms of construction and deliverability. Each may have a unique parameter that would allow an objective quantification. Some others may not, although it may help estimation of the benefit of each type of track. However, the relative significance of construction factors will depend on the area, local practices and environment. These construction variables have a major effect on the installed cost and thus on the LCC. Logistics, labour and plant variations play a major part in the outturn cost and in order to have quantification as independent as possible from the local characteristics, it is necessary to ring fence the parameters.

10.7.1 Feasibility

The assessment of the different trackforms in terms of construction and deliverability parameters is mainly focused on cost and time (ability to deliver within time allocation) in order to analyse if the track system could be competitive in the market.

The cost Global KPI is assessed taking into account several parameters (contributing KPI´s) such as: availability of materials, and specialist equipment and resource requirements.

The time (ability to deliver within time allocation) Global KPI is assessed taking into account several parameters (contributing KPI´s) such as: interface between construction activities, speed of installation and susceptibility to weather conditions.

10.7.1.1 Availability of Materials (Contributing KPI)

When considering Constructability, either for new tracks, or renewal operations, the availability of materials is to be kept in mind. It has major significance at the time of making decisions for new tracks, where the availability of materials will have an impact on the whole life cycle of the track. Usually the measurement of this item is based on a monetized approach, although a global parameter which controls the influence of this aspect is the availability of good transport corridors and the average distance in Km, from the material location (Ballast quarries, concrete etc.) and their influence on the different trackforms. In any case, the value of this KPI depends on local environment, local practices and the construction market. Being site specific therefore, the values or the significance of this parameter cannot be extrapolated from one place to another. For comparison purposes specific typical scenarios including whether the trackform is a new installation or replacement of an existing track, have been considered.

Specialist equipment and labour (Contributing KPI)

Regarding specialist equipment, in the construction phase, the use of different types of machinery due to the use of different designs and materials is generally considered systematically. The measure of this parameter is the impact of the access and restrictions for machinery and, the time of installation. Some equipment requires significant track occupation. All these equipment factors affect the unit cost of the trackform. Labor may be also be measured by the experience and qualifications required for specialist contractions.

Interface between construction activities (Contributing KPI)

The most important issue is the extent to which the construction activities are independent of each other. A high degree of independence lowers the risk of not completing on time. A difficulty in one activity may not affect others or be critical. This is measured as a high/low interdependency of construction activities. It affects the planning of the works especially in the initial construction stages.

Construction time may be shorter if the constructed supporting structure can be used as a working path. For instance, an asphalt layer can be used for this purpose, as long as it provides a protection for the sub-grade layer (track systems founded on asphalt layers achieve high construction productivity because asphalt does not require hardening and can be subjected to loading immediately after cooling). It can make easier and shorter construction stages, as a limited access on a single line of works or not. This is a compound parameter which depends on the specific place, contractor's capabilities and other factors. It is taken into account when evaluating different possibilities of supporting structures.

This KPI could be measured as the result of the sum of the duration of every construction activity divided into the duration of the whole project.

This contributing KPI could be influenced by the available resources (labour, machinery, etc.) from the temporary point of view and the work productive time.

Speed of installation (Contributing KPI)

In the assessment of this KPI, the following factors related to speed of installation should be taken into account: concreting techniques, high output machines, time-consumption of critical construction activities, etc.

The construction performance of a track system depends on the number of in-situ works. There are always critical steps which determine the overall construction performance

This speed of installation KPI could be measured in meters/day.

The speed of installation KPI could be influenced by several factors such as: high level of mechanization, ease of installation, delay of critical activities (interface between construction activities), susceptibility to weather conditions, etc.

Susceptibility to weather during the construction

In terms of buildability the sensitivity to the weather conditions of the track system is a crucial factor.

Rain, wind and extreme temperature could affect the progress of the installation process or even could interrupt it. For this reason, the availability of concreting options (slip-form, precast, in-situ) is an important parameter to be taken into account in terms of susceptibility to weather conditions due to the adaptability to different scenarios.

This KPI could be measured as the lost days (due to weather conditions) percentage compared with the number total of days of the project.

This KPI could be influenced by the location and the seasonality factors and the availability of concretion options (slip-form, precast, in-situ).

10.7.1.2 Summary

These Constructability and delivery KPI's depended strongly on local characteristics of the market, local practices, means and methods of a specific contractor or project, and even work schedules. Therefore, the choice of options needs to be determined for the specific project being analysed.

