Project no. TIP5-CT-2006-031415

INNOTRACK

Integrated Project (IP)

Thematic Priority 6: Sustainable Development, Global Change and Ecosystems

2.3.3 Design and Manufacture of Embedded Rail Slab Track Components

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Final

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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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Glossary

Abbreviation / acronym	**Description**
BBERS	Balfour Beatty Embedded Rail System
ERS	Embedded Rail System (non-Balfour Beatty solutions)
FRP	Fibre Reinforced Plastic
LCC	Life Cycle Cost
MkI	First incarnation
MkII	Second incarnation
SP	Sub-project
WP	Workpackage

1. Executive Summary

We consider that our fundamental task is to support Innotrack in their endeavours to deliver to the Commission, proof that track infrastructure can be both manufactured and installed at a cost 30% less than currently available in the marketplace.

We believe we have demonstrated that the essential elements of such a solution exist. In the first phase of this project, we have analysed and designed a product. It has been developed from proven engineering principles to be simpler, easier, quicker and cheaper both to manufacture and to install.

In addition, we have identified where operational cost can be reduced to meet a potential LCC reduction of 30%. This applies, not just to some components, but to the overall track system. Indeed savings may be extended further into the operational cost of vehicles using such a system e.g. elimination of tamping fleet.

This report documents the design for manufacture and installation of components for the Balfour Beatty Embedded Rail System. The main design modifications between MkI and MkII systems are examined, along with details of the further optimisation of components. In addition, a description of the manufacturing method for each component is summarised.

To prove the design of the MkII system, a series of static tests were undertaken. The tests were based upon existing British and European Standards for railway track applications. The sub-system was subjected to three tests; longitudinal rail restraint, vertical rail restraint and vertical stiffness. The performance of the embedded rail system was found to meet or exceed the requirements as defined by the trans-European high-speed rail system.

The key installation techniques for a cost effective installation of an embedded rail system have been considered, including a pre-cast slab, slip-formed slab and a cast in-situ slab. The new *'clipped lid'* installation device, which facilitates the setting of both the embedded rail sub-system components and final track alignment, has also been illustrated.

For the next phase of the project, we need to test the components to confirm the track quality retention, robustness and to validate the LCC assumptions. We also anticipate, one of the Infrastructure Managers to provide an opportunity to deliver for the Commission, a real in track demonstration to prove the LCC saving are a reality. The project will then have been visibly successful to the credit of all its participants.

2. Introduction

Balfour Beatty Rail have been invited to work with a European-led project that will undertake research with an aim to reducing the life cycle costing (LCC) of rail infrastructure by a minimum of 30%.

2.1 INNOTRACK

The *'Innovative Track Systems'* project (INNOTRACK) provides an opportunity for infrastructure controllers and industry suppliers to work together with an aim to reducing the LCC of the rail infrastructure.

The main objectives of INNOTRACK are to enable a reduction in track LCC by a minimum of 30% by 2020. This is in order to improve the business case for rail transportation when compared against other modes of transportation.

These intentions will place greater demands on the track, resulting in more track damage and an increased maintenance schedule. As a result, the Innotrack project's main focus is innovation, rather than infrastructure investment alone.

INNOTRACK has been split into sub-projects and then further broken down into workpackages. Balfour Beatty Rail is primarily involved with sub-project 2 and workpackage 2.3.

2.2 Sub-project 2 – Support

Sub-project 2 is primarily involved in investigating the steps required to enable the track system to withstand the demands of increased traffic density and higher performance vehicles. The sub-grade and superstructure influence both rail stresses and the tracks ability to maintain correct geometry.

The greater demands imposed on the superstructure will also affect the track maintenance schedule, so research will be undertaken into new track concepts that reduce the both the frequency and number of tasks involved in maintenance work.

Objectives

- Support distinct decisions, based on LCC and duty recommendations, whether construction work is necessary and, if so, how much
- Provide low (or no) maintenance tracks (less activities, easier/automatic/self-inspection, diagnosis and monitoring)
- Identify changes in track-structure to provide better load distributions and/or higher load carrying capacities
- Identify and provide cheaper materials (e.g. in new build formation)
- Identify and provide cheaper construction
- Identify and provide shorter construction time & reduced renewal possession
- Maintenance with minimal traffic interruptions

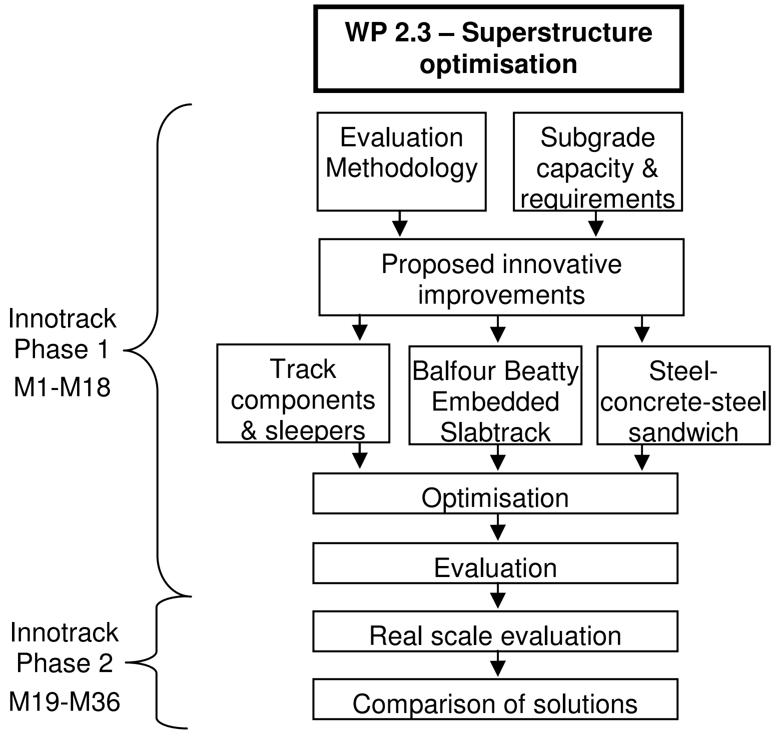
2.3 Workpackage 2.3 – Superstructure improvements

Workpackage 2.3 concentrates on optimising the design of innovative trackforms and its components. The continuously supported rail concept, of which the Balfour Beatty Embedded Rail System (BBERS) is an example, has been put forward for development and evaluation.

Objectives

Optimisation, validation and implementation of innovative solutions for superstructure improvement

Structure of WP2.3



Description of WP 2.3 activities

Task 2.3.2 **Design and modelling of the innovative BBEST trackform**
Design and development of components for cost effective manufacture and installation

Task 2.3.3 **Testing of the innovative BBEST trackform**
Testing of prototypes to confirm performance and support LCC

Task 2.3.4 **LCC evaluation**
Identification and evaluation of key elements for SP6

2.4 Deliverables achieved

The optimisation and initial evaluation work has delivered a considered view that track infrastructure can be both manufactured and delivered to a cost 30% less than currently available. This element has demonstrated that the essential elements of such a solution exist. In this phase of the project, we have analysed and designed a product. It has been developed from proven engineering principles for manufacture and installation.

It has been identified where operational cost can contribute to potential LCC reductions. This applies to the overall track system.

To prove the configuration of the manufactured components, static tests were undertaken. The tests were based upon existing standards for railway track applications. The sub-system was subjected to three tests; longitudinal rail restraint, vertical rail restraint and vertical stiffness. The performance was found to meet or exceed the requirements as defined by the trans-European high-speed rail system.

Methods and installation techniques for an embedded rail system have been considered, including a pre-cast slab, slip-formed slab and a cast in-situ slab.

3. Main section

3.1 Embedded Rail System for Track Superstructure

3.1.1 Background

The concept of ballasted track has been around since the birth of the railway. The design has evolved over the years but the current trackform is still highly recognisable as a descendant of the original. The problem with basing an infrastructure system on a 200 year old idea is that development of installation, maintenance and inspection procedures is severely limited. A fundamental design review is required in order to enjoy a reduction in life cycle costs.

Therefore, an innovative solution is required that has low installation and maintenance costs. A solution that has been engineered from first principles, incorporating the latest advances in materials technology, structural and geotechnical understanding will provide both cost savings and performance improvements.

If rail transport were to be invented today it is reasonable to say that the track form would be very different. The envisaged embedded rail system is the first significant main line variant from the classical track forms still generally in use. This variance is best illustrated by the unique rail section which is designed as part of a holistic systems approach rather than the evolution of an individual component. This system is inherently a low risk, high quality, high performance, simple engineered product.

Figure 1 - Length of MkI BBERS

3.1.2 BBERS Development

The history of BBERS dates back to the late 1990's, developing on concepts from other European countries; the initial system was produced with the specific objective to creating a long-lasting, low maintenance embedded rail system. The MkI version of the embedded rail system was developed in the early 2000's and successfully installed at Medina el Campo, Spain in 2002 and in Crewe, UK in 2003 *see* Figure 1).

