Project no. TIP5-CT-2006-031415O

INNOTRACK

Integrated Project (IP)

Thematic Priority 6: Sustainable Development, Global Change and Ecosystems

D1.3.4

Report on the most appropriate tools for evaluation of the issues raised within InnoTrack where no proven method already exists and the Balfour Beatty Embedded Rail System; An example of Technical Evaluation

Due date of deliverable: 31 October 2009

Actual submission date: 31 December 2009

Start date of project: 1 September 2006 — Duration: 36 months

Organisation name of lead contractor for this deliverable: Network Rail

Revision Final

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	**X**
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Glossary

Abbreviation / acronym	Description
BB	Balfour Beatty
BBERS	Balfour Beatty Embedded Rail System
BBEST	Alternative name for BBERS
DB	Deutsche Bahn
FMEA	Failure Modes & Effects Analysis
FMECA	Failure Modes & Effects Criticality Analysis
GB	Great Britain – note that NR is responsible for GB and not UK infrastructure
IM	Infrastructure Manager
LCC	Life Cycle Cost
MMU	Manchester Metropolitan University
NR	Network Rail
RAMS	Reliability, Availability, Maintainability and Safety
RISRAS	Railway Intelligent Safety Risk Assessment System
RSSB	Rail Safety & Standards Board (GB)
SP	Sub-project
TUM	Technischen Universität München
VCSA	Vossloh Cogifer SA
WP	Work-package

Executive Summary

Significant reduction in the cost of ownership of railway infrastructure requires step changes. This report discusses the need for thorough technical evaluation before innovative products or processes are introduced into railway infrastructure. Failure of adequate evaluation together with manufacture and installation of a lower quality than planned has occasionally introduced new risks and this has contributed to the perceived reluctance of infrastructure managers to accept new technology.

Examples of evaluation from different InnoTrack Work Packages have been selected to demonstrate a variety of the tools available.

A detailed worked example for the evaluation of an embedded rail slab track and the use of FMECA and fuzzy reasoning tools are discussed.

The technical evaluation of the Balfour Beatty embedded rail system supports the findings of the LCC analysis for this design in that the BBERS will probably perform better than a conventional ballasted track and will have a lower LCC at higher annual tonnage. As with all track systems key issues are the ground preparation before forming the slab, and process control during manufacture and installation of the rail support. The integrity of the design will also depend upon the detail design of transitions and the interface with switches and crossings.

1. Introduction

The motivation for installing new railway assets will generally be to improve RAMS and reduce LCC. The objective of InnoTrack is to reduce LCC by 30%, but if the innovation fails to perform to specification the LCC may be increased by more than 100% if the IM is required to undertake major modifications. An essential requirement when considering the introduction of new technology is to determine the risk of the performance being lower than calculated and the effect of reduced performance on the LCC. This risk may be minimised by a comprehensive test programme to determine that the product or system performs to specification. If a test programme is sufficiently representative of the service conditions the probability of a given proportion of the products achieving a specified life or number of load cycles may be calculated.

When the innovative product is significantly different from existing products, present test methods may not be applicable. For instance, if the present product is manufactured from steel and fails by a fatigue mechanism, a new product manufactured from plastic or composite materials may well fail in a different manner, and the previous test method will not be applicable.

It is the purpose of this report to explain how new products that represent a step change in design, may be evaluated to minimise the risk that they will fail to perform to specification.

This will be demonstrated by examples of technical assessment from InnoTrack deliverables and a detailed worked example of the evaluation of a novel embedded rail slab track.

1.1 Analytical Approach and Stochastic Models

Simple mathematical calculations have traditionally been used as a design tool to ensure that a new product has a factor of safety that experience has shown results in an acceptably low level of failures under known loading conditions. Historically the factor of safety took account of variations in materials and manufacturing quality, service loads, corrosion allowance and less well understood failure modes such as fatigue. This approach may be satisfactory where large structures are subjected to mostly static or quasi static loading conditions, but dynamic, variable and cumulative loads, and the need to reduce weight has resulted in the a more rigorous approach to optimise design and avoid failure.

If a stress calculation assumes all the worst cases, such as minimum material properties, poor support conditions and the most severe loads, it may be proven that the present product, that in practice has a satisfactory performance, is incapable of sustaining the applied loads. Deliverable D4.2.6 [1] provides a demonstration of a probabilistic approach that has been developed to avoid the conclusion that designs must be strengthened or in this case minimum actions increased, to meet the worst-case condition. The first point to note from the work of this WP is that the comparison of emergency speed restrictions for different defect sizes for the IMs participating in the InnoTrack project indicates that there is currently no sound technical basis for these decisions, and nominal values chosen have previously not been fully refined with experience and analytical ability.

The task sets out to demonstrate the method for determining the remaining usable life for a cracked rail taking into account the variability of material properties, rail support conditions, traffic and initial crack length. Statistical distributions for each variable are developed and the remaining life of the rail before failure is calculated by sampling values from each distribution. This process is repeated until a statistical distribution for remaining life is developed. The process has been further developed to overcome the problem that without breaking open the rail, the crack size at detection is not accurately known. This is done by developing a curve for the probability of detecting a crack at a given size.

The above is an example using a Monte Carlo simulation. This is a useful tool for generating a statistical distribution for an outcome where the inputs are highly variable. An example of where this form of analysis could be used would be the determination of the probability of a new design of switch failing within a specified time. This would require statistical distributions for actuating force, frictional resistance, support stiffness, traffic, wheel condition, temperature and other parameters found to influence switch performance, including maintenance interventions and the probability of blocking due to extraneous objects or ice. Clearly this requires the collection of a great deal of data, but is preferable to an approach of installing a large number of new design switches to then discover that a redesign is necessary as the mean time before failure is unacceptable.

1.2 Evaluation of a process or system

Condition monitoring of railway infrastructure is a popular concept as it offers the possibility of reducing the cost of maintenance and train delays due to poor reliability without improving the performance of the unreliable infrastructure. The benefits of any monitoring system must be validated in the same way as any other component of infrastructure. The deliverable D3.3.6 [2] identifies 4 levels of fault detection, with level 0 being the base level of system works/system faulty that is generally the starting position for most IMs. Level 4 diagnoses all potential faults with time to failure and determines the maintenance plan based on priorities.

Validation of the system level 4 requires determination of the following parameters:

- Probability that the system will detect all positive indicators
- Probability of correct diagnosis
- Probability of correct estimation of remaining operating life before intervention
- Probability of false positives
- Probability of an instantaneous failure or accident (unpredictable events)

This example has similarities to the example in 1.1 above, as a statistical value for the remaining life before intervention is required. The difference lies in the fact that if the switch fails earlier than predicted we have not increased the risk of an accident as would be the case for minimum action rules that did not ensure rail replacement before a break. This allows a simpler method for evaluation.

Once values for the parameters have been estimated it is possible to calculate the LCC benefit for a system at a given level for a specific route.

D3.3.6 demonstrates the use of a capability model that determines the net present value of the savings achieved through the use of condition monitoring systems having different levels of fault detection from detection only through to detection, diagnosis and identification. A sensitivity analysis is performed to demonstrate the influence of discount rate selected. In a similar manner, a sensitivity analysis would demonstrate the affect of changing the value in the input parameters on the calculated net present value.

A capability evaluation similar to that demonstrated in D3.3.6 may be performed for any process that delivers a calculable saving by converting the net savings for each year to a net present value using the formula

$$PV = - R_0 + R_t /(1 + i)^t$$

Where

t is the time of the cash flow; i is the discount rate

R_t is the net cash flow at time t; R_0 is the initial cost

The calculation again depends on the confidence that can be attributed to the determination of the net savings delivered by the process

1.3 Simulation using Numerical Models

The advent of powerful desktop computing has resulted in the development of many numerical models for the simulation of service conditions. These have been used extensively within the InnoTrack project and details of the high-resolution models employed in this project are given in D1.3.6 Part 2 [3].

A numerical model that is a close representation of the actual service conditions may be used as a tool to understand the causes of poor performance and failure, and then evaluate an alternative design to determine whether the problem conditions have been reduced or eliminated. A successful outcome for the use of numerical modelling depends upon validation of the model or models employed. Frequently the first developed models are simple in order to prove the concept. For instance, a distributed load may be represented as a single lumped mass that under some conditions may behave very differently from the actual situation. A fully developed model will still require validation and this should be at more than one point within the functional area. An example would be the simulation of vehicle track forces where a range of vehicle characteristics, speeds, loads and wheel profiles may exist. Demonstration that the model satisfactorily represents one set of conditions does not provide confidence that other conditions will be equally well represented, particularly if these are at the boundary of the models capability. Generic models covering the range of vehicles encountered on a mixed traffic route were developed and reported in D1.1.3 [4] to enable the simulation of the range of duty conditions that may be encountered on different routes.

A model that has proved suitable for examining the vehicle track interaction may also be a useful tool for evaluation of a new product. For this evaluation to be valid the conditions should be similar to those for which the model has been validated since the model may respond differently outside the range of validation. It is then necessary to determine whether other modes of failure may have been introduced. Failure mode effect analysis (FMEA) demonstrated in Annex C is one method for determining whether new failure modes may have been introduced.

An example of the use of a variety of models for simulating the passage of a freight wagon, running on Y25 bogies, through a switch will be found in Deliverable D3.1.4 part1 [5]. A comparison of measured and calculated wheel–rail contact forces is given. The forces calculated by use of the vehicle dynamics simulation software SIMPACK and GENSYS are compared with results from a field test in Härad, Sweden (contributions by Chalmers, DB, MMU and VCSA). In this example the correlation between the service conditions and the simulation indicate that the models are valid and although only one vehicle type was considered it is a useful demonstration of how development of a model could be expected to accurately predict the service response of a new product.