10.8 Compatibility

The track structure shall enable the installation of track equipment. This issue affects equally conventional track fixing equipment (fastening systems, switches and crossings, etc.), and track mounted equipment, which includes equipment added to the track after the construction, such as axle counters, AWS magnets, Hot box detectors, sensors, etc.

10.8.1 **Compatibility with existing equipment (Global KPI)**

Several components shall be added to the track in order to guarantee two functions of the trackform:

- the support of the rails by the track, ensuring at the same time an efficient clamping and a thermal dilatation;
- the traffic management, enabling the trains to change directions using switches and crossings, and enabling to identify the trains using track circuits.

Two elements are studied regarding the behaviour of the rails and their fastening to the track: the fastening systems and the expansion switches. Major criteria are the space needed to install those elements and the design modifications the installation requires.

Switches and crossings are essential track equipment, enabling the trains to change direction and thus introducing flexibility in the railway network, especially in the train stations. They are complex track equipment and can be composed of several major components.

Track circuits are used to identify the train position along the track, which is needed for the traffic management and safety. Insulated bonded joints are introduced into the track, in order to separate the rails belonging to two different track circuits.

Point operating equipment also needs to be accommodated in the track system.

For all those track components, the issue is to assess the ability of the trackform to accommodate the components at the desired location.

10.8.1.1 Fastening systems (contributing KPI)

The rail fastening system is a means of fixing the rail to the sleeper, or directly to the track. As trains pass over the rails, they exert an outward force on the rails. The fasteners provide the counter-force keeping the rails in place. Without a strong enough counter-force, the rails can move apart over time, increasing the risk of a derailment where the train falls from the rails. Therefore fasteners maintain gauge by keeping both rails firmly attached to the sleepers. They are laid on each side of the rail and attached to the sleepers by spikes or bolts. In the case of embedded rails they are fixed by an elastomer in a concrete slot. Some elasticity can be introduced into the fastening system. However the more the rail is held/fixed by the fixings, the elasticity/resilience is reduced.

10.8.1.2 Expansion switch (contributing KPI)

The installation of an expansion switch in the trackform could require significant design modification between the rail files or next to the rails. For example, the clamping of the expansion switch needs some space and could require an excavation or a preformed box out. This installation should be performed without major impact on the construction works or on the track design, i.e. without extensive modification of the track design and a large excavation, which would cost time and money.

10.8.1.3 Insulated bonded joint (contributing KPI)

An insulated Block Joints (IBJ) is an isolating device which joins two rails. They enable the identification of broken rails and train location. In conventional tracks, the rails are linked by a splice bar. For keeping the isolation function, there is therefore an epoxy resin between the splice bar and the rail. The main function of the IBJ is isolate two rails belonging to two different track circuits, keeping the track circuit's isolated one from another. The isolating profile is made up with polymeric resin or with an organic matrix component. In a Vignolle rail this device weakens the rails ends because of the holes made in the rail web and of the discontinuity between the two rails. The usual mitigation is to reduce the spacing of the sleepers and of the rail clamps at the location of the IBJ.

The KPI will focus on the ability to provide a fastening system which avoids a fast degradation of the rail end.

10.8.1.4 Switches and crossings (contributing KPI)

The components of the turnouts have to be installed without major impact on the track design, for example without excavation or significant design modification. Driving rods and swing nose crossings need space inside the 4-foot between the sleepers. The point locking device can be mounted independently or integrated within the switch drive system. In both cases, it has to be verified that there is some space available for it. Especially in the case of an independent mounting, the locking device is situated along the stock rails. The point motor can be installed at different places: in the 4-foot, on the sleeper, shoulders, or integrated in a hollow bearer. This has to be provided by the chosen trackform, while allowing the track and the point components to be maintained. This means that the point components require space to be installed and an easy access for the maintenance workers.

The installation of the point components shall not prejudice the track support. They have to be installed while guaranteeing a sufficient support for preventing the track from settling and thus weakening the track mounting.

The compatibility with the maintenance operation should be studied too, such that the installation of the point components enables the maintenance of the track to be performed (e.g. Tamping, if relevant). The maintenance operations have to be carried out without being hindered by the track equipment or without risking deterioration of the equipment.

Finally, the functioning of the S&C shall not be compromised by track elements. For example in ballasted track, some ballast stones may obstruct the movement of the switch rails.