The trial installation at Crewe has product acceptance from the UK infrastructure operator.

3.1.3 Optimisation of MkI BBERS Track Components

The MkI trial installations identified several opportunities for improvement with respect to meeting the Commission's objective, thus the modifications needed further development through the Innotrack project. As a result, a comprehensive design review process was undertaken in order to identify areas that could benefit from performance improvement. This included reviewing the manufacturing, installation and maintenance processes. From this review, several options were evaluated and a final design for MkII was chosen. Figure 2 details the main design changes between the MkI and MkII sub-systems. Details of areas that require optimisation are summarised below;

Improvement Opportunities for MkI Shell Design

- Maintaining the as-built dimensions of the shell (installation improvement)

In spite of the good manufacturing tolerances of the shell material itself, maintaining the top aperture dimension of the shell during installation was time consuming and required much care. This dimension is critical to maintain the grip of the pad on the rail.

- Limited rail protrusion (maintenance improvement)

The shell protruded high up the rail giving a normal allowance for head wear and only a little space to grip the rail in the event of its removal. The concrete clearance was also a limitation in the use of some rail head grinders.

- The shape

The small radii of the shell corners could lead to unnecessary stress concentration in the grout.

- Installation

The rail shell and pad had to be installed as a system using the traditional cross beams for alignment at approximately 1.5m centres.

Improvements Implemented in MkII Shell Design

The shell has been redesigned/modified as shown in the comparative Figure 2.

- Reduced height of shell sides

Provides 50% potential extra rail head wear/life.

Easier to grip the rail during installation and removal.

- Introduction of sockets for clipped lid and pad

This enables the new lid (see next section) and pad to be integrated into the system to aid installation.

- Bonding to concrete/grout

Introduction of peel ply on the shell sides to improve the bond with the concrete, thus enabling removal of the difficult to manufacture external tangs.

- Addition of internal bonding to the shell

The introduction of peel ply to the inside face of the shell has increased the bond between pad and shell, and thus both reduced risk of low longitudinal grip and an improved rail installation.

Improvement Opportunities for MkI Pad Design

- Insertion of rail

During rail insertion, the pad had a tendency to ruck-up under the rail.

- Longitudinal restraint

In spite of the care taken, previously lateral grip on the rail was not always consistent.

Improvements Implemented in MkII Pad Design

- Integration of the seals

The seal function has been integrated into the pad, thus reducing the three previously manufactured components to one. As a consequence, there has also been a cost saving in the elimination of the seals.

- Material saving

In addition, since the pad walls are lower by 10mm, there is also a saving in pad material volume, but taking into account the seal volume, the overall benefit remains cost neutral.

- Reliable and repeatable rail restraint

With the confidence of the shell width maintained by the clipped lid, the pad thickness now provides the required pre-compression at all times. The rail is held to the ideal/design value of restraint.

Elimination of Seals as a Separate Component

The seals added two components, effectively doubling the number of components to be maintained. The seals were either difficult to insert or too easy to come out.

Introduction of Clipped Lid Component

A new item has been designed/introduced which fundamentally optimises and changes the economics and performance of the system. The lid top profile has been designed to mimic the rail head (e.g. CEN60/ UIC60).

The clipped lid enables:-

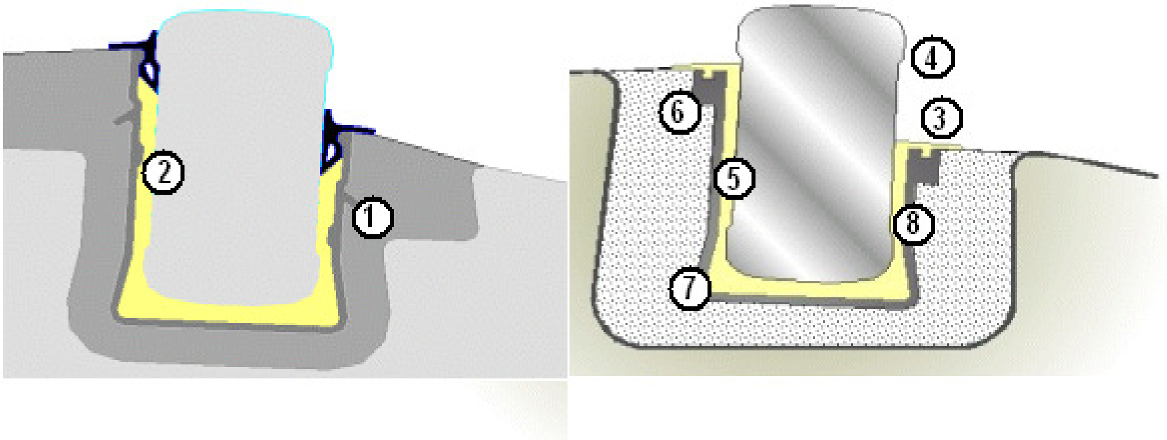
- The shell width to be maintained at the ideal design value to provide the grip required to the rail, both longitudinally and vertically. The shell and lid to be installed without the rail and pad.
- The installation to be clear of grout during grouting.
- The top down construction process in which the rail alignment can be checked (albeit against a dummy FRP rail head), prior to that alignment being permanently grouted in.
- Note – the clipped lid is a reusable component.

The “wings” on the clipped lid enable the shell and lid assembly to be installed and aligned using automated travelling equipment. By design optimization and rationalisation, the shell, pad and lid are all intimately integrated in the socket design at the top edge of the shell. Further retention of the pad during rail installation is a by product of the pad fixing into the shell socket. This was not achieved with the previous solution.

Cost Savings

The overall integrated design has optimised manufacture, installation, maintenance and performance. The benefit of the optimisation of the components is the time and cost impact on the installation process. We have enabled separation of the concrete installation from the rail alignment and from the rail installation, allowing;

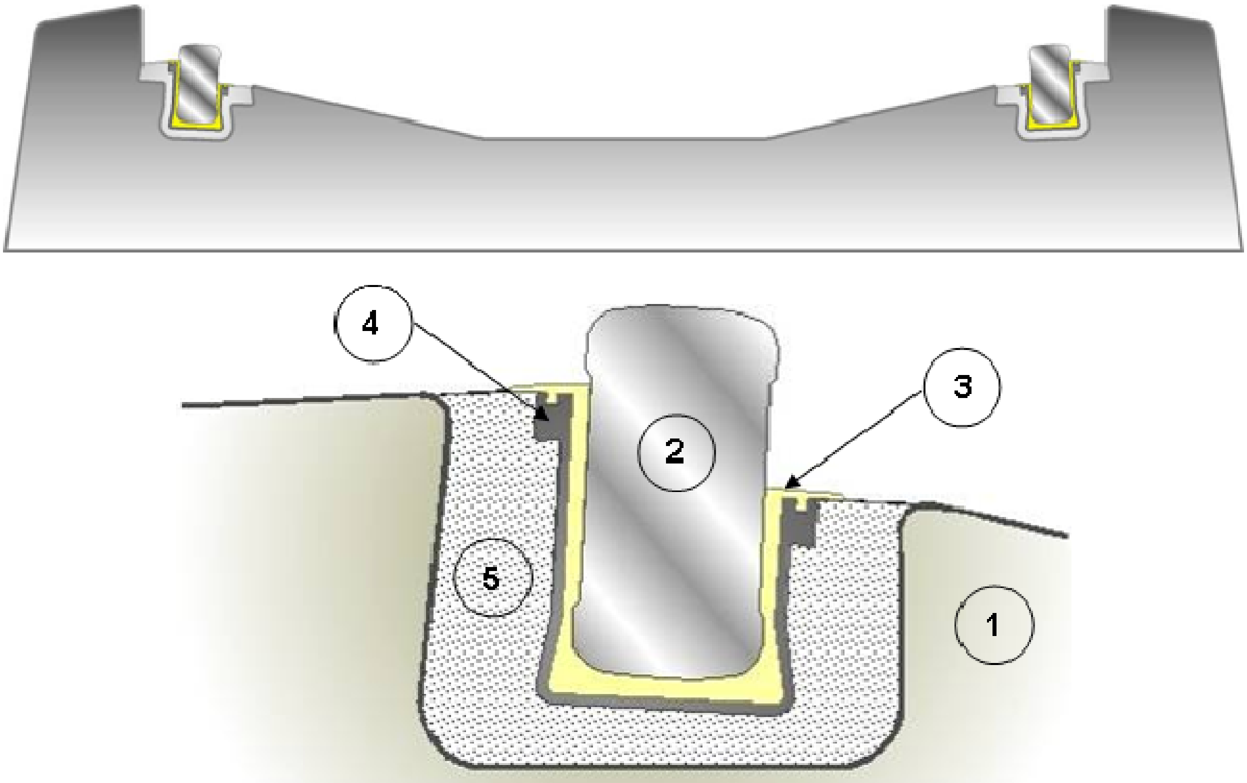
- Efficient low cost equipment can be used for each part of the process.
- Programme dependency risk of programme overrun is eliminated.
- An improved RAMS and operational performance is achieved.