High resolution models (HRM) are proving to be useful tools for investigating dynamic conditions for a specific location where data on critical parameters is available. These high resolution models may be used to develop simpler low resolution models (LRM) that are sufficiently representative of the general case to be used as decision support tools for maintenance and longer term strategic planning

Linking of different tools may further extend the use of these models. A process for linking tools has been developed in D1.4.3 [6] and D1.4.5 [7].

2. The Balfour Beatty Embedded Rail System

2.1 Description

The history of BBERS dates back to the late 1990s and the initial system was produced with the specific objective of creating a long-lasting, low maintenance embedded rail system. The MkI version of the embedded rail system was developed in the early 2000s and successfully installed at Medina el Campo, Spain in 2002 and at Crewe, UK in 2003 (see Figure 1). The trial installation at Crewe has product acceptance from the GB Infrastructure Manager (Network Rail) and has now been in service for 6 years.

Figure 1 – Length of MK1 BBERS

The MKI trial installations identified several opportunities for improvement and a comprehensive design review was undertaken that included the manufacturing, installation and maintenance processes. From this review a MKII design was developed. Further details of the improvements from the MKI to the MKII design are given in Report D2.3.3 [8] ‘Design and Manufacture of Embedded Rail Slab Track Components’.

A schematic diagram of the MKII BBERS is given in Figure 2 and details of the manufacturing and installation processes are given in D2.3.3.

Figure 2 – Cross section of MKII BBERS

2.2 Test sites, laboratory tests and evaluation by BB

Following the development of the MKII BBERS, a series of laboratory tests and theoretical analyses have been carried out to evaluate its performance. Because of the novel nature of the design, no specific test criteria exist for the performance of such a track system. However various British and European standards for railway track application have been applied where they relate to similar subsystems. Where necessary the key performance requirements have been adapted to provide relevant criteria against which to measure the BBERS.

Further details of the testing are given in D2.3.3 'Design and Manufacture of Embedded Rail Slab Track Components'. A number of these tests have been reviewed as part of the Technical Evaluation described below.

2.3 Technical Evaluation for specified applications (boundary conditions)

Balfour Beatty have provided data for use in the Life Cycle Costing performed by SP6 and it was necessary for this data to be independently reviewed. This review was separated into two parts:

- Commercial Evaluation
- Technical Evaluation.

The Commercial Evaluation covered the costing and other financial data and was conducted by SP6 under conditions of strict confidentiality.

The Technical Evaluation is the subject of this report.

2.3.1 Process for Technical Evaluation

The process used for the Technical Evaluation of the BBERS can be summarised in the following stages:

- Identify the areas of concern to be addressed
- Document the areas using the product breakdown structure (PBS) of the Life Cycle Costing model

- Obtain responses from BB for each of the areas, with supporting evidence for statements made
- Review the evidence provided and question further if required
- Confirm or change the technical claims for the BBERS
- Document the conclusions for input to the LCC

An FMEA assessment was also carried out as part of the evaluation and this is reported in section 2.4.

2.3.2 Identification of Areas of Concern

The potential areas of concern for the technical performance of the BBERS were identified through meetings, review of the documentation and the FMEA process. The following meetings discussed the design, installation and maintenance of the system in order to highlight any concerns. The later meetings also reviewed the emerging assessment and made further comments:

- SP1 meeting, Utrecht 29th January 2009
- Technical meeting BB, NR, RSSB in Derby 13th March 2009
- SP1 meeting in Paris 2nd April 2009
- Technical meeting (and telephone conference) BB, RSSB, DB in Derby 18th May 2009
- SP1 meeting in London 30th June 2009
- SP1 meeting in Prague 16th September 2009
- Technical meeting BB, RSSB in Derby 21st October 2009
- SP1 meeting in Berlin 3rd December 2009

The areas of concern identified were entered into a spreadsheet in accordance with the product breakdown structure used for the LCC assessment. This used several levels; the first two were used for the Technical Evaluation:

Level 1 breakdown (where appropriate for BBERS):

- 00 System
- 01 Rail
- 02 Rail fastening
- 05 Substructure
- 06 Slab
- 08 Drainage
- 09 Environment – Sound Insulation

Level 2 breakdown:

- 01 Procurement
- 02 Operation
- 03 Maintenance
- 04 Non-Availability

Thus an area of concern associated with Maintenance of the Slab would be categorised under 06.03.

The final version of the spreadsheet is attached in Annex A of this report.

2.3.3 Review of Supporting Documentation

All of the areas of concern which were identified were then discussed with Balfour Beatty and an initial response entered into the spreadsheet. BB then provided technical documentation in support of their response. The list of 26 technical documents provided as evidence, together with an indication of which areas of concern were addressed by each document is attached in Annex B of this report.

The technical documentation was reviewed to assess whether it adequately addressed each of the areas of concern. Where the initial calculations and review indicated that further questions remained, then discussions with Balfour Beatty led to further documents being made available. In some cases this review also identified new areas of potential concern and these were added to the items requiring validation as the work continued.

Following a number of cycles of review a large majority of the issues were satisfactorily closed out and this is recorded in the spreadsheet (Annex A). In a small number of cases it was not possible to completely close the issue, usually because of the lack of service history in these areas. For these issues the current position is also noted in the spreadsheet.

Where any residual uncertainty over the technical performance of the BBERS remains, then all safety critical items were validated and cleared and the balance can be taken into account by sensitivity studies in the LCC.

2.4 Failure mode effects and criticality analysis

Failure Modes, Effects and Criticality Analysis (FMECA) is the process for evaluating all possible faults a system can exhibit, the effects (i.e. the functions which are adversely affected by the fault) and the criticality (i.e. the magnitude of the fault's consequences). The key system parameters to monitor are those which are connected to functions or components whose failure modes are most critical. By using FMECA we can look at one area of the problems caused by failures, which is the effect a failure mode has on the system. The cost of repairs and the time taken can also be factors, as well as the safety implications of a failure.
For the purposes of maintenance planning, the key parameters to monitor are those where failure modes cost most, take longest to repair, and reduce the functionality of the system by the greatest degree. Clearly some trade off has to be made where these variables do not correlate well. In the railway industry the number of train delay minutes associated with each failure mode provides an indication of its financial criticality, whereas the likelihood of causing a wrong side failure (i.e. a failure that may result in an accident of loss of life) provides the safety criticality.

2.4.1 A failure mode and effects (FMEA) review and the FMECA

An FMEA review starts by asking the following questions about a system to determine its functions, functional failure, failure modes and failure effects:

- What are the functions and the associated performance standards of the asset? (*Functions*)
- In which ways does it fail to fulfil its functions? (*Functional Failures*)
- What causes each functional failure? (*Failure Modes*)
- What happens when each failure occurs? (*Failure Effects*)

The FMEA can be extended in order to identify the criticality of each failure mode (making the analysis an FMECA), and also by considering what action (if any) should be taken to reduce or mitigate the failure mode. The following questions are then addressed:

- In what way does each failure matter? (*Criticality*)
- What can be done to prevent each failure? (*Preventative Action*)
- What should be done if a suitable preventative task cannot be found? (*Default Action*)

Actions prevent the failure under scrutiny. The preventative task will be either:-

- corrective - fix it when it goes wrong
- preventative - scheduled replacement or overhaul
- predictive - on-condition maintenance

The frequency of a scheduled preventative task is governed by the age at which the item or component shows a rapid increase in the conditional probability of failure. Scheduled preventative tasks are only feasible if:

- there is an identifiable age at which the item shows a rapid increase in the conditional probability of failure
- most of the components survive to that age
- the task restores the original resistance to failure of the asset

On-condition tasks entail checking for potential failures, so that action can be taken to prevent the functional failure or to avoid the consequences of the functional failure. On-condition tasks are feasible if:-

- it is possible to define a clear potential failure condition
- the 'warning time' of failure is reasonably consistent
- it is practical to monitor the item at intervals less than the 'warning time'
- the net 'warning time' is long enough for action to be taken to reduce or eliminate the consequences of the functional failure

2.4.2 BBERS Functional Overview

The primary functions of the BBERS were initially established using the simple overview diagram shown in Figure 3.

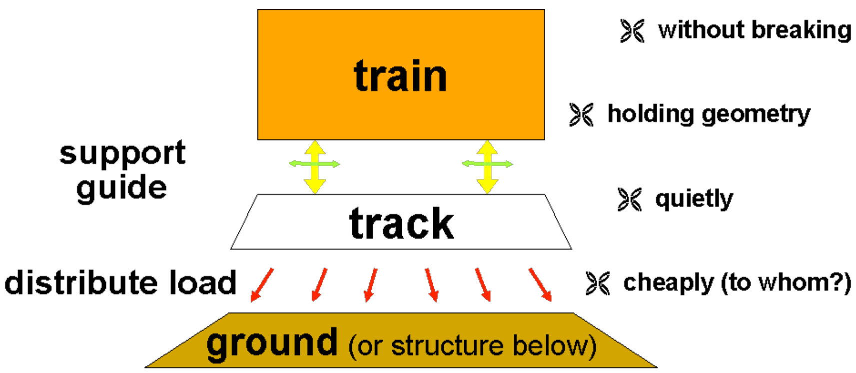

Figure 3 – Functional model of railway track

These functions were further developed to identify a full list, which included:

1. Withstand train forces;
2. Maintain correct train position;

3. Provide effective wheel-rail interface;
4. Provide effective track braking interface;
5. Withstand dynamic forces;
6. Withstand external influences
    a. Withstand temperature fluctuations;
    b. Manage incoming substances;
    c. Withstand fire;
    d. Withstand impact of track maintenance;
7. Accommodate train control systems;
8. Accommodate electrification systems
    a. Accommodate traction feed;
    b. Accommodate traction return
        i. Provide adequate electrical insulation between rail and ground;
        ii. Allow return bond connections;
9. Allow effective transition with other track systems, structures and switches;
10. Have acceptable environmental impact;
11. Provide safe surface for walking humans;
12. Accommodate emergency recovery equipment.

From these functions the Functional Failures and their Failure Modes and Effects were identified.