10.8.2 Compatibility with future equipment (Global KPI)

Track equipment may be added once the track is laid and in-service. These might be embedded sensors (accelerometers, stress gauge, etc.), axles counters, track circuits, balises, etc. Their installation shall be possible whatever the track structure. Such equipment is usually mounted on rails or on sleepers. In assessing the trackform, access to the rail foot, the rail web, the sleeper (or the track surface if there is no sleeper), and the fastening systems, has to be checked to ensure that it is possible to enable attachment of components to these track parts, as well as the possibility to draw cables to these embedded components. Some general contributing criteria can be identified.

10.8.2.1 Accessibility to track components (contributing KPI)

The introduction of track equipment in the trackform requires access to the track component on which the track equipment will be attached. For example, axle counters are laid on rails. Access to the track components is also needed to perform the maintenance of the track equipment, or to draw cables to feed them with electricity (e.g. for some monitoring sensors).

10.8.2.2 Space available for the installation (contributing KPI)

The trackform shall leave enough space available to install the track equipment without compromising the train operation or the track design. For example, it is common practice to install cab signalling repetition devices, such as Automatic Warning Systems, crocodiles, or other beacon types in the track. They are usually laid between the rails and need space for their installation. They also need a method of fixing to the track (sleepers constitute easy fixation means). Hot box detectors are usually installed between the rails. The fixing of check rails is a special case of this issue.

10.8.2.3 Summary

The ability to install track equipment raises issues about the trackform. The main issue is about the space needed to install the track equipment, which preferably should not require significant modification of the track design or an excavation. The rail fastening system should also be flexible enough to enable modifications of the spacing of sleepers or of the trackform itself.

Nevertheless some opportunities to simplify the installation of track equipment are currently under development. It consists in designing new equipment, which would be simpler and requires less space, particularly for switches and crossings. The issue of enabling the thermal dilatation of the rail, thanks to embedded rails, advances in the fastening system, and expansion switches, remains but is less of a concern for all track types.

Compatibility with embankments and structures

Railway tracks are rarely laid directly on the soil but, because of topographic parameters, the track layout has to be adapted to the surrounding topography. That is why embankments and structures like bridges are built along the track. Embankments may also be required on weak soils to prevent the track from settling. The mechanical properties of the embankments and structures along the track have to be adapted to the track properties, to avoid deformation of the track, to guarantee an appropriate behaviour of embankments and structures, and to respect some constraints linked to the track layout, for example the gauge and rail head alignment. Therefore good track properties can reduce the requirements on embankments and structures, making them easier to design and to build.

10.8.3 Compatibility with infrastructure (Global KPI)

The study of the compatibility of the track structures with the embankments and structures is the analysis of the required track support (soil and structures) parameters in these different zones. The very low deformation values required in the railway construction generally involve high Young modulus values in the first layers of soil (form layer, subgrade). Minimum thickness values of these layers are also required. The influence of new trackform stiffness could allow the reduction of the required values of formation modulus and thicknesses. In this case, this would reduce the need for foundations works and improve the compatibility of the track with weak soils.

On bridges, the constraints of the project sometimes involve reduction of the thickness of the trackform and the ballast layer in order to decrease the static weight of the track, or to increase the available space above the track. In some cases, the trackforms could allow reduction of the track thickness while guaranteeing a sufficient stiffness, and addressing local issues. Calculations are necessary to assess the positive effect of any new trackform stiffness on the ballast layer reduction research. The parameters used into these calculations are stiffness modulus, Young modulus and bearing resistance.

10.8.3.1 Compatibility with embankments (Contributing KPI)

Compatibility with embankments depends on the required Young and stiffness modulus of the embankments layers (form layer and subgrade). The required values of modulus and thicknesses of the form layer and the subgrade are calculated using a numerical model, a function of the train velocity and the static loads. A high stiffness of the hybrid trackforms could reduce the required modulus and thicknesses values of the form layer and of the subgrade. The compatibility of trackforms with low modulus and thickness values for the embankments and the comparison with the required values to a classic trackform allows us to compare the studied trackforms.