	Mk I	Mk II	Reason for change
1	Tangs to anchor into grout	Fibrous coating on shell externally	Lifting angles retained in thickened top section but tangs were a weak point and peelply now is designed to anchor shell into grout.
2	Indent removed	Pad has equal thickness of pad height	Indents hindered rail removal and replacement. Removing them would have no effect on performance characteristics
3	Three subsystem components	Integral seal reducing number of components and eliminating all associated problems from a separate seal	Separate seal proved unsuccessful . Reduce installation processes
4	Field and gauge clearance heights	Field and gauge clearance heights increased	Meets European Standard for clearance and gives better access to rail head for installation and maintenance.
5	6mm max pad thickness on wall sides	7mm pad thickness on wall sides	Better shear qualities for rail renewal ease.
6	Thin shell top section	Thickened shell top sections	Plug for the seal and extra strength
7	Shell corner radii 3mm	radii of 8mm	Strengths shell. Experience has shown the shell to break at this point quite frequently
8	Smooth Pad / Shell interface	Roughened Pad and fibrous coating applied to internal shell locations	Increase in coefficient of friction between pad and shell increased longitudinal restraint of system.

Figure 2 - Comparison between MkI and MkII sub-systems

3.1.4 BBERS MkII System Details



Key

1 Concrete slab
2 Rail
3 Pad
4 Shell
5 Grout

Figure 3 - Cross section of MkII BBERS system

The efficient design and small number of parts that make up the sub-system means that it is a very low maintenance trackform is achieved. The continuously supported rail provides an optimum, reliable and repeatable wheel/rail interaction.

No fastenings are required for the embedded rail system. The shell is set in grout accurately (+/- 1mm) and when the pad and rail are installed a designed “restraining” load is applied to the rail.

Resilience in the system is provided by the pad. This pad is the heart of the system and provides the unique performance. A key aspect of the pad design is its load distributing structure which can accommodate both softer sub-grades and the forces involved in higher axle loads.

Track support can be achieved by a number of options, based on a slab, beam or a plate approach maximising the designer’s ability to provide the optimum support structure.

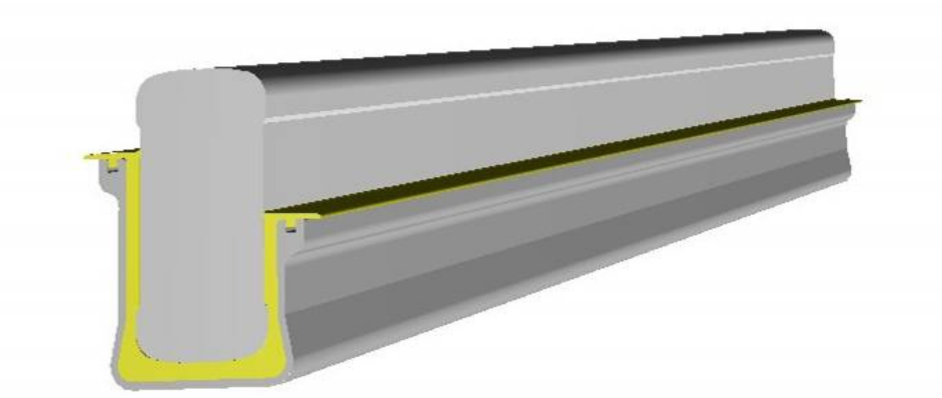


Figure 4 - Short visualisation length of the embedded rail components

Track quality/cost performance is improved over systems which require two layers of resilience to overcome the problem of clamping a rail directly onto a concrete support and thus losing the resilience of the rail pad. The rail shape and embedment are very effective in reducing noise (see Figure 5).

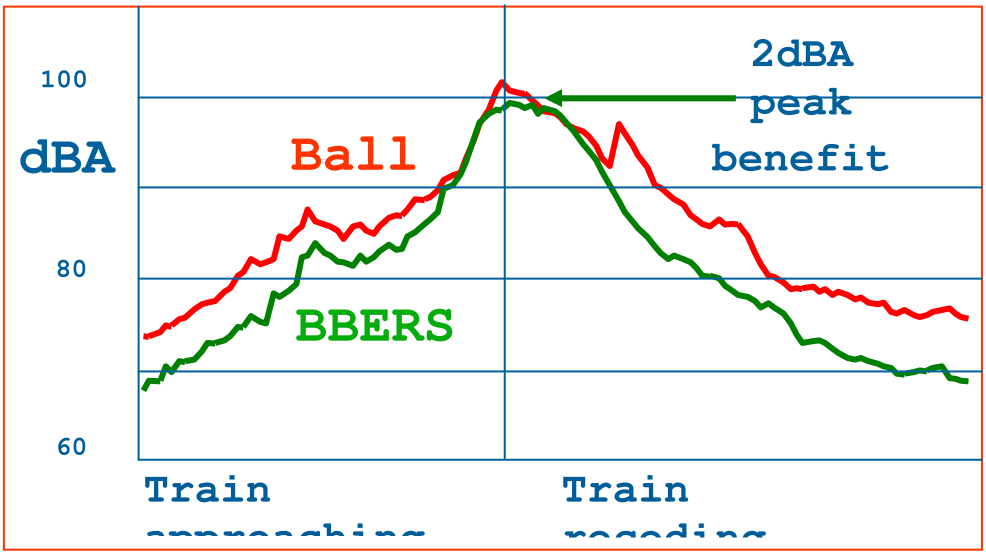


Figure 5 - Noise recording results from BBERS track at Medina el Campo, Spain

The use of standard civil engineering plant and processes also reduces specialist railway costs. The envisaged system will also offer savings on construction time and thus minimise disruption to operations. In specific circumstances the construction cost can be less than that of ballasted track.

The embedded rail system scores highly on reliability, primarily because 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, disruption to traffic is thus minimised. Additionally, the slab can be produced to protect against the potentially consequences of derailment.

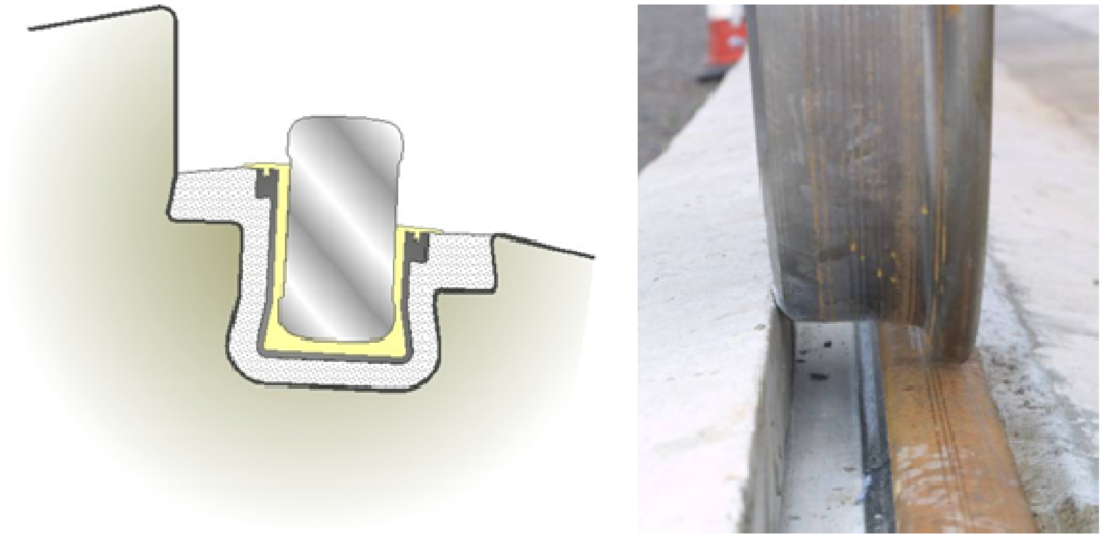


Figure 6 - Visualisation and testing of the embedded rail derailment protection

3.2 Component Design for Cost Effective Manufacture

3.2.1 Background

Following on from the completion of the component design, the next task was to convert the prototypes into a series of components that were suitable for manufacturing in production line quantities.

Each component has been optimised for its ease, speed, economic manufacture and its performance. The system as a whole has also been optimised by analysing how the components in intimate contact behave in relation to one another. Together this provides an engineered high performance at an economic overall system price and simplicity, and improved speed of installation.

The advantage of a shell system is that it facilitates a ‘top down’ construction methodology. The main advantage of this method is that it separates civil tolerances (generally +/- 10mm) from mechanical tolerances (+/- 1.0mm). In addition, by eliminating the risk of holding the rail during the concreting phase, it allows rail alignment to be set against a solid working surface.