The FMEA for the BBERS slab track is general in nature and does not consider a specific line or traffic situation. The FMEA could be refined for specific boundary conditions, to assess the impact on a specific scenario. For example, an embedded rail system may exhibit strong benefits where it is necessary to run freight traffic on a route that requires to be maintained to a quality level for high speed trains. Additionally, the criticality of each Failure Mode Effect could be assessed by arriving at a criticality ranking based on a matrix of failure mode severity and failure mode frequency, as below:

Severity			
Description	**Guidance**	**Rating**	**Equivalent fatalities**
Catastrophic	Multiple Fatalities	4	5
Critical	Single Fatality	3	1
Serious	Major injury	2	0.1
Marginal	Minor injury	1	0.005
Negligible	No injury	0	0

Table 1 – Failure Mode Severity Table

Frequency			
Description	**Guidance**	**Rating**	**Equivalent frequency of accident per year**
Frequent	Likely to occur frequently in period of concern	5	> 5
Probable	Several times in period of concern	4	1 to 5
Occasional	Some time in period of concern	3	0.1 to 1
Remote	Unlikely but possible in period of concern	2	0.01 to 0.1
Improbable	So unlikely that it can be assumed it will not occur	1	0.001 to 0.01

Table 2 – Failure Mode Frequency Table

	Severity	Catastrophic	Critical	Serious	Marginal	Negligible
Frequency		4	3	2	1	0
Frequent	5	20	15	10	5	0
Probable	4	16	12	8	4	0
Occasional	3	12	9	6	3	0
Remote	2	8	6	4	2	0
Improbable	1	4	3	2	1	0

Table 3 – Criticality Ranking Matrix by Severity

2.4.3 FMECA worked example

An example of an FMECA for the BBERS compared to the ballasted track base case is shown in Annex D.

The failure mode severity and frequency were defined as in Tables 1 and 2 above. The highest criticality ranking for both the BBERS and the ballast track base case was 8 (Frequency Occurrence Remote and Consequence Severity Catastrophic) and in no failure mode was the BBERS Criticality higher than the base case. This analysis could be repeated a number of times by different experts to develop a distribution of outcomes.

2.5 Fuzzy Reasoning Approach (FRA)

In a complex system, in order to evaluate the whole system performance it may be necessary to evaluate the severity and occurrence frequency at a number of subsystem levels each of which contributes to the whole system performance. Data may be available for some failure modes to provide a value with known confidence, while for other failure modes it may be only possible to describe the severity and frequency of a failure mode. Quantified risk assessment processes rely on the supporting statistical data and do not handle uncertainty well. A fuzzy reasoning approach allows the use of language (linguistic variables) to describe the failure occurrence (FO) and consequence severity (CS) of an event as well as discreet values where these are known. The fuzzification process converts the linguistic variables into distributions i.e. where three values are given (the most likely and upper and lower limit values) the distribution will be a triangle, and if four values are specified (the range of probable values and upper and lower limits) the distribution will be a trapezoid. Other probability distributions are possible such as a Gaussian distribution.

IF-THEN rules are then established for the range of FO, CS and outcome risk levels (RL), for example

IF failure occurrence is *frequent* **AND** consequence severity is *critical*, **THEN** risk level of the failure mode is *high*

The distributions for failure occurrence, consequential severity and risk level are defined and where more than one failure mode satisfies the IF-THEN rule they are combined as shown in the figure below. The outcomes are represented as a risk score and also a risk category with a percentage indicating possibility.

In a bottom up assessment process the risk assessment is initially carried out at component level. The outcomes are then used in the subsystem evaluation and this process is repeated at the system level.

The Safety, Risk and Reliability Management Group at the University of Birmingham has developed the RISRAS (Railway Intelligent Safety Risk Assessment System) [9] software for railway safety risk analysis using the fuzzy reasoning approach.

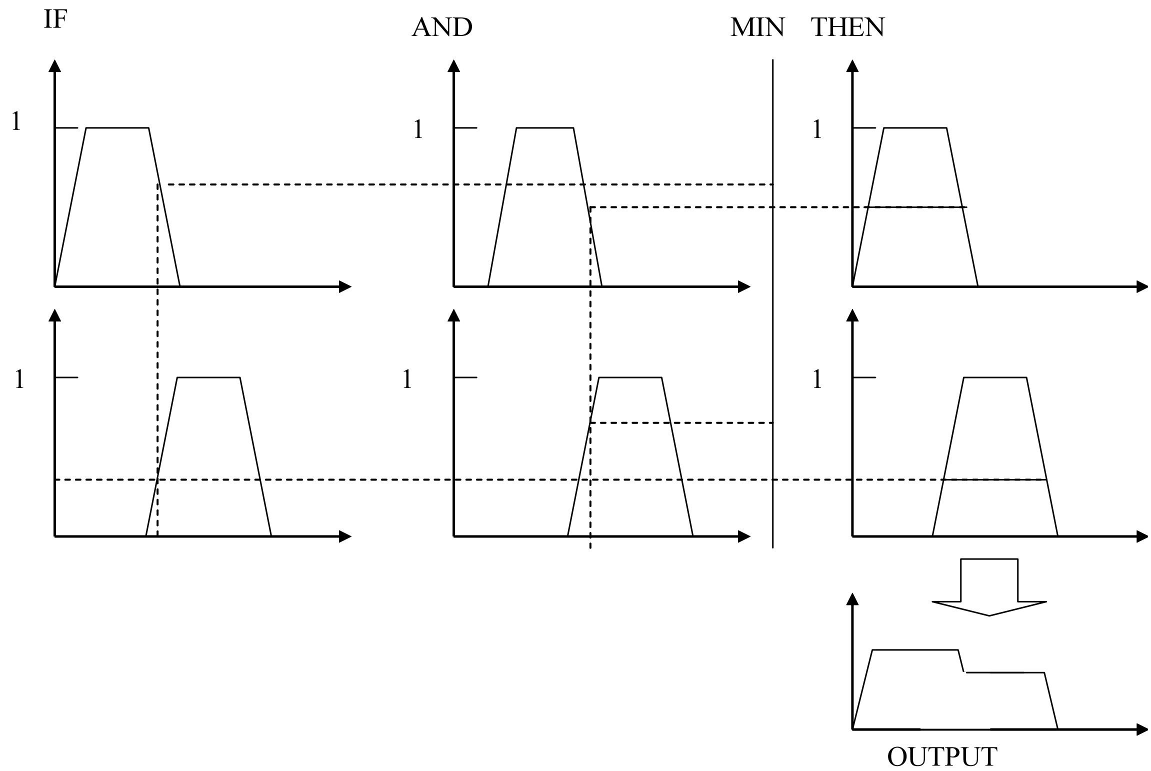

Figure 4 – Fuzzy reasoning process

2.6 Discussion of technical and LCC evaluation

The LCC calculation carried out by SP6 for the BBERS is described in D6.5.3 [10] Comparable LCC analysis for SP2 to SP5. The boundary conditions and the parameters taken into account and excluded from the LCC calculations for the BBERS and ballasted track reference case are as shown below.

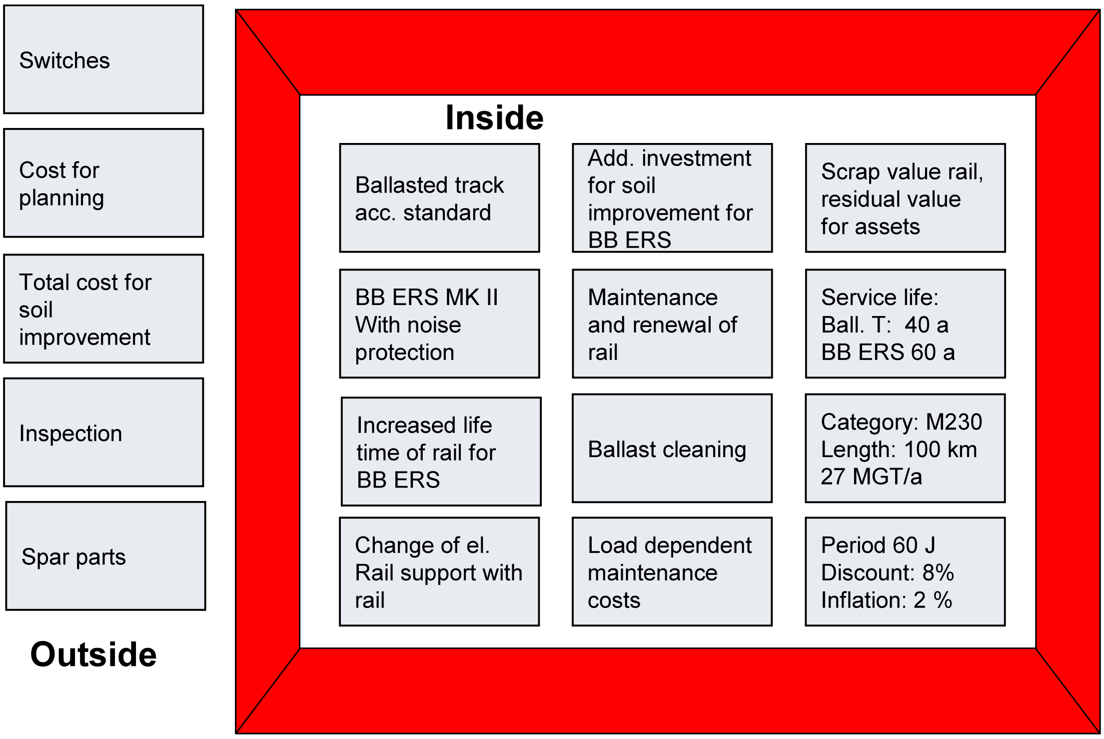

Figure 5 – In/Out Frame for BBERS taken from D6.5.3

The net present value for the BBERS compared to the ballasted track reference case is also reproduced from D6.5.3 below

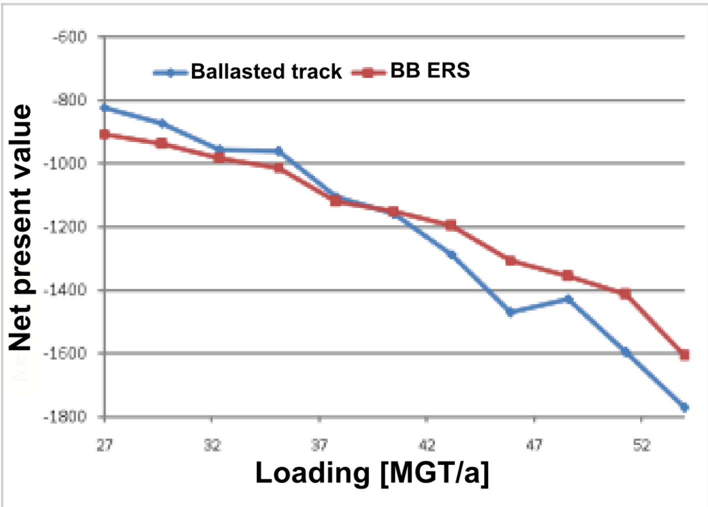

Figure 6 – Net present value versus MGT per annum

The calculation is based on a higher initial investment in subgrade improvement for the slab track and a 40 year life for the ballasted track against 60 years for the BBERS. The possible need for noise reduction has been included, but costs for switches and inspection are excluded. Discount and inflation rates have been set at 8% and 2% respectively.