The parameters analysed in the evaluation are the stiffness of the trackform and its bearing capacity. This last one frequently needs assumptions before the realization of geotechnical investigations. Those parameters directly impact the treatment of the soil layers. Actually the soil modulus and the thickness of the soil layer are then adapted to the track mechanical properties, in order to minimise the track deformations. A numerical model of the soil layer and the track is usually constructed to test different solutions for the soil treatment. After the construction, the deformation can be measured with deformation gauge fixed on the rail. The measures carried out on an existing trackform enable validation of the modelling. In conclusion, a high bearing capacity and high track stiffness increase the compatibility with low modulus and thickness values of the embankments, and with weak soils. This could lead to thinner formation layers or subgrades and to less foundations works.

10.8.3.2 Compatibility with civil structures (Contributing KPI)

Compatibility with structures is defined by the possibility of using the trackform on bridges and in tunnels, particularly when the project imposes some constraints, like a minimum clear height requiring a reduced structure. The important parameter is the thickness of any selected trackform in comparison with a classical trackform. For example, if a new trackform can guarantee a sufficient level for the track stiffness, it could allow reduction in the required ballast layer or slab thickness. Modelling is required to define the thicknesses of the ballast layer and of the trackform. An important reduction of the track thickness could be an answer to an imposed constraint when the classical ballast track couldn’t do it, leading to a smaller track load. Where a trackform needs only a lower stiffness of the formation significant savings can be made to the Civil Engineering costs of providing an adequate sub base. Parameters necessary to the calculations are stiffness modulus, Young modulus and bearing resistance. The cost saving in the Civil construction works from a thin trackform is often an order of size greater than the cost of the trackform itself.

The compatibility with structures should also ensure a free thermal dilatation of the trackform when laid on a civil structure. Since the trackform and the civil structure usually do not have the same dilatation behaviour, it is necessary to leave the possibility of a relative movement between them. Some of the selected trackforms overcome this issue.

10.8.3.3 Summary

Embankments are designed to guarantee a high enough bearing capacity of the track. This requires high values of Young and stiffness modulus, and a high thickness. A low propensity of the track to settle has consequences on its compatibility with weak soils and with embankments, because it reduces the requirements on embankments. The compatibility with structures takes also into account the thickness of a trackform to fit with height constraints. Therefore a compromise should be found between the thickness of the trackform and its bearing capacity.

Although the soil properties can be measured by several geotechnical investigations on site (penetrometer) or in a lab (triaxial test), numerical calculations have to be performed to check the compatibility with embankments and with structures. A track solution requiring a low level of support is attractive due to the preparation cost and time needed to provide it.

11 Annex B – Assessment Criteria Descriptions

The following criteria were used in the best value assessment of the selected track systems.

Assessment Criteria	Description
Design Performance	
Suitability for tunnel (e.g. no structural alterations required)	Is the track system suitable for use in tunnels given modern engineering requirements? e.g. Fire, gauge, height, width , Kinematic envelope
Suitability for structures (e.g. no structural alterations required)	Is the system suitable for use on structures given modern engineering requirements? e.g. Fire, gauge, weight.
Corrosion susceptibility	Corrosion affecting components (rail, fittings, etc.) or structural reinforcement.
Contamination ingress	Ingress of debris (e.g. sand, spillages, and vegetation etc. Into the fittings, expansion gaps or ballast / structure / ladder track etc.) That could affect performance or adjustment of the track system.
Construction depth and clearances	Increased excavation depths, moving overhead componentry, reshaping embankments and cuttings, additional earthworks.
Long System design life	The track systems proposed design life.
Ease of approvals	The level of compliance with existing standards and engineering practises. Ease of acceptance.
Simplicity and No. components	Complexity of systems assembly, number of components.
Compatibility with S&C	Compatibility with existing fixed rail componentry.
Water management	Managing the water ingress away from the track formation. Resilience to extreme weather effects e.g. flooding. Allows water to get to a drainage system.
Simplicity of transition options	Does the system require a complex transition design? Can it use existing transition arrangements/techniques?
Suitability for electrification (e.g. 3rd and 4th conductor rail	Can the system incorporate ground based electrified conductor rails?
Ease of incorporating check rail	Can the system incorporate check rails
Can system accommodate tight curves	Minimum permissible track system radius.
Low stress on formation	Stress placed on system formation through self-weight and operational loads.