As a result, the component manufacturing tolerances are the limiting factor when aligning track. In addition, the ability to rely on manufacturing accuracy provides repeatable and reliable installation tolerances. Figure 7 shows that the embedded rail manufacturing tolerances are well within the required design tolerances for UK rail infrastructure (Figure 8).

Component	Tolerance	
	Cross Section	Along Length
Shell / Lid	±0.25mm	±0.4mm/m
Pad	±0.25mm	n/a
Rail	±0.3mm	Vertical flatness ±0.5mm/m Horizontal flatness ±0.8mm/1.5m

Figure 7 - BBERS manufacturing tolerances

Parameter	Speed		
	65-95mph	100-125mph	>125mph
Vertical alignment (top)	+0,-30mm	+0,-30mm	+0,-30mm
Horizontal alignment (line)	±15mm	±10mm	±10mm
Cross level (cant)	±5mm	±3mm	±2mm
Twist (rate of change over 3m)	7mm	6mm	6mm
Gauge (plain line)	1435-1441mm	1435-1441mm	1435-1440mm
Gauge (S&C-1435mm nom)	1435-1438mm	1435-1438mm	1435-1437mm

***Figure 8 - Example track design tolerances for UK rail infrastructure*[1]**

3.2.2 Embedded Rail Concrete Slab

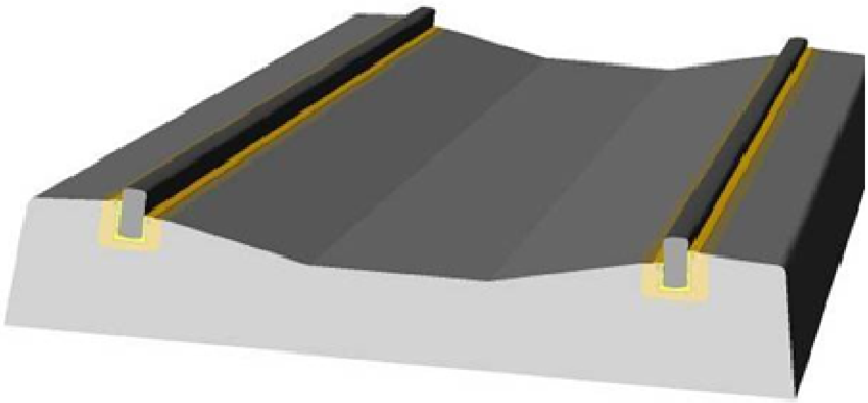


Figure 9 - Short visualisation length embedded rail concrete slab

The concrete slab incorporates the necessary slots to enable the rail sub-system to be embedded into the slab after the slab has been constructed. The constitution and strength of the slab is engineered to best match the local conditions. As such, further information on installation methods can be found in section 3.4.

The shell is held in its final position by means of a poured non-shrink, cementitious grout. The grout is generally specified to have a 28-day strength that is approximately 30% higher than the surrounding concrete.

Slab Manufacturing Details

As with all rail sub-structures, the production method is largely dependent upon site conditions. Please refer to section 3.4 for more information on slab manufacturing methods.

[1] NR/SP/TRK/0049 Track design handbook

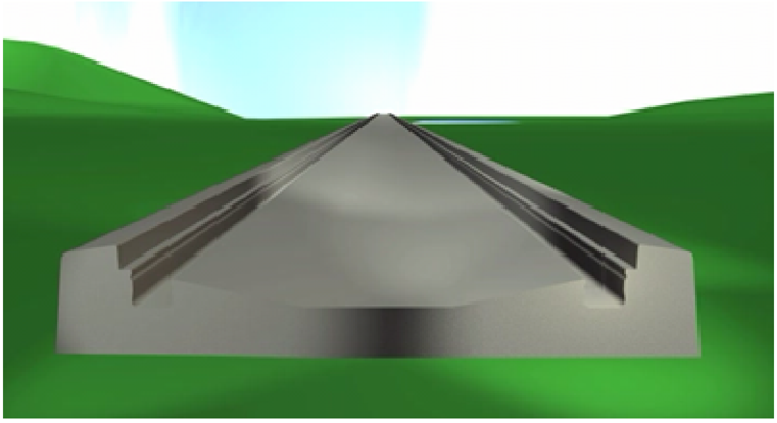


Figure 10 - Short visualisation length of the embedded rail concrete slab

3.2.3 BB14072 Embedded Rail

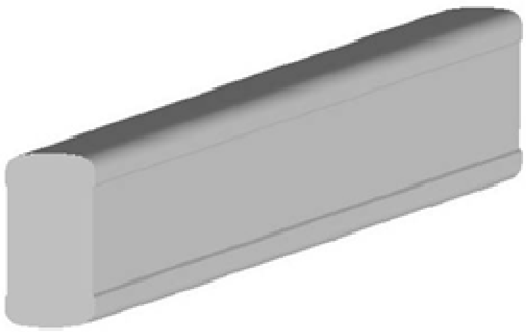


Figure 11 - Visualisation of the BB14072 embedded rail

The Balfour Beatty BB14072 rail is a new rolled profile, with head surface geometry (radii, width at gauge point, etc.) identical to that of the CEN 60 rail. It has both vertical and horizontal axes of symmetry. This rail is held in position inside a rigid shell by means of a 'U'-shaped resilient rail pad (see below).

The rail has been designed, in combination with the rail pad, to maintain the live load stress range in accordance with fatigue strength requirements. The rail is intended to be installed as continuously welded rail (CWR) and is restrained by the shell and pad to resist vertical and lateral buckling. This allows the rail to be set stress free at ambient temperature within a relatively wide range; the usual requirement for a closely prescribed stress-free temperature range being unnecessary.

The whole rail section of BB14072 can be ultrasonically tested from the railhead, unlike other rail sections. As up to 40% of rail-breaks can occur from ultrasonically undetectable defects[2], i.e. in the rail foot, the system is significantly safer the flat bottom rail sections.

[2] Presentation at the systems integration at the vehicle/track interface seminar, 28/11/2006

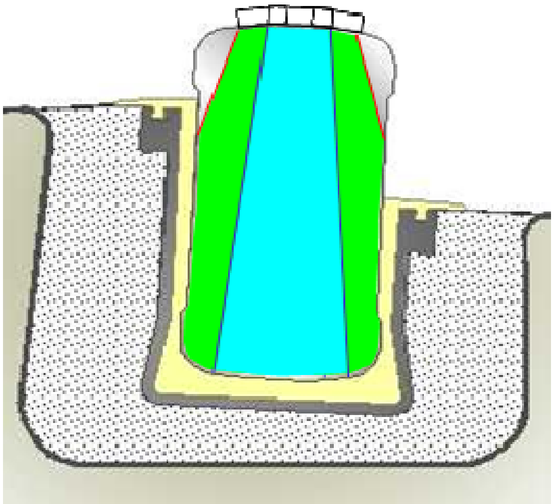



***Figure 12* - Ultrasonic testing of BB14072 rail**

Manufacturing Details

The rail is hot rolled in a rolling mill and can be delivered in any length required. Production rates for the rail are 150 tonnes/day (10km/week) and typical manufacturing tolerances are +/- 0.3mm. The rail design is based upon the European standard BS/EN/13674-1:2003 *Vignole Railway rails 46kg/m and above*.

Figure 13 - Manufacture of the BB14072 embedded rail

Figure 14 - BB14072 rail cooling in rolling mill

3.2.4 Embedded Rail Pad

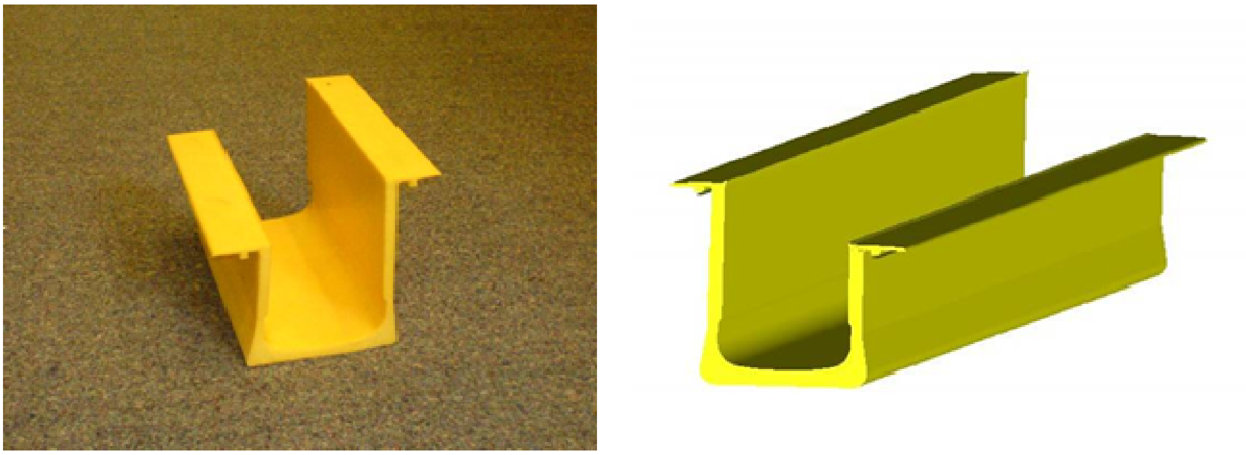


Figure 15 - Short prototype length and visualisation of the embedded rail pad

The U-shaped resilient elastomeric rail pad supports the side and base of the rail, holding it in the correct attitude and position so as to guide the wheels and not suffer excessive lateral deflection, twist or rollover. The elasticity of the vertical support distributes the wheel point load evenly along the supporting slab, with reduced resultant peak stress concentrations in the slab compared with discrete rail support systems.