The results indicate the same LCC at 38 MGT for the BBERS and reference system with the lower LCC for the slab track at higher tonnage and a break even point between 10 and 20 years. For further details see D6.5.3 Comparable LCC analysis for SP2 to SP5.

From figure 7 below it can be seen that the cost of ballasted track is always higher than the embedded rail cost if only cumulative costs are considered. The choice of discount rate determines the MGT at which the BBERS has the lower LCC.

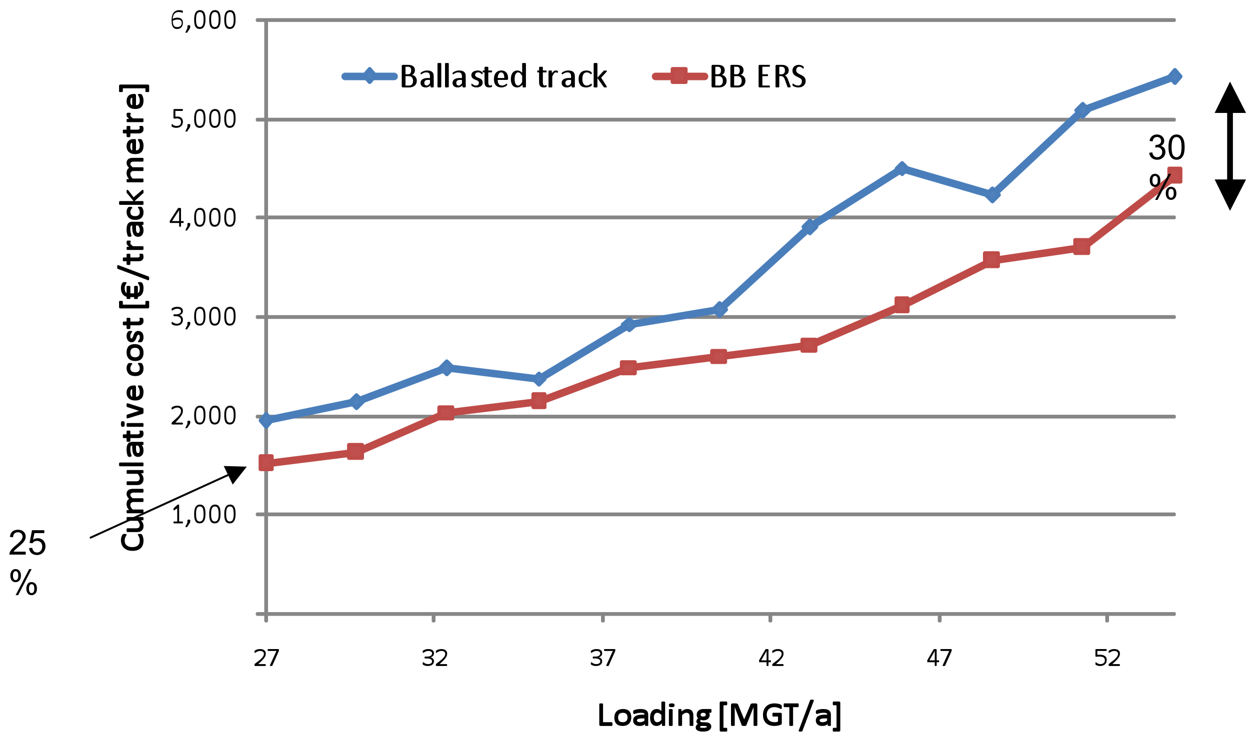

Figure 7 – Cumulative cost versus MGT per annum

The technical evaluation considered 51 issues relating to the performance of the BBERS. However if only the components that are truly innovative are considered as in the LCC calculation, only three modes of failure need to be considered. These are

- 01 Failure of the rail
- 02 Failure of the rail fastening – pad, shell and grout
- 06 Failure of the slab

With regard to the life or failure of these components, the evaluation accepted the following responses supported by the documentation referred to in 2.3.2 and detailed in Annex B; List of Supporting Technical Documents from Balfour Beatty

2.6.1 Failure of the rail

In response to questions regarding the basis for the claimed 35 year life for the embedded rail and the reduction in the second moment of area for the slab and rail system when the rail is worn to the maximum limit, this evaluation accepts the Balfour Beatty response that this life is based on:

- More allowable head wear
- Continuous lateral and vertical rail support leading to less corrugation, fatigue defects and thus less rail grinding
- 80% less vertical maximum deflection giving less fatigue with BBERS
- Less bending stress due to rail support detail
- Less residual manufacturing stress in rail (30%)

Based on 650 MGT life of CEN60 rail gives 64 years rail life or 1170 MGT.

The additional load distribution from the worn rail is accounted for in the slab design and is well within the design range.

2.6.2 Failure of the rail fastening

Testing suggests that the rail pad will last the life of the rail and exceed the life of normal pads. However, results of the water ingress tests and the planned six year examination of the NR installed trial section are not yet available.

2.6.3 Failure of the slab

The concrete slab is different in structural nature to other slab tracks. Steel fibre in the concrete leads to a distribution of cracks of 0.1mm with a maximum crack of 0.2mm rather than cracks of 0.5mm which allow for moisture ingress and corrosion of steel. The BBERS cracks will undertake analogous healing. With the BBERS system there is no problem for the rail bridging cracks in the slab. The concrete is designed in accordance with normal practice and EU codes require slabs to be 50 or 100 year life. This includes crack width limits. There are no critical locations for incidence of cracks in the BBERS. There is no evidence of adverse cracking at Crewe.

A major repair (200m) could be completed within 52 hours and a minor repair due to an isolated subgrade collapse would return to service in around 6 hours.

2.6.4 Result of Technical Evaluation

The technical evaluation concludes that the projected life for the rail, rail fixing and slab claimed by Balfour Beatty was supported by the design concept and supporting technical documentation with the exception that documentary evidence of the resistance to mechanical deterioration of the pad leading to water ingress is not yet available.

2.7 Whole system evaluation

The above technical and safety evaluation considers the design for the slab system and examines a number of issues relating to boundary conditions such as the transition to ballasted track and the treatment of bridges. Questions relating to the treatment of switches and crossings (S&C) as with any slab/ballast interface have also been briefly covered (2.3.3). The importance of these details should not be overlooked. The transition from the slip formed slab to the switch bearing slab has the possibility of introducing a discontinuity that requires carefully detailed design. The successful implementation of the Balfour Beatty Embedded Rail System as with any slab track system will depend greatly on the whole, site specific system design and not only on consideration of the slab, rail and rail support.

3. Conclusions

Evaluation of the BBERS is simplified if only the components unique to the slab track are considered. Excluding non core components such as electrical bonds and signalling equipment, failure of the system is limited to structural failure of the slab, rail failure and failure of the rail support (pad, shell and grout).

Rail failure is a feature of conventional ballasted track, and it is a reasonable assumption that the embedded rail would perform better than a flat bottom rail supported on sleepers.

The use of slip formed concrete is not new, and the life of the slab is mostly dependant on the quality of the subgrade. Key issues are the ground preparation before forming the slab, and process control during manufacture and installation of the rail support. The integrity of the design will also depend upon the detail design of transitions and the interface with switches and crossings. It is argued that the advantage of ballasted track lies in the ability of tamping to reinstate the track quality, but this claimed advantage is a major reason why infrastructure maintenance is considered costly and track availability is restricted. Clearly ground investigation and preparation before forming the slab are key ensuring a long fault free slab life, but this is true for any new track of whatever construction, whether conventional, a slab design, or a highway. If a slab failure does occur it will cause inconvenience but is not insolvable.

Tests of the embedded rail support system at component level indicate that the rail support should have a life similar to that of the rail provided that the installed quality is as good as the samples provided for test. Process control during manufacture and installation of the rail support is therefore a second key activity.

In conclusion the technical evaluation supports the findings of the LCC analysis for this design in that the BBERS will probably perform better than a conventional ballasted track and will have a lower LCC at higher annual tonnage.

