Publishable Final Activity Report

Project acronym:	**Sustainable Bridges**
Project full title:	**Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives**
Contract No.:	**TIP3-CT-2003-001653**
Project coordinator:	**Jan Olofsson**
Project coordinator organisation:	**Skanska Sverige AB, Teknik, Sweden**
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Author/s:	**Lennart Elfgren, Jan Olofsson, Brian Bell, Björn Paulsson, Ernst Niederleithinger, Jens S Jensen, Glauco Feltrin, Björn Täljsten, Christian Cremona, Risto Kiviluoma, Jan Bien**
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PRIORITY 6
SUSTAINABLE DEVELOPMENT
GLOBAL CHANGE & ECOSYSTEMS
INTEGRATED PROJECT

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The Periodic Report to the European Commission, describing the project activities during the fourth year (Year 4), comprises the following parts.

- Activity Report - Year 4
- Management Report - Year 4 (included in the Final Management Report)
- Deliverables

In addition there is also a Final Report, comprising the following parts.

- Publishable Final Activity Report (This report)
- Final Plan for using and disseminating the knowledge
- Final Management Report

In the same way as the annual project reports, deliverables are supplied to the Commission both electronically and as hard copy, and are also available on the project web site www.sustainablebridges.net for readers with access rights. Access rights may be provided by the project management on request.

Final versions of the Guidelines and their major supporting Background Reports are directly accessible from the public part of the website.

1. Project Execution

Figure 1. Three types of existing railway bridges being studied: Masonry Arches, Steel Beams supported by Reinforced Concrete Arches and a Steel Truss carried by a Steel Arch.

The aim of the "Sustainable Bridges" Project was to help to increase the use of the European railway network. For bridges, this can only be achieved by allowing higher axle loads on freight vehicles and by increasing the maximum permissible speed of passenger trains. In turn, any strengthening or maintenance work on the existing bridge stock to help in meeting this challenge must be undertaken without causing unnecessary disruption to the carriage of goods and passengers, and without compromising the safety and economy of the working railway. This was the overall goal of Sustainable Bridges.

A consortium, consisting of 32 partners drawn from railway bridge owners, consultants, contractors, research institutes and universities, carried out the Project, which had a gross budget of more than 10 million Euros. The European Commission's 6th Framework Programme provided substantial funding, with the balancing funding coming from the Project partners. Skanska Sverige AB provided the overall co-ordination of the Project, whilst Luleå Technical University undertook the scientific leadership.

The "Sustainable Bridges" Project has developed improved methods for computing the safe carrying capacity of bridges and better engineering solutions that can be used in upgrading bridges that are found to be in need of attention. Other results will help to increase the remaining life of existing bridges by recommending improved strengthening, monitoring and repair systems. All this will produce savings throughout Europe.

Background and Objectives

In a sustainable society, rail transport should play a far greater role than it does today. In order to facilitate this, the capacity of the existing railway needs to be increased.

The objective of the project "Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives" was to concentrate on the part played by bridges in meeting this need and was focussed onto three specific goals:

- **Increase the transport capacity** of existing bridges by allowing higher axle loads (up to 33 tons) for freight traffic at moderate speeds or by allowing higher speeds (up to 350 km/hour) for lighter passenger traffic
- **Increase the residual service lives** of existing bridges by up to 25 %
- **Enhance management, strengthening, and repair systems**.

A **consortium** consisting of 32 partners, representing the whole supply chain from user to producer / designer / developer, carried out the project. The gross budget was more than 10 million Euros. The partners were drawn from bridge owners (25%), consultants (9%), contractors (9%), research institutes (19%) and universities (38%). Skanska Sverige AB, Teknik, Sweden provided the overall co-ordination of the project, whilst Luleå University of Technology undertook the scientific leadership. The partners are listed in the following box.