Assessment Criteria	Description
Extent of formation treatment required	Amount of preparatory earth works required prior to system construction e.g. EV2>120MPA
Tolerance to variations in formation stiffness (bridging).	The track systems tolerance to variable ground stiffness.
Suitability for wide range of operational scenarios. High /low speed, Passenger/freight, weekend/week replacement,	Speed, weight, frequency, load types.
Longitudinal and lateral restraint	Longitudinal and lateral restraint of the rail e.g. heat expansion, braking, buckling. Rail head movement
Robustness (e.g.	Ability to withstand heavy duty abuse e.g. vehicle strikes, wheel flats, on/off tracking machines, derailment.
Smart infrastructure	Ability to condition monitor & auto inspection, embedded sensors, fibres cables etc
Ability to accommodate other services	Integration of additional services e.g. telecommunications, signalling, leaky feeders etc.
Buildability	
Use of standard construction equipment	Able to use standard construction equipment such as diggers, dozers, cranes etc from the construction marketplace during construction.
Min Installation resources required	Labour, specialist equipment, time etc.
Speed of installation	Can the construction be optimised through the use of high output machines, concreting techniques etc.?
Susceptibility to weather during construction	Is the construction of the system weather sensitive? E.g. rain during concrete pour, high winds, high or low temperatures, formation protection.
Ease of achieving accurate alignment	The ability to achieve final rail head alignment quickly at construction. Low risk of upsetting the alignment during construction.
Materials availability and logistics. (Low interdependency of construction activities)	Does the system require anything that has extensive lead times or specialist manufacturing techniques/requirements? Getting equipment, materials and people to construction site. Storage and construction adjacent to worksite.
Flexibility	The impact of construction on adjacent running lines. Options for single line working

Assessment Criteria	Description
	closure etc. Level of inter dependency of the critical activities.
Safety	
Maintainer safety	Physical safety for the workers trackside coming from slips, trips, slippery surfaces, live electricity.
Low frequency of human access (rail staff)	Reducing the overall exposure of people to live railway.
Ease of evacuation, and access for pneumatic tyred vehicles	The ability for people to be able to walk safely along the track to a safe exit point. This does not including the exit from vehicle to track. Smooth and sufficient surface for emergency and maintenance vehicles
Failsafe	Is the track system likely to fail safe, Is the risk compounded/increased? Rail break, fixing failure etc.
Derailment protection (user safety)	Can the system incorporate derailment protection/containment?
Environmental	
Noise	The level of acoustic radiation being transmitted to the surrounding environment.
Vibration	The level of ground bourn vibration being transmitted to the surrounding environment.
Ambience / visual intrusion	The impact of the track systems aesthetic appearance on its local environment.
Carbon footprint	The system's carbon footprint.
Contaminate drainage management	Is the system able to contain/manage contaminated wash out, spillage, pollution?
Maintenance	
Frequency of grinding regime	Alterations to the frequency of grinding.
Frequency and level of inspection	The need for Manual, RCM, and train borne inspections.
Long component life	Increased component life allows for synchronisation of maintenance activities e.g. rail renewal.
Track quality retention	The system's ability to retain designed track geometry.
Ease of minor alignment (line and level) adjustment	Rail alignment adjustments plus/minus 5mm (Achieved in adjustment of fittings)
Ease of major track structure alignment adjustments.	Track system alignment changes e.g. remodelling of infrastructure. Achieved in adjustment of Superstructure
Ease of minor component replacement	Fastener and above e.g. Rail, pads, fasteners

Assessment Criteria	Description
Ease of major component replacement.	Below fastener e.g. Slab, ballast, precast section, sleepers.
Easy in situ repair of major components	Ability to make repairs rather than replace large structural components.
Extent of maintenance resources/ plant required	Requirements for plant, people, planners, trainers.
Ease of rail head repairs and in situ welds	Ability to perform rail head repairs on site.

12 Annex C - System Scoring Data

The table lists the data collected from the online collaboration assessment exercise.

The table shows each of criteria, weightings and individual scores. The scores from all participants were totalled and averaged to give a final score.