4. Bibliography

1 INNOTRACK Deliverable 4.2.6 - **Recommendation of, and scientific basis for minimum action rules and maintenance limits**

2 INNOTRACK Deliverable 3.3.6 - **Quantification of benefit available from switch and crossing monitoring**

3 INNOTRACK Deliverable 1.3.6 - **The state of the art of the simulation of vehicle track interaction as a method for determining track degradation rates: Part 2 – High Resolution models and the level of validation generally**

4 INNOTRACK Deliverable 1.1.3 - **Final output datasets of vehicle characteristics for use in determining vehicle track forces**

5 INNOTRACK Deliverable 3.1.4 - **Summary of results from simulations and optimisation of switches**

6 INNOTRACK Deliverable 1.4.3 - **Process for the linking of modelling tools**

7 INNOTRACK Deliverable 1.4.5 - **Prototype linking of multiple tools to aid with an appropriate case study**

8 INNOTRACK Deliverable 2.3.3 - **Design and manufacture of embedded rail slab track components**

9 M An, W Lin, and A Stirling **Fuzzy-reasoning-based approach to qualitative railway risk assessment** DOI: 10.1243/09544097JRRT34

10 RISRAS

11 INNOTRACK Deliverable 6.5.3 - **Comparable LCC analysis for SP2 to SP5**

12 Milford, R. L. and Allwood, J. M. (2010) **Assessing the CO_2 impact of current and future rail track in the UK**, Transportation Research Part D: Transport and Environment, 15(2) 61-72,

Annex A Spreadsheet of BBEST Assessment

		Code	Area to be addressed	BB Response	Supporting evidence	Status
00 - System						
	01 - Procurement					
		00.01.A	What is difference in vertical stiffness between slab track and ballasted?	BBEST stiffness is between ballasted track on soft formation and ballasted track on a very stiff formation. The design aims for 1.0 to 2.0mm of deflection at the railhead, this can be adjusted by varying the stiffness of the pad. The slab track also allows much softer pads as there is not the issue of head roll that is experienced in ballasted track.	**Ref A**: Technical paper "The dynamic response of a slab track construction and its benefits with respect to conventional ballasted track" Authors Yann Bezin et al. and **Ref E** MMU report TS102/2000/5454-1 Performance tests on BBEST under service conditions	CLOSED
		00.01.B	Different transitions exist for BBEST, which is being proposed here?	Variations are generally according to speed/load. Detailed design is carried out in accordance with relevant deisgn codes and depends on the particular circumstances such as the rail stresses, expansion joints, etc. A machined rail transition has been used so far based on Vo1-60.	**Ref B**: Technical paper BBRPL/STS/5312 Issue 3 and **Dwg D**: Number TS102/2000/57061	CLOSED
		00.01.C	Will higher vertical stiffness lead to corrugations under high axle loads?	The stiffness is the same as other slab track and the pin-pin mode is eliminated by continuous support. This should reduce the propensity to corrugate. DB experience is that slab track corrugates in a similar way to ballasted track. Additional data may be available from ProRail.	We have no evidence to show that corrugation will occur. There is no evidence of corrugation at Crewe, Refer inspection reports.	CLOSED
		00.01.D	Is there a switch solution for BBEST?	BB have a switch solution in development but currently can use surface mounted switches	N/A	CLOSED
		00.01.E	How are electrical track circuits handled?	Track circuits are installed and functioning at the Crewe site where extensive insulation tests were undertaken. Protected boxouts are provided for cable bonding to the rail. BBEST meets the Network Rail track resistance standards for track circuits. Electrical resistance requirements for level crossings should also be applied.	**Ref C:** 5174-1 BBEST Crewe trial summary report. **Ref D:** TS102/200/5447 Issue 1 "DC track circuit test report"	CLOSED
		00.01.F	Higher vertical stiffness may give a higher risk of head checks (rolling contact fatigue)	Stiffness can be selected to suit the needs of the application and does not need to be higher than conventional track.	**Ref E** MMU report TS102/2000/5454-1 Performance tests on BBEST under service conditions	CLOSED
		00.01.G	How does the BBEST behave under low temperature conditions (ice, frozen ground support etc)?	The frost protective layer is designed as per standard. The BBEST slab is integrated with this similarly to any other track slab system.	**Ref F:** " Track Compendium - Formation Pway maintenance, economics " Author Dr Bernhardt Lichtberger EU rail Press 2005	CLOSED
		00.01.H	How to deal with changes (transitions) in sub-soil support stiffness such as on/off bridges etc ?	This is an issue for all track systems. Appropriate Civil engineering design will address this in accordance with the circumstances and the appropriate standards. Similar issue and solution to all other systems.	N/A	CLOSED
		00.01.I	How to deal with areas where differential expansion may be required, eg bridges?	Either traditional expansion joints are used each side of the bridge / structure or opportunity is taken of the ability of the BBEST rail to slip through the pad. The longitudinal grip on the rail can be set at a lower level by adjusting the pad side thickness to enable this 'fuse' to operate and protect the structure or the rail system in the event of excessive movement by the other.	N/A	CLOSED

		Code	Area to be addressed	BB Response	Supporting evidence	Status
00 - System						
		00.01.J	How to deal with rail mounted lubricators, if required and what is the effect of the presence of lubricant on the BBERS?	Rail mounted lubricators can be fitted if required. The polyurethane material of the shell is resistant to lubricants and is often used in applications exposed to such materials. Some pad degradation might be expected over service life but lengths of pad can be replaced if required.	N/A	CLOSED
	02 - Operation					
		00.02.A	Inspection frequency is based on traffic type and line speed.	Inspection interval is increased due to innovation and must not be constrained by regulation.	**Ref C:** 5174-1 BBEST Crewe trial summary report and **Ref I**: 7102 BBEST Crewe Kidsgrove Maintenance Manual	CLOSED
		00.02.B	Experience will be needed before the Regulations on inspection interval can be changed. There will be a cost associated with preparing the justification.	Note Network Rail experience	N/A	CLOSED
	03 - Maintenance					
		00.03.A	Potential for mechanical deterioration in connection between pad and rail over lifetime leading to water ingress and consequential deterioration. Does this require inspection and/or maintenance?	Testing is planned with worn pads in "flooded" condition to check for signs of pumping. No problems are expected. (CP notes that there have been problems with different designs where the pad is not under pre-compression)	TU Munich tested the Mk1 pads under water, no formal report at this stage. Results on Mark 2 worn pads from Munich water tests due early 2010. 6-year inspection planned for Crewe by Network Rail. This will back-up effects of long-term tests.	CLOSED
		00.03.B	Question lifetime of track of 60-100years	Chosen value for this application is 80years lifetime of slab. The concrete slab is designed in accordance with normal practice. EU codes require slabs to be 50 or 100 year life.	Crewe was designed for 60 years. **Ref H:** TS102/2000/5902.- "Form A Embedded Slab Track Design"	CLOSED
		00.03.C	What are the main maintenance and renewal tasks with BBEST	Network Rail used their normal inspection regime. There are very few additional requirements and many standard ones that are not required. Maintenance is essentially only the rail and pad with processes for repair of rail defects. As confidence increases inspection intervals can be stretched out.	**Ref I:** 7102 BBEST Crewe Kidsgrove Maintenance Manual	CLOSED
		00.03.D	Elecrical degradation of the connection between pad and rail over lifetime also needs to be considered	Agreed	No evidence to suggest that this is a problem but will be reviewed and taken into account in design of future installations	CLOSED
		00.03.E	What time is required for renewal of the complete system (eg over 200m length)?	Depends on conditions like site access etc. N.B. the formation will already be in.	On basis of Crewe, removal and reinstallation should be possible in 52 hours of possession.	CLOSED
	04 - Non-Availability					
		00.04.A	What are the key failure modes and effects?	See FMECA analysis, Annex C		

		Code	Area to be addressed	BB Response	Supporting evidence	Status
00 - System						
01 - Rail						
	01 - Procurement					
		01.01.A	Requirements for stress free temperature range less restrictive than for ballasted track	BB have done many rail stress calculations and tests and have shown that the stress condition in the rail is more favourable than a flat bottomed rail. The stressing should be set at a recorded temperature, potentially to match adjacent track sections. Calculations and tests have shown a large safety factor against vertical buckling.	**Ref J:** BBRPL/STS/5378 - Technical note "Rail stress calculations" and **Ref G** 5913 Mott MacDonald design report GIF Dual Gauge Configuration.- Appendix E1	CLOSED
		01.01.B	Rail stressing at transitions?	Ballasted track transitions need to be stressed. The way that the slab grips the rail allows for stressing the slab at transitions. The potential exists for the expansion joint, if fitted, to be used to isolate the rail transition as well as the stressing..	**Ref B:** BBRPL/STS/5312 Issue 2 Technical note 12 - Transition to ballasted track. **Ref I**: 7102 BBEST Crewe Kidsgrove Maintenance Manual (Sec 4.0 and 7.0)	CLOSED
		01.01.C	Tolerances when levelling and aligning?	Grout is used to take up the difference in construction tolerances so the civil engineering can be produced with 10mm tolerances and the grout is used to reduce that to 1mm tolerances at the rail head.	**Ref K**: Doc 6831 LIAN support Doc	CLOSED
		01.01.D	Quality of welds	A full set of tests on aluminothermic welds were completed to Network Rail agreed spec by Nottingham Trent University. 19 samples were ultrasonically tested and found satisfactory. Bend tests also met all requirements. Information on flash butt welds?	**Ref C:** 5174-1 BBEST CreweTrial Summary Report	CLOSED
	03 - Maintenance					
		01.03.A	Lifetime of rail (35years cf 20 years) from larger allowance for wear / grinding and what effect the reduction in rail section over the life has on loads etc into the slab	Based on: More allowable head wear; continuous lateral and vertical rail support leads to less corrugation, fatigue defects and thus less rail grinding; 80% less vertical maximum deflection gives less fatigue with BBERS; less bending stress due to rail support detail; less residual manufacturing stress in rail (30%) Based on 650 mgt life of CEN60 rail gives 64 years rail life or 1170 mgt. The additional load distribution from the worn rail is accounted for in the slab design and well within the design range.	**Ref J**: BBRPL/STS/5378 - Technical note "Rail stress calculations", **Dia A:** "BBERS Head Wear"	CLOSED
		01.03.B	Problems with rail inclination on curves?	Design of the BBEST provides good support and makes roll of the rail very difficult. In addition each rail can be individually inclined to suit the science	**Ref R1:** BE-2524 and **Ref E** MMU report TS102/2000/5454-1 Performance tests on BBEST under service conditions	CLOSED
		01.03.C	How to replace damaged section of rail?	Slit the rail , if not already split, by drill and wedge. Rail can be replaced by jacking out rail, cutting out and re-welding new section back in. To provide a straight alignment for welding will need approx 6m of rail. Only 8 tonne manual hydraulic jack is required,.	**Ref I:** 7102 BBEST Crewe Kidsgrove Maintenance Manual	CLOSED