The pad design also features an integrated seal that prevents the ingress of moisture and contaminants into the system. This seal locks into the underlying shell and is inclined such that water and debris drain away from the rail.

The pad is made from a high quality foamed polyurethane, formed by a precision injection moulding process in lengths of 2 metres. Pads can be produced with different spring coefficients by varying the density of the injected material and/or by selecting different base dimensions.

The pad also prevents buckling upwards of the rail under extremes of temperature, while still enabling replacement and/or repair of the rail without necessitating replacement of the pad. Dynamically the pad absorbs impact loading and reduces the transmission of vibration from the rail to the supporting/adjacent structures over a frequency range appropriate to the application.

Manufacturing Details

The microcellular polyurethane pads are cast in 2 metre lengths in a positive-pressure injection mould. Production rates for the pad are 1600m/week and typical manufacturing tolerances are +/- 0.25mm.

The system performance and track quality retention depend on the pad, not least its stiffness. The pad supports the rail resiliently both horizontally and vertically. The pad stiffness is governed by its:

- thickness;
- temperature;
- density and;
- fatigue life.

and these affect the following:

- ride comfort;
- propagation of corrugations in the rail;
- longitudinal restraint of the rail;
- ride wear of the rail;
- corrosion of the rail;
- vertical uplift of the rail.

The manufacturing process has been refined and optimized to enable large quantities of pads to be manufactured quickly and economically. A range of stiffness is possible from 10kN/mm/650mm upwards.

The manufacturing process means that specific traffic needs and transition zones can be met by pads of the required stiffness at no extra cost or difficulty. The required dimensional tolerances are achievable.

3.2.5 Embedded Rail Shell

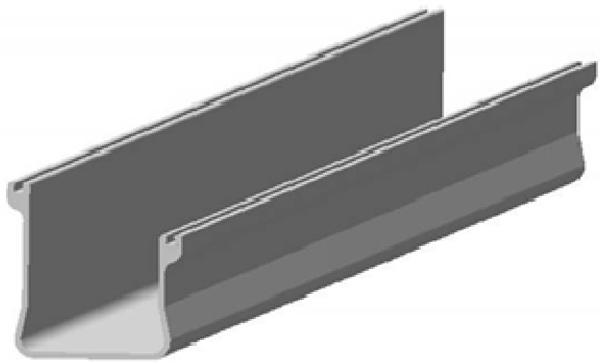


Figure 16 - Visualisation of the embedded rail shell

The shell is a Fibre Reinforced Plastic (FRP) composite, a material commonly employed in the construction industry. A good quality chemical-resistant grade resin has been used to ensure that the glass fibre component is protected from the alkaline concrete environment.

The main function of the shell is to form a dimensionally accurate slot, to ensure the correct action of the elastomeric rail supports. The shell remains dimensionally stable while exposed to the atmosphere, provides secure support to the elastomeric pads and transmits the live loads, vertical, longitudinal and transverse, from the train through to the surrounding concrete.

The shell form is robust, but lightweight for ease of handling. During the installation process it is butt-joined in a grout-tight manner by the use of adhesive tape. The shell forms part of the electrical insulation afforded by the system and in conjunction with the elastomeric pad provides efficient insulation and effective mitigation of stray current leakage.

Manufacturing Details

The shell is manufactured in pultruded glass reinforced plastic (see Figure 17 and Figure 18) and can be delivered in any length required. Production rates for the shell are 1000m/week and typical manufacturing tolerances are +/- 0.25mm.

Figure 17 - Embedded rail shell Manufacturing process

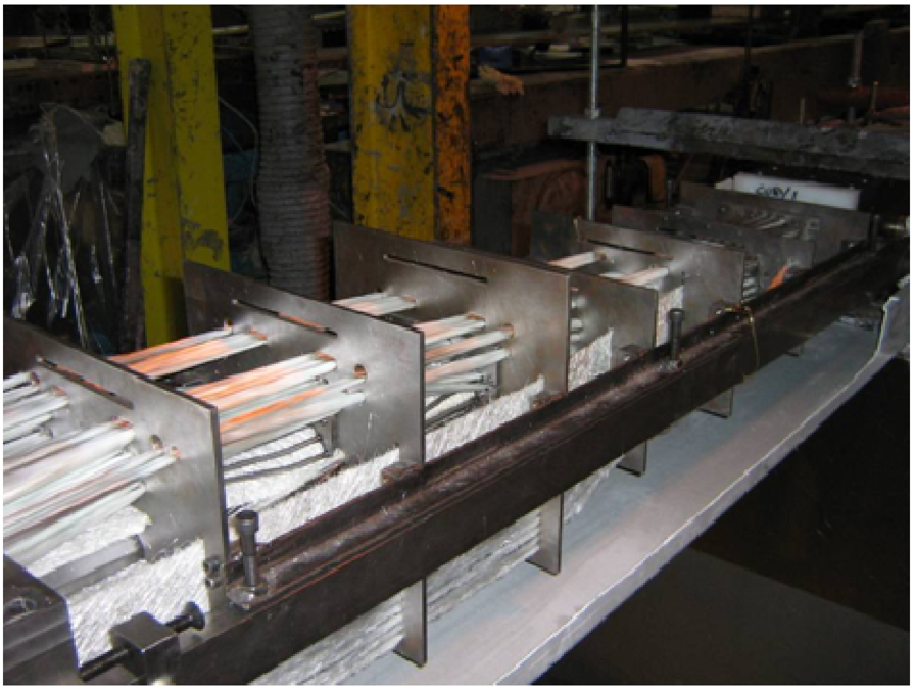


Figure 18 - BBERS shell Manufacturing process

The difficulties of design and manufacture that have been overcome include:

- Obtaining the required tolerances of the finished product;
- Providing a mechanism for future automated installation;
- Holding the mandrel central in the clipped lid;
- Getting the necessary amount of reinforcement into the unit;

- Obtaining a clipped lid head profile in the same position when assembled as the rail head profile when inserted into the pad in service;
- Achieving a good clipping action between the lid and the shell;
- Removal of the original independent ride seals.

The tolerances are critical, not only to the match fit of the other components, but also to the performance of the system. Not least of these is the dimension across the shell top, which is determined by the propping action of the lid. This dimension controls the amount of pre-compression in the pad and consequently the longitudinal restraint of the rail.

The shell has been modified by increasing the corner radii, for the following reasons:

- to reduce stress in the grout;
- by reducing its height to enable more rail head wear, better clearance of the wheel flange from the concrete and easier rail removal;
- by providing a socket for the pad and clipped lid. This retains the pad when the rail is inserted;
- by the inclusion of peel ply to increase the pad/shell and shell/concrete bond strength. Various grades of peel ply have been trialled to optimize this;
- the upper nibs of the rail have been shaped to eliminate air traps during grouting.

3.3 Embedded Rail System Testing

3.3.1 Background

A series of static tests were undertaken in order to prove the performance of the system. Owing to the unique design of the system, no specific test criteria currently exists to measure its performance. However, the following British / European standards for railway track applications relate to similar sub-systems. Adapting their key performance requirements provide relevant criteria against which to measure the BBERS system;

BS/EN/13146:2002 Railway Applications – Track – Test methods for fastening systems

BS/EN/13841:2002 Railway Applications – Track – Performance requirements for fastening systems

Three main performance criteria for a rail sub-system are defined by the standards; longitudinal rail restraint, vertical rail restraint and vertical stiffness.

3.3.2 Longitudinal Rail Restraint Test

The embedded rail system does not have discrete rail supports with clip fasteners to constrain the rail. Instead, a continuous resilient pad surrounds the rail and is itself continually embedded in a permanent shell. This complete system is then set in concrete. A combination of pad pre-compression and friction coefficient between pad, rail and shell provides the force required to resist longitudinal movement.

The longitudinal restraint testing procedure shall be based on the method described in BS/EN/13146-1. The technical specification for interoperability relating to the infrastructure sub system of the trans-European high-speed rail system defines the requirement of longitudinal restraint to be greater than 9kN. However, a safety factor has been added to the standard requirement as a result of the cross sectional area of the BB14072 rail being 22% greater than that of UIC 60 rail.