Partners by country: *Czech Republic:* Cervenka Consulting; *Denmark*: COWI A/S; *Finland:* Finnish Road Administration, Finnish Rail Administration, University of Oulu, WSP Consulting – Kortes; *France:* Société Nationale des Chemins des Fer Français (SNCF), Laboratoire Central des Ponts et Chaussées (LCPC); *Germany:* Deutsche Bahn AG, Bundesanstalt für Materialforschung und prüfung (BAM), Universität Stuttgart, Rheinisch-Westfälische Technische Hochschule; *Norway:* NORUT Technology A/S; *Poland:* PKP Polish Railway Lines, Wroclaw University of Technology; *Portugal:* Universidade do Minho; *Spain:* Universitat Politècnica de Catalunya (UPC); *Sweden:* Skanska Sverige AB, Banverket (Swedish Rail Administaration, Vägverket, (Swedish Road Administration), Luleå University of Technology, Chalmers University of Technology, Royal Institute of Technology, Lund University of Technology, Swedish Geotechnical Institute, Sto Scandinavia AB, Designtech AB; *Switzerland:* Eidgenössische Materialprüfungsanstalt (EMPA), Ecole Polytechnique Federal de Lausanne (EPFL); *United Kingdom:* Network Rail, City University, and University of Salford.

The consortium brought together experience of the different types of challenges facing European railways. In central Europe, flooding from big rivers crossing a flat landscape is a major problem, whereas frost damage predominates in northern Europe. There are also different demands on railway lines; heavy iron ore traffic crossing the wilderness of northern Scandinavia and intense passenger traffic in the densely populated areas of central Europe and the UK.

Some highlights of the work of the project are given below.

European Railway Bridges

A group of railway owners mapped the existing stock of railway bridges and made an overview of relevant problems. The data from the survey covers over 220,000 bridges owned by 17 different railways and is considered to be representative of the well in excess of 300,000 railway bridges across Europe. Examples of some bridge types are given in Figure1.

The **proportion of bridge types** was fond to be:
- 41 % Arches of masonry, stone or concrete;
- 23 % Concrete bridges;
- 22 % Steel beam bridges; and
- 14 % Steel/concrete composite bridges.

More than 35% of the bridges are over 100 years old, while only 11 % are less than 10 years old. Small span bridges predominate, with 62% of the bridges spanning less than 10 m, while only 5% have spans larger than 40 m.

The railway owners listed the following **top ten priority research areas**:

- Better assessment tools
- Non-disruptive maintenance methods
- Verification of theoretical dynamic factors for both design and assessment
- Use of new materials
- System for diagnosis & maintenance needs selection
- Ageing/deterioration of concrete bridges
- Indirect inspection and monitoring dynamics for evaluation/crack detection in metallic bridges
- Repair and waterproofing of concrete
- Better testing methods for existing bridges
- Serviceability of arches

All these areas have been addressed and new and improved innovative methods have been proposed.

Figure 2: Automatic non-destructive testing (NDT) with radar and ultrasonic echo was used to check the concrete and reinforcement conditions in a redundant reinforced concrete bridge in Örnsköldsvik, Sweden. The bridge was then tested to failure to compare assessment predictions with the real ultimate load-carrying capacity.

The mapping showed that masonry arches formed a larger portion of the existing bridge stock than had been originally envisaged. Consequently, the project plan was revised to allocate more resources to the study of arch bridges. Results were exchanged with a Masonry Arch Bridge project run by the International Union of Railways (UIC) to minimise duplication of research effort.

Inspection and Condition Assessment

One group made extensive studies of **measurement methods** available for quantifying the present condition of bridges. Non-destructive methods can be used to verify construction plans and check for deterioration in steel, concrete and masonry as well as in foundations and embankments. Radar tomography and ultrasonic echo methods were developed. Automatic measurements and combination of methods were major topics. Tests at bridges in Germany, Poland and Sweden have been performed (Figure 2 and 3). To make information more readily accessible to bridge engineers a toolbox listing available measurement techniques has been produced. In addition, proposals for the use of measurement techniques in condition assessment systems and suggestions for a unified defect classification scheme have been made.

Monitoring

A second group evaluated existing **monitoring techniques** (sensors, data communication and data processing) and carried out research into wireless sensor networks based on fibre optical sensor technologies and micro electro-mechanical systems (MEMS). Fibre optical sensors fit well in railway bridge applications because of their high immunity to electromagnetic fields. MEMS, consisting of small-integrated devices or systems that combine electrical and mechanical components, can significantly reduce the cost of monitoring. A long term field test has been carried out on the Stork Bridge outside Zürich; an open access web page (www.nomotida.net) contains graphical representations of the measurements. Problems related to the interaction between data processing and basic network functionality could be solved by fragmenting the data in tiny subsequent processing steps. Figure 4 illustrates a wireless solar cell based monitoring system for a remote railway bridge.