		Code	Area to be addressed	BB Response	Supporting evidence	Status
00 - System						
		01.03.D	Need to justify increased inspection interval	Better inspection- ultrasonics can inspect whole rail section, rather than just rail head. Rail is continually supported and continuously clamped. In the event of a rail break the consequences are much less. There are no fittings to come loose. The increased inspection will be determined by the " Duty of care holder' He will make this decision with experience of the track at any location.	**Ref L:** 5355-1 Ultrasonic Inspection of the BB 14072 Rail. **Ref I**: 7102 BBEST Crewe Kidsgrove Maintenance Manual	CLOSED
		01.03.E	Rail maintenance requirements?	Rail head maintenance is similar to ballasted track and squats etc can be treated with the usual methods. Rail grinding can be carried out using existing grinding machines. If a derailment guard is fitted then an alternative grinding machine would be used. The S&C grinding machines can work with the derailment guard.	**Ref I:** 7102 BBEST Crewe Kidsgrove Maintenance Manual	CLOSED
		01.03.F	Have corrosion tests been carried out?	Tests have shown that embedded rail performs better than flat bottomed rail. The space around the rail is filled with a pad under precompresion so prevents water and oxygen getting in.	**Ref O** BBRP/STS-02/TE 52 Corrosion testing, **Photos A**: " Summary of corrosion photos 170103" and **Ref C**: 5174-1 BBEST Crewe trial summary report	CLOSED
		01.03.G	What inspection frequencies are required	Ultrasonic Rail Inspection 1 year or 220 mgt; Camera 1 year or 220mgt; Rail profile recording 1 year or 220mgt; gauge measurement 1 year or 220. These are the responsibility of and fixed by the duty holder	**Ref I**: 7102 BBEST Crewe Kidsgrove Maintenance Manual	CLOSED
		01.03.H	What are the processes for rail stressing if a section of rail needs to be replaced?	Some compressive stress can be tolerated as the rail is constrained in the pad and risk of buckling is much reduced. Process is given in Maintenance manual	**Ref I:** 7102 BBEST Crewe Kidsgrove Maintenance Manual Appendix I	CLOSED
		01.03.I	How is the change in rail section managed if a new rail section is installed next to a worn one with reduced height?	A transition length of rail (prepared off site) can be used to provide a suitable length of transition between the worn and unworn sections. This is likely to be longer than for conventional rail as the change in section may be greater. If the length is short then a rail with a worn profile can be used	Use normal Rail change practice	CLOSED
		01.03.J	How are insulated joints (for track circuits) included?	Designs exist for insulated joints but these have not yet been installed in track. An alternative is to use standard IBJ with a gap in the rail support.	Refer BBERS development photo file	CLOSED
	04 - Non-Availability					
		01.04.A	What are the key failure modes and effects?	See FMECA analysis, Annex C		

		Code	Area to be addressed	BB Response	Supporting evidence	Status
00 - System						
02 - Rail fastening						
	03 - Maintenance					
		02.03.A	Deterioration of rail pad, particular concern over use of softer rail pad.	BB quoted TUM view that system could handle a softer rail pad. Yes a softer rail pad can be used to suit the required value. Pads of various stiffnesses have been tested to date and a wide range of pad stiffnesses upwards from 10kN/mm/650mm manfactured to determine the quality limits.	N/A	CLOSED
		02.03.B	What is lifetime of pad and how is this affected by stress/strain and temperature variation? Need to consider extreme temperatues (high and low) and annual variations.	Testing suggests that the rail pad will last the life of the rail and exceed the life of normal pads.	**Ref M:** Technical Note Titled " Dynathane Performance and Durability" **Ref R1:** Munich tests results showing track quality retention with accellerated load tests.	CLOSED
		02.03.C	Strength of grout to withstand lateral loads?	This is part of the design, many proprietary grouts are available from fast setting to normal and cement / polymer etc	**Ref N:** Technical Note Titled "5212 Grout Specification"	CLOSED
		02.03.D	A single direction line may suffer from the elastomer being stretched and flowing in direction of traffic.	This does not happen, the elastomer is not between the wheel and rail and the friction between pad and shell is very high due to being continuous. Rail pads in conventional track can creep out but BBEST is a much more secure situation. No problems have been identified at trial sites.	**Ref C:** 5174-1 Crewe trial summary report	CLOSED
		02.03.E	Current rail pads wear, how does this problem translate to BBEST?	The relative surface pressure on the U-shaped pad is significantly lower than on a conventional pad (particularly the dimpled type). Therefore wear is expected to be significantly lower.Similar materials have been used for standard rail pads. Material tests carried out in accordance with NR standards have passed the abrasion resistance requirements.	**Ref Q:** "5405 Abrasion test on Dynathane materials" See also **Ref M:** Technical Note Titled " Introduction to Polyurethane" **Ref R1 & R2:** Munich tests results showing track quality retention with accelerated load tests.	CLOSED
		02.03.F	What tests and evidence of lifetime are there?	The Mk1 has been in service at Crewe (UK) for more than 5 years and for more than 6 years at Medina (Spain) with several million tonnes of traffic. No maintenance has been required on the rail or pad system. Lab tests have shown that the properties are retained after fatigue load tests carried out at TUM, NTU and Loughborough University.	**Ref C:** 5174-1 BBEST Crewe trial summary report. Site inspection sheets available. Typical sheets provided. No change during the last 6 years	CLOSED
		02.03.G	What inspection is required for the pad?	A performance check (stiffness, damping etc) is all that is proposed unless a problem is found. If required the pad can be inspected by removing both rail and pad and completing a sample check (every 5 years?).	**Ref I:** 7102 BBEST Crewe Kidsgrove Maintenance Manual	CLOSED
		02.03.H	What is the effect on the pad of in-situ repair of rail when very high temperatures may be reached?	In-situ repair methods involve lifting the rail clear of the pad so that the pad is not heat affected.	**Ref I:** 7102 BBEST Crewe Kidsgrove Maintenance Manual - rail removal and replacement	CLOSED

		Code	Area to be addressed	BB Response	Supporting evidence	Status
00 - System						
	04 - Non-Availability					
		02.04.A	What are the key failure modes and effects?	See FMECA analysis, Annex C		
05 - Substructure						
	01 - Procurement					
		05.01.A	Need (or not) for pre-treatment of soft soils / substrata. BB claim to be able to use same or less preparation as ballasted track. BR concerned that additional preparation is required	A specific subgrade is normal in beam slab design. The ground is less stressed under a beam slab but ground preparation is of course still required to ensure adequate compaction and stiffness levels are known. Various reports available. In **Ref G**, 5913, the value of 80MPa is comparable with requirements for modern ballast construction. The design value at Crewe was lower .	**Ref G** 5913 Mott MacDonald design report GIF Dual Gauge Configuration and Innotrack SP1 Simulation support for Balfour Beatty SP2.3 activities. Vehicle track interaction modelling for ballasted track and BBEST slab track.	CLOSED
		05.01.B	Reduced weight of construction compared to ballast gives benefit for substructure?	The low profile slab track weighs less than the ballasted track with an equivalent performance. The supporting structure will not need to be as robust.	N/A	CLOSED
	04 - Non-Availability					
		05.04.A	What are the key failure modes and effects?	See FMECA analysis, Annex C		
06 - Slab						
	01 - Procurement					
		06.01.A	Quality of slip formed concrete slab compared with prefabricated concrete	Generally pre-cast concrete is high quality. Hand placed in-situ concrete in which it is embedded is often not as high. Slipform concrete is by its nature and being machine controlled, required to be far more consistent, not least in order to achieve a slipformable mix with an acceptable finish.	N/A	CLOSED

		Code	Area to be addressed	BB Response	Supporting evidence	Status
00 - System						
	03 - Maintenance					
		06.03.A	Cracking of concrete slab over life, maintenance / repair procedures, ability of reduced rail section to give adequate support. Does this lead to problems with track geometry?	The concrete slab is different in structural nature to other slab tracks. Steel fibre in the concrete leads to a distribution of cracks of 0.1mm with a maximum crack of 0.2mm rather than cracks of 0.5mm which allow for moisture ingress and corrosion of steel. The BBEST cracks will undertake analogous healing. With the BBEST system there is no problem for the rail bridging cracks in the slab. The concrete is designed in accordance with normal practice and EU codes require slabs to be 50 or 100 year life. This includes crack width limits. There are no critical locations for incidence of cracks in the BBERS . There is no evidence of adverse cracking at Crewe.	**Ref I:** 7102 BBEST Crewe Kidsgrove Maintenance Manual	CLOSED
		06.03.B	What are the effects of soil settlement?	The BBERS is designed to accomodate soft support over limited lengths (approx 2metres) Significant soil settlement would have to be addressed as with ballasted or other track.	**Ref A:** draft Technical paper "The dynamic response of a slab track construction and its benefits with respect to conventional ballasted track" by Yann Bezin et al. In the rare event of settlement taking place the appropriate remedial measures are contained in **Ref S:** BBRP/STS/TE/5313- Settlement adjustment in slab track	CLOSED
		06.03.C	What maintenance is required at transitions to/from ballasted track?	See Crewe experience.	**Ref I:** 7102 BBEST Crewe Kidsgrove Maintenance Manual	CLOSED
		06.03.D	What is the effect on settlement etc of the reduced section of the worn rail?	The additional load distribution from the worn rail is well within, and accounted for in, the slab design. Hence there is no effect on settlement	**Ref G** 5913 Mott MacDonald design report GIF Dual Gauge Configuration	CLOSED
	04 - Non-Availability					
		06.04.A	What are the key failure modes and effects?	See FMECA analysis, Annex C		