Track Selection Value Analysis System Assessment

Assessment Criteria	Criteria Weighting	Traditional Ballasted Track	Ballast over Asphalt	Bogl	Booted Sleeper	Embedded Rectangular Rail	GETRAC	Japanese Shinkansen Slab Track	Moulded Modular Multi Blocks 3M	PORR	Pre-cast frame on ashphalt	Rheda 2000	Rhomberg Sersa Ives	Systra Slab track
Construction/ Installation	**13 %**	**17 %**	**15 %**	**12 %**	**13 %**	**13 %**	**13 %**	**12 %**	**13 %**	**12 %**	**13 %**	**12 %**	**13 %**	**13 %**
Buildability	**12 %**	**14 %**	**12 %**	**11 %**	**11 %**	**11 %**	**11 %**	**11 %**	**11 %**	**11 %**	**11 %**	**10 %**	**11 %**	**11 %**
Ease of achieving accurate alignment	7	7	7	6	7	6	7	6	6	7	6	6	7	6
Extent of Standard construction equipment	5	6	6	5	6	5	6	5	5	5	5	5	6	5
Materials availability and logistics	8	6	5	5	6	6	5	5	5	5	5	5	5	5
Min Installation resources required (incl labour and plant)	6	6	6	5	5	7	5	5	5	5	5	5	6	5
Speed of installation (eg high output equip (ballast, slipform, asphalt)	7	7	6	4	4	6	5	4	4	4	4	4	5	4
Susceptibility to Weather during construction	5	7	5	6	6	5	5	6	6	6	5	5	6	6
Disruption	**2 %**	**3 %**	**2 %**	**2 %**	**2 %**	**2 %**	**2 %**	**2 %**	**2 %**	**2 %**	**2 %**	**2 %**	**2 %**	**2 %**
Flexibility (e.g. options for single line working closure etc.)	6	7	6	5	5	6	6	5	6	5	6	5	6	5
Design/ Performance	42 %	44 %	45 %	46 %	46 %	46 %	44 %	46 %	44 %	46 %	45 %	46 %	45 %	44 %

		Ability to accommodate other services	3	7	6	5	6	5	6	6	6	6	6	5	6	6
		Can system accommodate tight curves	5	6	7	5	6	6	6	4	5	5	5	5	6	5
		Compatibility with S&C	9	7	7	7	7	4	6	6	5	6	6	7	6	4
		Construction depth and clearances	7	5	5	6	6	8	6	6	5	6	6	6	6	4
		Contamination ingress	4	3	4	6	6	7	6	6	6	6	5	7	6	7
		Corrosion susceptibility	2	6	7	6	6	7	7	6	6	6	6	6	7	6
		Ease of approvals	2	8	6	6	7	6	6	7	4	7	6	7	6	3
		Ease of incorporating check rail	3	7	7	5	5	4	6	5	4	6	5	5	5	3
		Extent of formation treatment required.	8	6	5	4	5	6	5	4	5	5	6	6	6	7
		Long System Design Life	8	4	5	7	7	7	6	7	6	7	6	7	7	7
		Longitudinal and lateral restraint (Buckling etc.)	9	4	4	7	7	8	6	7	7	7	6	7	6	6
		Low stress on formation	8	4	5	6	6	8	6	6	6	7	7	6	6	8
		Robustness (e.g. ability to withstand heavy duty use (Wheel flats, Seismic or heavy equipment)	7	5	6	6	6	7	6	6	6	6	5	6	6	6
		Simplicity and No. components	7	5	5	6	6	8	6	6	5	6	6	6	6	4
		Simplicity of transition options	6	7	6	6	6	4	6	5	5	5	5	5	6	4
		Smart Infrastructure (Ability to condition monitor & auto inspection, Embedded sensors, fibre cables etc)	6	5	6	6	6	6	6	6	6	6	6	6	6	6
		Suitability for Electrification (e.g. 3rd and 4th conductor rail)	2	7	7	5	5	4	5	5	4	5	4	5	5	4
		Suitability for structures	8	5	5	7	7	6	6	7	6	7	6	7	7	4
		Suitability for tunnels (e.g. no structural alterations reqd, fire)	8	4	5	7	7	8	7	7	7	7	6	7	7	3