3.3.3 Vertical Rail Restraint Test

The rail is designed to be removable from the pad and shell without damaging any component. This requires the pad to provide vertical resistance to a limit and then deform to allow rail removal. Initial resistance to vertical movement determines the ability of the system to resist vertical buckling and deformation each side of loads applied to the rail.

The purpose of this test was to determine the degree and extent of the elasticity of the vertical restraint, i.e. the rate of the resistance and the point of maximum load that when applied to the rail and released, the rail returns to its original position in the pad and shell.

The elastic limit is defined as when the rail remains 0.2mm above its original position once the load is released. This is considered a conservative estimate since the rail requires a considerable amount of additional force in order to be removed from the sub-system (ultimate pull-out load).

3.3.4 Vertical Stiffness Test

Part of the requirements for the testing of rail support systems is a vertical stiffness test to simulate how the BBERS system deforms under in-service loads. The embedded rail system does not use discrete supports and individual rail pads to support the rail. Instead, a continuous resilient pad surrounds the rail and is itself continually embedded in a permanent shell. This complete system is then set in concrete.

In conventional track systems, the rail is fastened down against the compression of the rail pad, thereby reducing any shock absorbing properties of the pad. The embedded rail system, in contrast, constrains the rail by a combination of geometric shape and lateral pressure on the rail waist. As a result, the section of pad directly under the rail foot is compressed by only the weight of the rail. By comparison, the embedded rail pad has only the singular task of absorbing traffic load.

3.3.5 Embedded Rail System Test Results

Test	Longitudinal Restraint	Vertical Restraint	Vertical Stiffness
Result	16.2 kN	18.0 kN	34.1 kN/mm/650mm

Figure 19 - Test results for MkII Embedded Rail System

The test results in Figure 19 show that the system exceeds the requirements set by the referenced British and European track standards. This proves that the system works not only as a concept, but also as a prototype length.

Furthermore, the results have shown that that there is scope for utilising a softer pad. This illustrates the wider capabilities of the sub-system and will be particularly effective where a greater level of noise attenuation is required.

3.4 Superstructure Design for Cost Effective Installation

3.4.1 Background

An embedded rail solution offers flexibility in terms of construction options. Consequently the Engineer is not constrained by the limitations of other slab or ballasted track construction methodologies and plant.

The embedded rail solution has been developed with the following installation principles in mind,

- Use of Standard Civil Engineering processes and equipment
- Minimise the work required on site.
- Minimise the total work carried out.
- Use proven processes, technology and plant.
- Maximise construction flexibility

This approach has the potential to significantly reduce the cost of track installation compared to ballasted track or other slab track systems.

3.4.2 Installation Overview

The advantage of a continuously supported embedded rail track system such as the Balfour Beatty product is that it allows an efficient structural beam to be engineered for the tracks structural support. The possibility of making this beam pre-cast, slip-formed or even in-situ poured using pumped concrete maximises the opportunity for the construction process to be optimised for the constraints of time, space, traffic and available railway construction and renewal resources.

Adjustability after installation is not normally envisaged but, if ever required, is achieved by cutting through the grout using disc saws and lifting the rail and shell, or lifting and grouting the slab.

The typical construction height of embedded rail track is much less than alternative options. For example ballasted track from top of rail to bottom of ballast is in the order of 600mm. The embedded rail system can be half this. The effect of embedding the rail ensures that the maximum use is made of characteristics of slab, beam or plate design.

The geometry retention properties of embedded rail are excellent. The continuous vertical and lateral support ensures the rail rotation and deflection is both predictable and at a minimum. The pad is not highly stressed and retains its designed stiffness for the life of the rail.

Maintenance other than occasional inspection and rail grinding is eliminated. The frequency of rail grinding is reduced as the rail is less likely to corrugate due to the continuous support.

The embedded rail system has high build-ability and lends itself to high levels of mechanisation. The construction process uses established, cost effective and proven civil engineering techniques, plant, tools equipment and skills.

3.4.3 Clipped Lid

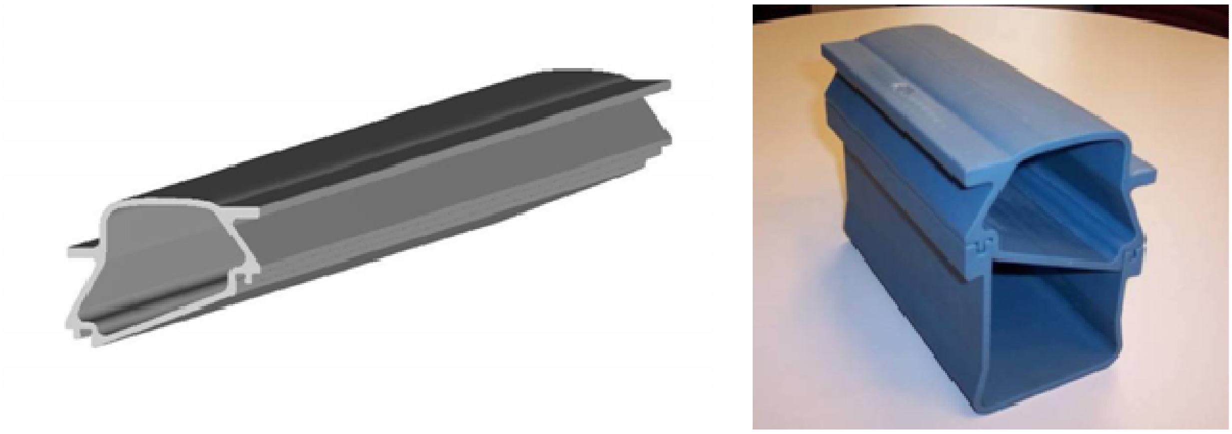


Figure 20 - Visualisation and prototype clipped lid

The shell has been designed to allow a lid to be “clipped” onto it. The lid is designed to share the same geometry and position of the running rail. This innovation therefore allows the shell to be accurately placed, lined, levelled and gauged prior to the shells final grouting or concreting into position.

This system avoids the typical slab track construction complexity implicit in the need to provide support to sleepers, slab or rails while concrete is cast. The temporary works for pouring and vibrating concrete whilst maintaining tolerances is an onerous task which the embedded system has eliminated. A significant problem in conventional slab track systems is protecting the fastenings from wet concrete, which this embedded rail system avoids.

A further advantage of the clipped lid concept is the flexibility it introduces into the installation process. The normal dependency of simultaneous concreting, aligning and railing is broken. These tasks can be undertaken independently allowing the maximum use of high output equipment e.g. slip formers and road-rail vehicles. The lid has been designed with wings (lugs) to allow ease of handling and support framing.

Manufacturing Details

The clipped lid is manufactured using the same method as the embedded rail shell. Pease refer to the shell manufacturing details in *section 3.2.5* for more information.

3.4.4 Slip Forming Installation Method

The embedded rail track form installed at Crewe used a slip-form methodology. Slip forming is a well established and proven technique. It presents a number of advantages, namely;

- low risk process
- good productivity
- skills plant and equipment are readily available
- produces a high quality product
- prices and costs can be benchmarked against construction industry norms.

Figure 21 - Slip formed slab at Crewe

Equivalent slip forming rates in construction can be 1.5 metres per minute.

Stages for a slip formed concrete solution

This is the classic Civil Engineering approach. Standard plant, tools, equipment and readily available skills and knowledge are used. It is a very efficient and effective solution for large scale jobs. The following assumes existing track is being relayed, however the same principles apply for a green field site.

The stages of work for a slip form solution are;

I. Take up existing track
II. Excavate and/or prepare formation depending on ground conditions
III. Place lean mix base for slab if required by design
IV. Place reinforcement
V. Slip form
VI. Align and fix sub system (shell and pad)
VII. Grout shell into final position
VIII. Distribute rails
IX. Weld and install rails

3.4.5 Pre-cast Concrete Slab Installation Method

A pre-cast version of this track form slab is being developed for the UK underground system. The pre-cast slabs will be 6m long, 2.15m wide, 0.35 m deep and weigh approximately 6 tonnes. The construction methodology has been based on using a panel relaying methodology. The slabs can be delivered to site with the shell already cast into the correct alignment.

The slabs will be accurately lined and levelled on site and grouted (or concreted) into position. The grout is a quick setting formula giving the required strength in less than 1 hour.

The most significant advantage of this approach is the absence of curing time. As soon as the rails are installed traffic can run.

Figure 22 - Example installation of pre-cast slab track level crossing

The option of installing the shell on site also exists. The advantage being reduced precision of the pre-cast slab placement and no pre-build. This can provide more flexibility and offer a potential time saving to the installer.

Pre-cast installation may be the optimum solution during the single line working stages.

Embedded rail pre-cast units are designed to be structurally connected to cater for the range of loads and stresses that will be applied to the system.

Stages of work for a pre-cast concrete slab solution

This solution is based on a project undertaken on the UK underground system. The emphasis is on installing the greatest amount of track in the shortest possible period of time, whilst also minimising on-site plant activities and specialist work. The following assumes existing track is being relayed, however the same principles apply for a green field site.