		Code	Area to be addressed	BB Response	Supporting evidence	Status
00 - System						
08 - Drainage						
	01 - Procurement					
		08.01.A	Won't extra drainage be required in curves, for example between the two tracks?	BBEST has been designed so that the profile accounts for curves and the same drainage system is used in straight lines as well as curves.	**Ref P:** "46 Drainage Aug 02"	CLOSED
	02 - Operation					
	03 - Maintenance					
		08.03.A	What maintenance is required on the drainage system?	Normal rodding when the manholes show signs of being full. Use of floating tell tale.	**Ref I:** 7102 BBEST Crewe Kidsgrove Maintenance Manual	CLOSED
	04 - Non-Availability					
		08.04.A	What are the key failure modes and effects?	See FMECA analysis, Annex C		
09 - Environment - Sound Insulation						
	01 - Procurement					
		09.01.A	What is the impact of noise and what sound insulation will be required?	Noise measurements of the section of Spanish track in the desert recorded noise levels at 2dB below that of ballasted track. However further testing should be carried out to determine the noise effects. It is expected that noise levels may be greater than for ballasted track, but should be significantly less than surface mounted slab track due to reduced rail surface area. Assume same values as ballasted track reference system. Surface mounted sound panels are fittable to the slab.	N/A	CLOSED at this stage
		09.01.B	What is the effect on ground bourne vibration?	No different to standard slab track in essence, improvement over ballasted track due to geometry and load ditribution effects in the near-field	N/A	CLOSED
		09.01.C	What is the effect on carbon footprint compared to ballasted track?	Study done - currently not yet issued	To be published by the University of Cambridge	CLOSED

Annex B List of Supporting Technical Documents from Balfour Beatty

Ref / Dwg ID	Title	Issues addressed
Ref A	The dynamic response of a slab track construction and its benefits with respect to conventional ballasted track Y.Bezin et al	00.01.A 06.03.B
Ref B	BBRPL/STS/TE/5312 Issue3. BBERST Technical Note 12 Transition to Ballasted Track	00.01.B 01.01.B
Ref C	TS102/2000/5174 (BBRP/STS/PAC/5174) Crewe Kidsgrove Trial Installation Final summary report of testing and inspection	00.01.E 00.02.A 01.01.D 01.03.F 02.03.D 02.03.F
Ref D	TS102/2000/5474 BBEST Crewe-Kidsgrove DC track circuit test report (February 2004)	00.01.E
Ref E	TS102/2000/5454-1 Performance Tests on Balfour Beatty Embedded Slab Track Under Service Conditions	00.01.A 00.01.F 01.03.B
Ref F	Extract of Track Compendium – Formation Pway maintenance, Economics. Author Dr Bernhardt Lichtberger EU Rail Press 2005	00.01.G
Ref G	BBRPL/STS/TEST/5913 Embedded Rail System Design Report GIF Dual Gauge Configuration & Appendix E	01.01.A 05.01.A 06.03.D
Ref H	TS102/2000/5902 Issue 3 Crewe-Kidsgrove BBEST. Form A: Embedded Slab Track Design	00.03.B
Ref I	TS102/5000/7102 Issue 6 Dec 2005. BBEST Crewe-Kidsgrove Maintenance Manual & examples of inspection sheets	00.02.A 00.03.C 01.01.B 01.03.C 01.03.D 01.03.E 01.03.G 01.03.H 02.03.G 02.03.H 06.03.A 06.03.C 08.03.A
Ref J	BBRP/STS/TE/5378 Issue 4. Rail Stress Calculations	01.01.A 01.03.A
Ref K	TS102/3000/6831 Issue 1 BBEST Work Instruction LIAN supports Crewe-Kidsgrove project	01.01.C
Ref L	BBRP/STS/TE/5355 Issue 1 Ultrasonic inspection of the BB14072 Rail	01.03.D

Ref M	Introduction to Polyurethane	02.03.B 02.03.E
Ref N	BBRPL/STS/MATS/5212 Issue A May2003. Specification Grout	02.03.C
Ref O	BBRP/STS-02/TE 52 Balfour Beatty Embedded Slab Track Technical Note 52 Corrosion Testing	01.03.F
Ref P	Drainage – the benefits of the BBEST System	08.01.A
Ref Q	BBRPL/STS/TEST/5405 Apr2003 Test report: abrasion test on Dynathane materials	02.03.E
Ref R1	TU Munchen Res Rep 2524 Repeat loading tests on the BBERS according to BBERS Testing Method Statement	01.03.B 02.03.B 02.03.E
Ref R2	Munich independent test results – rail head horizontal displacement	02.03.E
Ref S	BBRP/STS/TE/5313 Settlement Adjustment in Slab Track	06.03.B
Dia A	Wheel-rail position diagrams with up to 24mm head wear	01.03.A
Photos A	Corrosion testing photos	01.03.F
Dwg A	TS102/2000/57012 Crewe-Kidsgrove BBERST Slab Sections & details (sheet 1) (Drawing 57012-C00-A1	
Dwg B	TS102/2000/57013 Crewe-Kidsgrove BBERST Slab Sections & details (sheet 2) (Drawing 57013-C00-A1	
Dwg C	TS102/2000/57014 Crewe-Kidsgrove BBERST Transition slab section & details (Drawing 57014-C00-A1)	
Dwg D	TS102/2000/57061 Crewe-Kidsgrove Electrification Detail of STS 6m long transition rail BB140723 to CEN60E1 rail (Drawing 57061-00	00.01.B

Annex C Failure Mode and Effect Analysis

Functions **Provide a safe, even, continuous surface for trains to run on**	**Functional Failures**	**Failure mode**	**Code**	**Effect**
Withstand train forces	Fails to support trains vertically	Rail break	01.03.A	Derailment Poor ride quality
		Rail defect	01.03.A	Derailment Poor ride quality
		Slab break	00.03.B	Derailment Poor ride quality
		Pad deterioration	02.03.B	Poor ride quality
		Grout deterioration	02.03.C	Poor ride quality
		Shell deterioration		Poor ride quality
		Failure of support structure	06.03.B	Derailment Poor ride quality
	Fails to support trains laterally	Rail break	01.03.A	Derailment Poor ride quality
		Rail defect	01.03.A	Derailment Poor ride quality
		Slab break	00.03.B	Derailment Poor ride quality
		Pad deterioration	02.03.B	Poor ride quality
		Grout deterioration	02.03.C	Poor ride quality
		Shell deterioration		Poor ride quality
		Failure of support structure	06.03.B	Derailment Poor ride quality
	Fails to withstand traction and braking forces (including track brakes)	Interface failure between components	02.03.D	Failure to hold rail (Increased rail gap)

| Functions | Functional Failures | Failure mode | Code | Effect |

Functions	Functional Failures	Failure mode	Code	Effect
Maintain correct train position	Fails to maintain correct alignment (horizontal)	Failure of support structure	06.03.B	Derailment Poor ride quality
	Fails to maintain correct profile (vertical)	Failure of support structure	06.03.B	Derailment Poor ride quality
		Rail break	01.03.A	Derailment Poor ride quality
		Rail defect	01.03.A	Derailment Poor ride quality
		Slab break	00.03.B	Derailment Poor ride quality
		Pad deterioration	02.03.B	Poor ride quality
		Grout deterioration	02.03.C	Poor ride quality
		Shell deterioration		Poor ride quality
	Fails to maintain correct track gauge	Slab break	00.03.B	Derailment Poor ride quality
		Pad deterioration	02.03.B	Poor ride quality
		Grout deterioration	02.03.C	Derailment Poor ride quality
		Shell deterioration		Poor ride quality
	Fails to resist flange lateral movement	Slab break	00.03.B	Derailment Poor ride quality
	Fails to manage safe train movement in derailment	Slab break	00.03.B	Severity of derailment increased
Provide effective wheel-rail interface	Fails to maintain running surfaces in operable position due to wear	As ballasted track	01.03.E	
	Fails to maintain adequate clearance for flange			
	Fails to maintain running surfaces in acceptable condition	Pad stiffens with time	02.03.B	Poor ride quality

Provide effective track braking interface	Fails to withstand track brake application	Insufficient adhesion	02.03.D	Increased stopping distance
		Overheating of rail	01.01.A	Rail buckling
Withstand dynamic forces	Fails to maintain running surface integrity	As ballasted track	01.03.E	
	Fails to withstand normal impact of rolling stock	Pad deterioration	02.03.B	Poor ride quality
		Grout deterioration	02.03.C	Poor ride quality
		Shell deterioration		Poor ride quality
	Fails to withstand excessive impact of rolling stock	Pad deterioration	02.03.B	Poor ride quality
		Grout deterioration	02.03.C	Poor ride quality
		Shell deterioration		Poor ride quality
	Fails to withstand traction and braking forces	Interface failure between components	02.03.D	Failure to hold rail (Increased rail gap)
	Fails to withstand on and off-track plant	Unanticipated forces	06.03.A	Damage to track
Withstand external influences				
Withstand temperature fluctuations	Fails to resist buckling forces	Slab shear failure	06.03.A	Rail buckling
		Excessive temperature change	01.01.A	Rail buckling
	Fails to resist rail contraction	Interface failure between components	02.03.D	Rail break (increased risk at weld)
		Excessive temperature change	01.01.A	Rail break (increased risk at weld)
	Fails to maintain correct alignment (horizontal)	Slab shear failure	06.03.A	Rail buckling
	Fails to maintain correct profile (vertical)	Pad deterioration	02.03.B	Rail buckling
	Fails to resist freeze-thaw action	Water ingress	01.03.F	Rail corrosion
			00.03.A	Rail lift
Functions	**Functional Failures**	**Failure mode**	**Code**	**Effect**
Manage incoming substances	Fails to adequately collect or shed incoming liquids	Blockage of cross fall and gullies	08.03.A	Flooding
		Cracked slab	00.03.B 06.03.A	Wash out
	Fails to resist damaging effects of aggressive agents (acids, oil...)	Blockage of cross fall and gullies	08.03.A	Component deterioration
	Fails to manage solid deposits			Pad wear and potential water