Suitability for wide range of operational scenarios	8	7	7	7	7	6	6	7	6	7	6	7	7	6
Tolerance to variations in formation stiffness (bridging)	8	4	5	6	6	7	6	7	6	7	6	7	7	8
Water management (incl min ingress into track formation) and 100yr storm	8	5	6	7	6	7	6	7	6	7	6	7	7	7
Environmental	**11 %**	**11 %**	**11 %**	**11 %**	**11 %**	**11 %**	**11 %**	**11 %**	**10 %**	**11 %**	**12 %**	**11 %**	**10 %**	**11 %**
Ambience / visual intrusion	4	6	6	5	5	6	5	6	5	5	6	5	5	5
Carbon footprint	7	5	5	5	5	5	5	5	5	5	5	5	5	5
Contaminate drainage management (Spillage pollution)	3	3	4	6	5	5	6	5	4	6	5	5	5	7
Noise (Measure of acoustic radiaion etc)	7	7	6	5	5	6	6	5	5	5	5	5	5	5
Space take (Vertical and Horizontal)	6	4	5	6	6	6	6	5	5	6	6	6	6	4
Vibration	8	6	5	6	6	6	6	5	5	7	6	6	6	5
Maintenance and renewal	**23 %**	**23 %**	**22 %**	**21 %**	**21 %**	**18 %**	**22 %**	**21 %**	**24 %**	**21 %**	**21 %**	**20 %**	**22 %**	**24 %**
Extent of maintenance	**8 %**	**5 %**	**7 %**	**9 %**	**8 %**	**9 %**	**9 %**	**9 %**	**9 %**	**9 %**	**8 %**	**9 %**	**8 %**	**9 %**
Frequency and level of inspect /condition monitor (Work to do)	7	3	4	6	6	7	6	6	6	6	6	6	6	5
Frequency of grinding regime	5	5	5	6	6	6	6	6	6	6	5	6	6	6
Long component life	7	4	5	7	6	7	7	7	7	7	6	7	7	7
Track quality retention (ability to retain designed alignment)	8	3	5	7	7	8	7	7	7	7	6	7	7	7
Maintainability	**15 %**	**17 %**	**15 %**	**12 %**	**13 %**	**9 %**	**13 %**	**12 %**	**15 %**	**12 %**	**13 %**	**12 %**	**13 %**	**15 %**
Ease of major (below fastenings) component replacement. Slabs, sleepers.	7	7	6	4	4	3	5	4	5	4	4	3	5	5

Ease of major track structure alignment adjustments.	7	7	6	3	4	3	5	3	5	4	3	3	5	5
Ease of minor (above and incl fastenings) component replacement	7	8	7	6	7	5	7	7	7	7	7	7	7	7
Ease of minor rail alignment (line and level) adjustment.	8	8	7	5	5	3	5	5	6	5	5	5	5	6
Ease of rail head repairs and insitu welds	7	7	7	7	7	4	7	6	7	7	7	7	7	7
Easy insitu repair of major components	6	7	6	4	5	3	5	4	5	4	4	3	6	4
Extent of maintenance resources/ plant required	7	4	4	6	6	6	6	6	6	6	6	6	6	6
Safety	**11 %**	**6 %**	**7 %**	**10 %**	**9 %**	**12 %**	**9 %**	**10 %**	**9 %**	**10 %**	**9 %**	**11 %**	**9 %**	**8 %**
Derailment protection (User safety)	8	3	4	5	4	7	5	5	4	5	4	6	5	4
Ease of evacuation, and access for pneumatic tyred vehicles	4	3	4	7	6	7	5	7	4	7	5	7	7	3
Failsafe (Risk does not get compounded /increase)	8	4	4	6	6	8	6	6	5	6	6	6	6	4
Low frequency of human track access	8	3	4	5	6	7	5	6	5	6	5	6	5	5
Maintainer Safety (The environment and activities, elec)	8	4	5	6	6	7	6	6	6	6	5	6	6	5
TOTAL SUM BENEFITS		**1,751**	**1,780**	**1,889**	**1,925**	**1,989**	**1,913**	**1,877**	**1,821**	**1,943**	**1,804**	**1,915**	**1,973**	**1,762**

13 Annex D - LCC Value Analysis Data

LCC analysis data for the four scenarios. The rankings for the systems for the installed cost and the LCC cost is highlighted in blue.