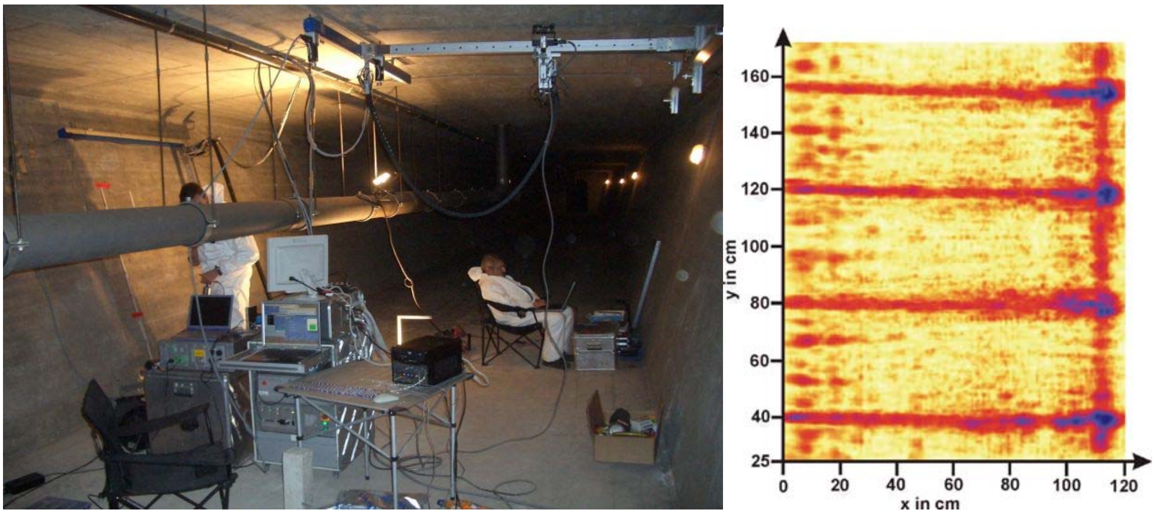

Figure 3. Non destructive technology (NDT) methods are used to check the position of tendon ducts in the top deck slab of a prestressed concrete railway box girder bridge in Duisburg, Germany. To the left he ultrasonic echo device can be seen scanning the slab from underneath. Results are visualized to the right.

Load Capacity and Resistance

A third group prepared a *"Guideline for Load and Resistance Assessment of Existing European Railway Bridges"*. This Guideline is supported by a large number of Background Documents, which represent the major scientific outputs from this work stream. Research into pertinent areas (railway bridge loads and dynamic effects, simplified probabilistic methods for assessment, Bayesian updating of test data, fatigue in steel and concrete bridges, reinforcement corrosion and its effects, non-linear analysis of bridges with non-linear finite element methods, structures and subsoil in transition zones, etc) has been completed. Also, a new algorithm has been developed for masonry arch bridges, SMART (Sustainable Masonry Arch Resistance Technique). This allows the opportunity to include new developments, such as Interactive Stress-Number-of-cycles (ISN) curves and introduces the new concept of Permissible Limit State (PLS). Figure 5 shows a suggested flow diagram for the assessment of existing bridges.

Repair and Strengthening

A fourth group studied **repair** and **strengthening methods** by carrying out many laboratory based investigations. The group focused on repair and strengthening methods that do not require long term bridge closures, that are environmental friendly and which can be economically justified. Hence CFRPs (Carbon Fibre Reinforced Polymers) were the main focus of the research. The group produced a guideline on the most popular repair and strengthening methods, but which explains the use of CFRPs in more detail for the benefit of those unfamiliar with the material.

Figure 6 shows the physical proving of this group's work during the summer 2007. Here near surface mounted reinforcement (NSMR) (where CFRP bars are bonded into grooves sawn into the concrete surface) was used for longitudinal flexural strengthening and CFRP tubes, placed in holes drilled across the structure, were used for transverse flexural strengthening. The cost savings for this single project corresponds to the whole budget for this group within the Sustainable Bridges Project.

Figure 4.Wireless strain sensors used at the Keräsjokk Bridge close to the border between Sweden and Finland.
Left: Low power base station. Centre: Base station with batteries as power supply and solar cell for battery recharge mounted on an abutment. Right: Four nodes mounted on the longitudinal girder.