The stages of work for a pre-cast slab solution are;

Option 1.

I. Take up existing track
II. Excavate and/or prepare formation depending on ground conditions
III. Lay slabs
IV. Jack, align and grout slabs into final position
V. Join slabs
VI. Distribute rails
VII. Weld and install rails

Option 2.

I. Slew rails to six-foot and cess
II. Take up existing sleepers
III. Excavate and/or prepare formation depending on ground conditions
IV. Lay slabs
V. Jack, align and grout slabs into final position
VI. Join slabs
VII. Thimble in rails
VIII. Key existing rails into position
IX. Re-rail with new BB14072 rail

3.4.6 Traditional Concrete Slab Installation Method (cast in-situ)

This methodology was used in Spain on the embedded rail system. This is a well established process and does not require any specialised plant, tools or equipment.

An attraction of this approach is its simplicity. Once the shuttering has been set up and forms placed to create the slots for the rail, concrete can be pumped or delivered from the adjacent road. This is an activity that could make effective use of Single Line Working (SLW) periods. Consideration would be given to any likely effect of vibration from trains on the adjacent track to the new concrete.

Figure 23 - Example installation of cast in-situ track slab in Spain

In this case the concrete can be cast to civil engineering tolerances and then mechanical tolerances applied during the installation of the shell and clipped lid.

Stages for a cast in situ solution

This solution is based on the methodology used in Spain for the embedded rail system. This is a well established process and does not require any specialised plant, tools or equipment.

An attraction of this approach is its simplicity. It could be carried out on one or both roads (where a two track railway exists) at the same time. The following assumes existing track is being relayed, however the same principles apply for a green field site.

I. Take up existing track
II. Excavate and/or prepare formation depending on ground conditions
III. Place lean mix base for slab if required by design
IV. Place reinforcement
V. Erect shuttering
VI. Pour concrete
VII. Strike formwork

VIII. Align and fix sub system (shell and pad)
IX. Grout shell into final position
X. Distribute rails
XI. Weld and install rails

3.5 LCC Analysis and Evaluation

The following section outlines the BBERS justification for a 30% reduction of life cycle costing when compared with ballasted track. The current costs of many of the items below are not known to the author and may vary from railway administration to railway administration. Consequently, the railway administration will be required to input their actual values into the model.

3.5.1 Investment

Ballast

Ballast is not required for an embedded rail slab track system.

Sleeper including fastenings

Sleeper including fastenings are not required for an embedded rail slab track system.

Rail (including freight)

The BB14072 rail is approximately 25% heavier than CEN60. As the price of rail is generally dependent on steel price the cost of BB14072 will be typically 25% more expensive than CEN60. However both wear and fatigue life is extended over discretely supported rail.

Under sleeper pad

An embedded rail slab track system does not require an under sleeper pad.

Subsoil measurement

In common with all track forms sub soil measurements will be taken for an embedded rail slab track system and used in determining the slab design.

3.5.2 Installation costs

Rail renewal

The rail renewal requirement for the BB14072 embedded rail system will be less frequent than that of other rail systems. The BB14072 rail section has a greater mass per metre than most rail sections. It is also continuously vertically and laterally supported which means it that does not act as a beam. It follows that greater headwear is allowable with BB14072 rail.

The shortest rail life for simply supported rail in Europe is approximately 7 years in normal conditions in the UK-France Channel Tunnel. By this stage the rails have carried in the region of 600 million gross tonnes. By using the BB14072 rail, extra rail life tonnage can be allowed if wear is allowed to exceed the 12-14mm limits commonly specified for flat bottom rail. This is due to the larger rail mass per metre and absence of a narrow web resulting in a lower rate of change in 2nd Moment of Area due to wear compared to standard section. This allows rail wear to be increased without risk of rail failure. Additionally the lower residual rail stress, continuous support, quality control and control of rail rotation will all contribute to a longer life. The BB14072 rail has been checked against the 40 tonne axles found in the USA. For these reasons we conservatively estimate that the BB14072 rail will have a minimum of a 30% longer service life.

For more information, please refer to section *3.4 Superstructure Design for Cost Effective Installation.*

Disposal or recycling of materials costs

With an embedded rail slab track system, there are fewer components to dispose of compared to ballasted track or other slab track systems. The rail can be recycled like any metal. The pad can be disposed of as inert waste or crumbed like road tyres for recycled use. After more than 60years, the concrete slab can be removed and broken up or crushed and the reinforcement extracted and recycled. This can be compared with the ongoing disposal of ballast, sleepers, insulators, clips and pads. Additionally the adverse environmental impact of continuous extraction and transport of ballast may become recognised as unsustainable.

Residual value

The design life for an embedded rail slab track system can be taken as a minimum of 60 years, but is dependent upon the client's requirement. The residual value is therefore equivalent to the difference between the life of ballasted track and an embedded rail slab track system.

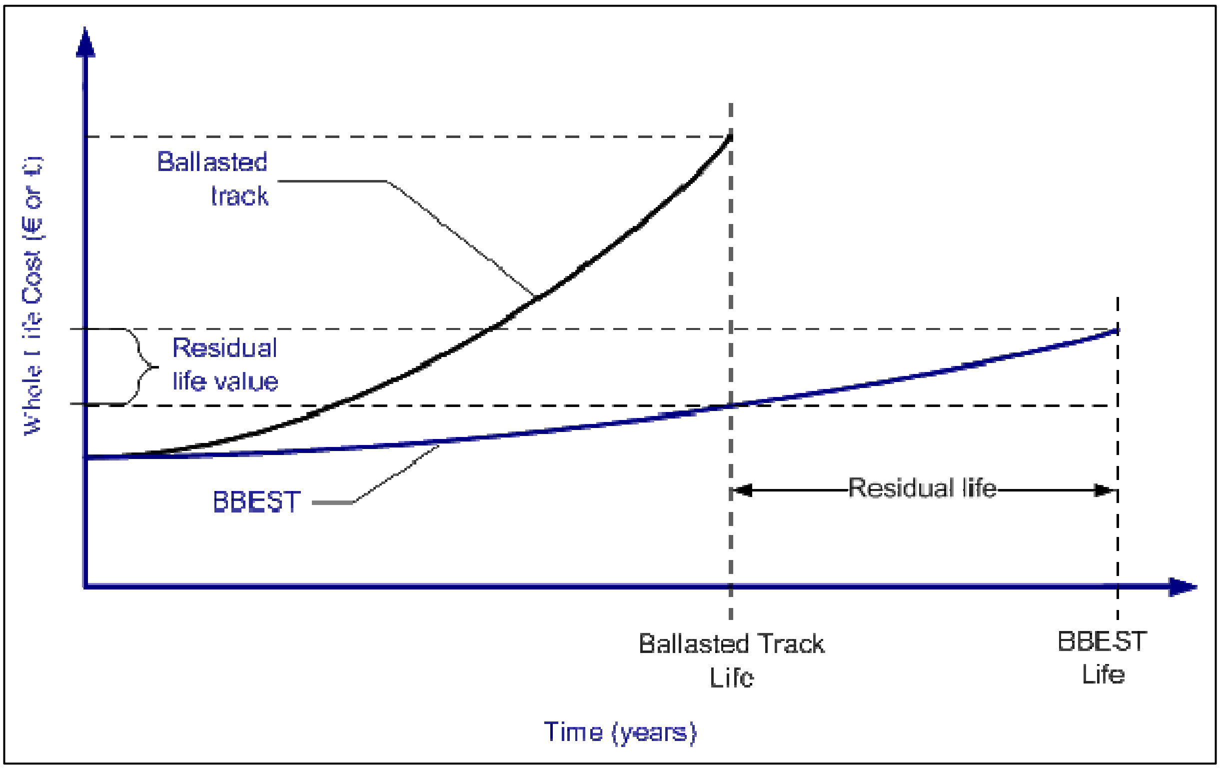


Figure 24 - Residual Value graph

Figure 24 illustrates how the residual life value may be determined. It is a concern that if this approach is adopted, the cost benefit of avoiding a ballasted track renewal at the end of the ballasted tracks life is not recognised.

3.5.3 Maintenance

Tamping

Tamping will not be required on embedded rail slab track system. The saving is therefore a direct comparison with the tamping costs for ballasted track with a given tonnage of traffic.

However there are other benefits associated with no tamping. The full cost of tamping including all back-up facilities, ballast drop and regulation needs to be included. Eliminating the need for tampers also increases the availability of the track.

Ballast cleaning

Ballast cleaning will not be required on an embedded rail slab track system. The saving is therefore a direct comparison with the ballast cleaning costs for ballasted track with a given tonnage of traffic.

However there are other benefits associated with no ballast cleaning. These include the requirement for a smaller fleet of ballast cleaners which reduces the number of trained staff to plan, operate and maintain the fleet. Eliminating the need for ballast cleaners also increases the availability of the track.