Functions	Functional Failures	Failure mode	Code	Effect
Accommodate electrification systems				
Accommodate traction feed	Fails to ensure insulation for feed system	Degraded insulator (external system)		Loss of power supply
	Fails to ensure stable base for feed system	Degraded fixing		Loss of 3rd rail alignment
Accommodate traction return				
Provide adequate electrical insulation between rail and ground	Fails to ensure adequate insulation between rail and ground	Pad and shell deterioration	02.03.E 02.03.B 00.03.D	Corrosion to external systems
Allow return bond connections	Fails to ensure stable attachment point for bonds	Bond fixing becomes high resistance		Touch potentials Traction failure
Allow effective transition with other track systems and structures	Fails to ensure appropriate stiffness transition	Pad deterioration Grout deterioration	02.03.B 02.03.C	Rail fatigue Rail fatigue
	Fails to ensure appropriate rail profile transition			
	Fails to ensure appropriate slab profile transition	Attrition of ballast at transition	00.01.H	Rail fatigue Pad degradation Grout degradation

Functions	Functional Failures	Failure mode	Code	Effect
	Fails to manage transition tensions	Insufficient anchorage of ballasted track	01.01.B	Failure to hold rail (Increased rail gap)
	Fails to ensure longitudinal relaxation (required compatibility with structures)	Excessive interface friction	00.01.I	Damage to structures (e.g. bridge bearings)
Have acceptable environmental impact	Fails to manage noise	Degradation of pad	09.01A 02.03.B	Excessive noise (3rd party discomfort)
	Fails to manage vibration	Degradation of pad	09.01.B 02.03.B	Excessive vibration (3rd party discomfort)
	Fails to manage substance flows with env. impact	Blockage of cross fall and gullies Cracked slab	08.03.A 00.03.B	Contamination of surround areas Contamination of surround areas
Provide safe surface for walking humans	Fails to ensure safe walking surface (maintenance)	Blockage of cross fall and gullies Build up of snow and ice	08.03.A	Slip risk Slip risk
	Fails to ensure safe walking surface (pax evac)	Blockage of cross fall and gullies Build up of snow and ice	08.03.A	Slip risk Slip risk
Accommodate emergency recovery equipment	Fails to accommodate emergency loading		06.03.A	

Annex D Failure Mode and Effect Analysis with numerical values

Base case 100km in a 1000km slab track environment
Mixed traffic
Life of track - 60yrs

Note: Does not include delay costs - 3rd party impact

Failure mode	Failure effect	Freq	Severity	Risk factor	Mitigation and Comments compared to ballasted track	Code
Rail break	Derailment	1 BBERS 2 Ballast	4 BBERS 4 Ballast	**4 BBERS** **8 Ballast**	BBERS is less likely to break than the reference track, due ability to ultrasonically inspect full section, limited deflections, removal of some of the initiators leading to rail breaks such tamping damage to rail foot, corrosion around fastenings, uncontrolled deflection and rail gall In the case of a rail break the severity is significantly lower due to the continual clamping of the rail and elimination of cantilever of the rail, severely reducing the probability of a derailment	01.03A
Rail defect	Derailment Passenger comfort	1 BBERS 1 Ballast	4 BBERS 4 Ballast	**4 BBERS** **4 Ballast**	In addition to the above the likelihood of a rail defect is reduced in BBERS by the elimination of defect initiators such as the effect of ballast crushed on rail head and also eliminate misalignment of track due buckling and also maintaining it's design geometry throughout it's life	01.03A
Slab break	Derailment Passenger comfort	1 BBERS	4 BBERS	**4 BBERS**	The slab is designed to modern design codes with sufficient margins of safety and redundancy for the sub-base. Slab failure modes are predictable and have been modelled, compared with the empirical understanding of ballasted track	00.03B
Ballast - sleeper break		1 Ballast	4 Ballast	**4 Ballast**		

Failure mode	Failure effect	Freq	Severity	Risk factor	Mitigation and Comments compared to ballasted track	Code
Pad deterioration	Passenger comfort	2 BBERS	1 BBERS	**2 BBERS**	The pad cannot fail catastrophically it is made of high quality material well proven in onerous environments and thoroughly tested in accordance with the standards.	02.03B
Ballast - rail pad		3 Ballast	1 Ballast	**3 Ballast**		
Grout deterioration	Derailment Passenger comfort	1 BBERS	3 BBERS	**3 BBERS**	The grout is designed to modern standards according to it's intended application and environment. Can be identified and rectified before failure.	02.03C
Shell deterioration	Derailment Passenger comfort	1 BBERS	3 BBERS	**3 BBERS**	Shell is inert	
Ballast - fastner failure		2 Ballast	4 Ballast	**8 Ballast**		
Failure of sub-grade	Derailment Passenger comfort	1 BBERS 2 Ballast	4 BBERS 4 Ballast	**4 BBERS** **8 Ballast**	System better distributes peak loading from the train and is less susceptible to soft spots. Water is managed away from the sub-base.	06.03B
Pad stiffens with time (see pad deterioration)	Passenger comfort	2 BBERS	1 BBERS	**2 BBERS**	See Pad deterioration above - tests indicate pad life similar to rail life	02.03B
Slab shear failure (see slab break)	Derailment Passenger comfort	1 BBERS	4 BBERS	**4 BBERS**	See slab break	06.03A
Excessive temperature change	Derailment Passenger comfort	1 BBERS 2 Ballast	4 BBERS 4 Ballast	**4 BBERS** **8 Ballast**	Continual clamping of rail exceeds current European standards, external independent consultants calculate a very high factor of safety against buckling	01.01A
Water ingress	Rail corrosion/ rail lift	3 BBERS 3 Ballast	0 BBERS 0 Ballast (if corrosion causes failure of rail - see rail failure)	**0 BBERS** **0 Ballast**	Frost protection layer would be provided as necessary and as other track systems. Expect to better than ballast due to improved water management and ultrasonic inspection of whole rail foot	01.03F 00.03A

Failure mode	Failure effect	Freq	Severity	Risk factor	Mitigation and Comments compared to ballasted track	Code
Blockage of cross fall and gullies/drainage path		2 BBERS 4 Ballast	0 BBERS 0 Ballast (if poor drainage leads to sub-structure failure see sub-structure failure)	**0 BBERS** **0 Ballast**	Cross falls are still designed to drain at worse cant scenarios. Track longitudinal drainage accommodates some blocked drainage. Easier to clean than ballast reference system.	08.03A
Attrition of ballast at transition (see above)					Systems are available in the market place to minimise ballast attrition	00.01H
Insufficient anchorage of track at transition (see rail break)	Derailment Passenger comfort	2 BBERS 2 Ballast	4 BBERS 4 Ballast	**8 BBERS** **8 Ballast**	Anchorage capability no less than ballasted track	01.01B
Pad deterioration at slab end (see pad deterioration)	Passenger comfort				See 6 and 10 above - Transition zone is designed to be within specification of pad - forces within transitions are managed	
Grout deterioration at slab end (see grout deterioration)	Derailment Passenger comfort				See 7 above - Transition zone is designed to be within specification of grout - forces within transitions are managed	
Fails to withstand traction and braking forces - interface between components	Failure to hold rail (failure of fastenings - see grout/shell/clip failure)				BBERS maintains grip as per standard	02.03D

Failure mode	Failure effect	Freq	Severity	Risk factor	Mitigation and Comments compared to ballasted track	Code

Fails to withstand on and off-track plant - unanticipated forces	Damage to track	2 BBERS 3 Ballast	0 BBERS 1 Ballast	**0 BBERS** **3 Ballast**	BBERS continuously supports rail and as rail is embedded expect the impact of unanticipated forces on the rail to be less compared to ballasted track	06.03A
Fails to ensure insulation for track circuit - presence of conductive debris at interfaces	Right side track circuit failure	4 BBERS 4 Ballast	0 BBERS 0 Ballast	**0 BBERS** **0 Ballast**	Expect a similar level of risk between BBERS and ballasted track	00.01E 08.03A 00.01E
Fails to ensure stable base for installed equipment - degraded fixing	Loose equipment (derailment risk)	2 BBERS 2 Ballast	4 BBERS 4 Ballast	**8 BBERS** **8 Ballast**	Expect a similar level of risk between BBERS and ballasted track, although the concrete slab should provide a better base for installed equipment	
Fails to ensure insulation for traction feed - degraded insulator (external system)	Loss of power supply	2 BBERS 2 Ballast	0 BBERS 0 Ballast	**0 BBERS** **0 Ballast**	Expect a similar level of risk between BBERS and ballasted track	02.03E 02.03B 00.03D
Fails to ensure stable attachment point for bonds - Bond fixing becomes high resistance	Touch potentials Traction failure	2 BBERS 2 Ballast	3 BBERS 3 Ballast	**6 BBERS** **6 Ballast**	Bond connection protected in a pocket in the case of BBERS	

Failure mode	**Failure effect**	**Freq**	**Severity**	**Risk factor**	**Mitigation and Comments compared to ballasted track**	**Code**
Fails to ensure longitudinal relaxation (required compatibility with structures) - excessive interface friction	Damage to structures (eg bridge bearings)	Both the same as designed to same standard			BBERS maintains grip as per standard and slides on overload	00.01.I
Fails to ensure safe walking surface - blockage of drains/build-up of snow and ice	Slip risk/trip risk	5 BBERS 5 BBERS	1 BBERS 1 Ballast	**5 BBERS** **5 BBERS**	BBERS - No trips - increased risk of slips in wet and icy conditions Ballast - No slips - increased risk of trips	08.03A