A	B	C	Japanese Slab Track	Bögl Slab Track	PORR Slab Track	Prefab Slabs on Asphalt	Rheda 2000	GETRACK Sleepers on Asphalt	Rhomberg	Booted Sleeper	BB Embedded Rail System	Moulded Modular Multi-Blocks	Systra Slab Track	Ballast Track on Asphalt layer	Ballasted Track
Ref			1	2	3	4	5	6	7	8	9	10	11	12	13
	Scenario	Benefits	1877	1889	1943	1804	1915	1913	1973	1925	1989	1821	1762	1780	1751
		Benefits Ranking	8	7	3	10	5	6	2	4	1	9	12	11	13
A	Base case	Installed costs	77.4	85.1	82.1	81.9	86.3	80.3	98.8	94.5	77.4	101.6	127.9	53	48.4
		Post installed costs	25.8	25.9	25.4	24.9	29.3	25.1	25.1	27.3	16.7	25.2	29.6	49.9	51.7
		Total Life Cycle costs	103.2	111	107.5	106.8	115.6	105.4	123.9	121.8	94.1	126.8	157.5	102.9	100.1
		Installed Cost Value rating	24.25	22.20	23.67	22.03	22.19	23.82	19.97	20.37	25.70	17.92	13.78	33.58	36.18
		Installed Cost Value ranking	4	7	6	9	8	5	11	10	3	12	13	2	1
		LCC value Rating	18.19	17.02	18.07	16.89	16.57	18.15	15.92	15.80	21.14	14.36	11.19	17.30	17.49
		% of Best LCC Value	86.0%	80.5%	85.5%	79.9%	78.4%	85.9%	75.3%	74.8%	100.0%	67.9%	52.9%	81.8%	82.8%
		LCC Value ranking	2	7	4	8	9	3	10	11	1	12	13	6	5
B	Extended working scenario	Installed costs	67.2	73.9	71.2	73.6	74.9	72.2	88.8	82	67.2	88.2	115	50.8	47.1
		Post installed costs	25.7	25.8	25.2	25.1	28.2	25.3	25.4	27.4	16.7	25.1	29.6	50.8	52.9
		Total Life Cycle costs	92.9	99.7	96.4	98.7	103.1	97.5	114.2	109.4	83.9	113.3	144.6	101.6	100
		Installed Cost Value rating	27.93	25.56	27.29	24.51	25.57	26.50	22.22	23.48	29.60	20.65	15.32	35.04	37.18
		Installed Cost Value ranking	4	8	5	9	7	6	11	10	3	12	13	2	1
		LCC value Rating	20.20	18.95	20.16	18.28	18.57	19.62	17.28	17.60	23.71	16.07	12.19	17.52	17.51
		% of Best LCC Value	0.85												
		LCC Value ranking	2	5	3	7	6	4	11	8	1	12	13	9	10
C	Soil -	Installed costs	77.5	85.4	82.3	82.2	86.7	80.5	99.5	95	78.1	102.3	129.3	53.2	48.5

	Formation case	Post installed costs	24.8	24.9	25.2	23.9	27.3	24.1	24.2	26.4	17.2	24.2	29.9	49.6	52.5
		Total Life Cycle costs	102.3	110.3	107.5	106.1	114	104.6	123.7	121.4	95.3	126.5	159.2	102.8	101
		Installed Cost Value rating	24.22	22.12	23.61	21.95	22.09	23.76	19.83	20.26	25.47	17.80	13.63	33.46	36.10
		Installed Cost Value ranking	4	7	6	9	8	5	11	10	3	12	13	2	1
		LCC value Rating	18.35	17.13	18.07	17.00	16.80	18.29	15.95	15.86	20.87	14.40	11.07	17.32	17.34
		% of best LCC value	87.9%	82.1%	86.6%	81.5%	80.5%	87.6%	76.4%	76.0%	100.0%	69.0%	53.0%	83.0%	83.1%
		LCC Value ranking	2	7	4	8	9	3	10	11	1	12	13	6	5
D	Low usage - Less Tonnage	Installed costs	113.5	124.8	120.3	120.1	126.4	117.7	144.8	138.4	113.5	148.9	187.5	77.6	70.9
		Post installed costs	22.7	22.8	22	25.3	26.4	21.7	21.8	25.1	12.6	21.9	28.4	29	29.1
		Total Life Cycle costs	136.2	147.6	142.3	145.4	152.8	139.4	166.6	163.5	126.1	170.8	215.9	106.6	100
		Installed Cost Value rating	16.54	15.14	16.15	15.02	15.15	16.25	13.63	13.91	17.52	12.23	9.40	22.94	24.70
		Installed Cost Value ranking	4	8	6	9	7	5	11	10	3	12	13	2	1
		LCC value Rating	13.78	12.80	13.65	12.41	12.53	13.72	11.84	11.77	15.77	10.66	8.16	16.70	17.51
		% of best LCC value	78.7%	73.1%	78.0%	70.9%	71.6%	78.4%	67.6%	67.2%	90.1%	60.9%	46.6%	95.4%	100.0%
		LCC Value ranking	4	7	6	9	8	5	10	11	3	12	13	2	1