Rail grinding

An embedded rail system does not eliminate the need for rail grinding. Owing to the continuously resilient support and high precision tolerances of the installed track, there is the potential for rail grinding frequencies to be reduced. The reason for this is that the continuously supported rail will be less prone to corrugation development and the high quality rail alignment will be maintained throughout its life.

Control of vegetation

As there is no ballast matrix for vegetation to incubate in the requirement for vegetation control is significantly reduced.

Manual visual inspection

The embedded rail system practically eliminates the need for manual (on foot) visual inspection. Slab track systems in general and the ERS in particular with its few components will allow visual inspection frequencies to be reduced and ultimately eliminated. It is noted however that this will require challenges to standards and acceptance of these challenges by the railway administration. Given the fully restrained rail automated inspection will be relatively easy to justify.

Inspection vehicle (e.g. Track recording vehicle)

The embedded rail system shall still be inspected by a track recording train. However, fewer inspection runs will be necessary since ERS has a low rate of deterioration, fewer failure modes and a predictable degradation pattern.

Ultrasonic inspection

The entire section of the BB14072 rail section can be ultrasonically tested from the railhead. As a direct result, many rail defects can be identified earlier than in other rail sections. The rail itself has lower residual stresses than other rail sections and thus defect growth is reduced (see ***Erreur ! Source du renvoi introuvable.***). The rail is continuously support vertically and laterally, so even if a break does occur the two ends will be retained as if clamped. Due to the critical defect size being larger (no fast fracture through web mode), the BBERS system has the potential for ultrasonic inspections to be reduced by up to 50% for the same level of rail integrity.

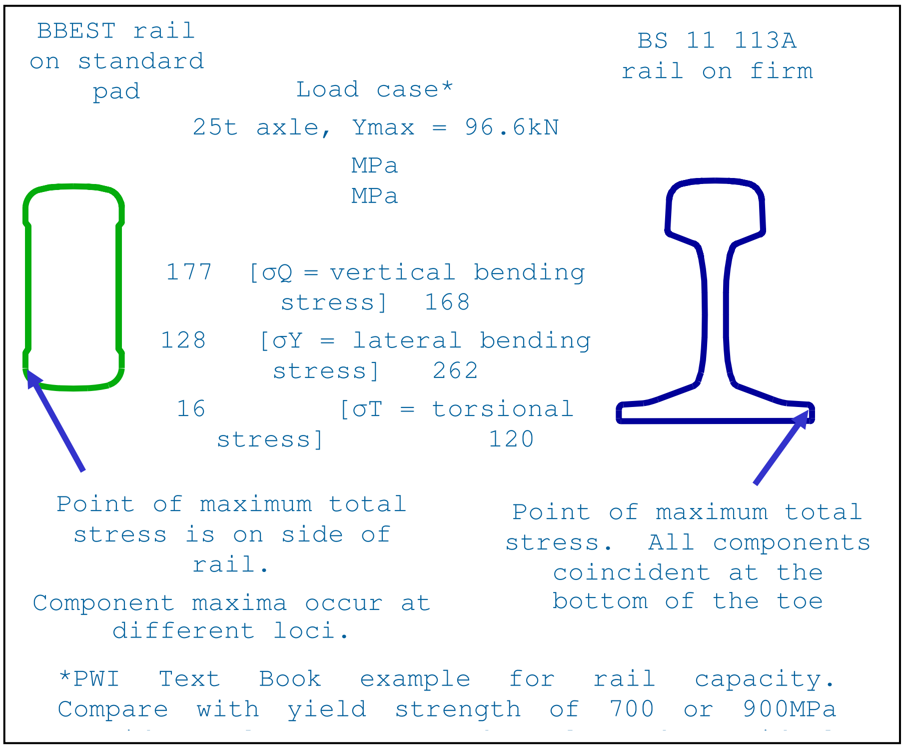


Figure 25 - Stress analysis comparison for BB14072 rail vs. BS113A rail

Drainage

Drainage is an essential element in any track form. An embedded rail system will not eliminate the need for drainage. However, the maintenance burden of drainage will be reduced for the following reasons; ballast will not be present to degrade under the action of traffic or maintenance and thus there will be little or no fines entering the drainage system, furthermore the presence of the slab structure will eliminate the problem of water entering the track structure.

Day-to-day track maintenance

Day to day track maintenance of conventional track includes replacing fastenings, discreet replacement of insulators, sleepers and ballast. It can also include minor drainage work. These tasks are eliminated with the ERS system.

Re-padding

UK experience suggests that rail pads (between sleeper and rail) require replacement after a given tonnage. Based on work in Munich on the MkI BBERS system[3], the pad in the embedded rail system is expected to have a life of more than twice that of rail pads.

3.5.4 Non-availability

Non availability planned

Day to day track maintenance

Many day to day track maintenance activities are eliminated. Infrastructure Managers measure how much time is made available for these activities. This time can be shown as a saving or an increased availability benefit to an embedded rail slab track system.

Tamping

Tamping is eliminated. Infrastructure Managers measure how much time is typically spent tamping ballasted track per tonnage. This time saving can then be allocated as a saving or benefit to an embedded rail slab track system.

Ballast cleaning

Ballast cleaning is eliminated. Infrastructure Managers measure how much time is typically spent ballast cleaning track per tonnage. This time saving can then be allocated as a saving or benefit to an embedded rail slab track system.

Rail grinding

Non availability due to rail grinding will be less than on ballasted track. The continuous vertically and laterally supported rail will be less prone to corrugation which requires preventative or reactive grinding. The absence of ballast means that on high speed lines the rail will not get damage by ballast getting crushed between rail and wheel.

Rail renewal including pads

See information relating to rail renewal

Non availability unplanned

Non availability for unplanned reasons needs to be compared with ballasted track.

Track stoppage

The following is a track related list of event that can cause a track stoppage.

- Broken rail

[3] Technische Universitat München, Research report n°1882 "Testing of the ERT" Non-ballasted tracj with embedded rails – New Designed Pads, 31/05/2001

- Buckle
- Loss of geometry

The likelihood of a broken rail is significantly lower with a continuously supported embedded rail system.

Speed restrictions

The following is a track related list of events that can require the application of a speed restriction.

- Broken rail
- Buckle
- Loss of geometry

3.5.5 Construction options and LCC Conclusion

This report has considered possible construction options and has evaluated the cost elements for the LCC model.

It has been argued that slab track systems require less maintenance than ballasted track form's, however this benefit is often outweighed by the perceived high first installation cost. This statement suggests that for slab track to be broadly adopted the high installation cost has to be closer to that of ballasted track.

The high first or installation cost of slab track compared with traditional slab track is a function of how slab track has developed over time. The rail generally being discreetly supported and clamped to the structure limits the opportunities for high output construction techniques and dictates a significant construction depth.

The areas where the BBEST trackform will provide LCC savings have been identified and quantified as far as possible at this stage. Our preliminary work suggests that the construction costs of BBERS will be less than many any other slab track forms (see below). This assertion is based primarily on the following considerations;

- A shallower construction depth is possible reducing the volume of excavation and new materials required. Indeed this will have a positive effect on the amount of construction traffic required.
- The embedded rail system allows the use of standard Civil Engineering plant, tools, equipment, methods and skills. This increases the supply base capable of doing the work and thus will create a more competitive market.
- The embedded rail system uses fewer components than other track forms and thus activities such as installing clips are eliminated or reduced.

To prove the embedded rail system can provide a 30% reduction in LCC a standard method for comparing the construction costs of slab track and ballasted track systems is required. The inputs to the LCC model go a long way towards this. However it is not yet clear how a comparative exercise can be done without say a specified reference track. We recommend that that this requirement is considered for the next stage of the project.

4. Conclusions

The optimisation for manufacture of MkII BBEST components has been completed and short prototype lengths have been manufactured. The test results in *section 3.3.5* show that the MkII BBEST system exceeds the requirements set by the referenced British and European track standards. This proves that the BBEST MkII system works not only as a concept, but also as a prototype length.

The key installation techniques for a cost effective installation of the embedded rail system have been considered, including a pre-cast slab, slip-formed slab and traditional cast in-situ slab. The new *'clipped lid'* installation device, which facilitates the setting of both the BBEST sub-system components and final track alignment, has also been illustrated.

The key elements to justify how the embedded rail system will provide a 30% reduction of life cycle costing when compared with ballasted track have been identified. One of the benefits presented by the embedded rail solution is the flexibility it provides in terms of construction options. Consequently the Engineer is not constrained by the limitations of other slab or ballasted track construction methodologies and plant. This report has considered possible construction options and has evaluated the cost elements for the LCC model.

4.1 Next Steps

- Full testing suite, including static and repeat loading tests, to compare the *'as new'* and *'used'* embedded rail system.
- Quantitative LCC evaluation of the embedded rail trackform and comparison against traditional ballasted track.
- Feasibility investigation for an in-track, trial installation
- Installation of a length of embedded rail system at an in-track location.