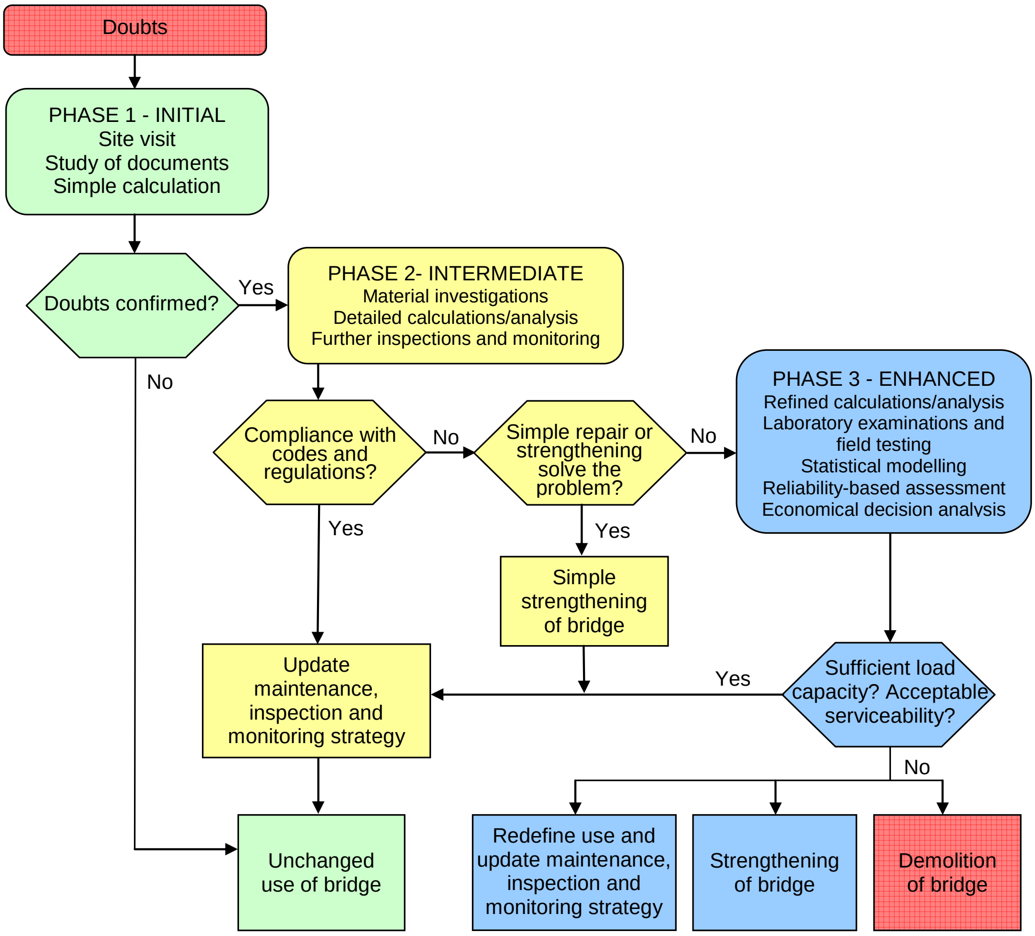

Figure 5. Flow diagram for the assessment of existing bridges. The work in the project concentrated on improving Intermediate and Enhanced methods (Phases 2 and 3).

Figure 6. Left: Drilling 9 m long 38 mm diameter holes for strengthening the bottom slab of a concrete railway trough bridge using 4 mm wall thickness 32 mm diameter CFRP tubes. Right: A close up view of the tube end.
To ensure good bonding, each hole was flushed with high pressure water and dried with compressed air and each tube was roughened with sandpaper and cleaned with acetone. The tubes were equipped with two self-adhesive external spacers every second metre, which centred them in the hole to allow easy penetration for the adhesive.

Demonstration and Testing

Two further groups worked with **demonstration and testing** on existing bridges. Their original plans were modified in order to integrate the test needs of other groups. A steel bridge in France, a concrete bridge in Sweden (Figure 2) and a masonry bridge in Poland were tested and the results evaluated for comparison with predicted values.
Monitoring methods were tested on five other bridges. In one case measurement of the real dynamic amplification factor showed that the bridge could carry a desired higher load well above predictions with existing codes.
The failure test illustrated in Figure 2 showed that the bridge without strengthening could carry not only one train, as it was designed to do, but eight trains on top of each other with an axle load of 250 kN, see Figure 7. After strengthening of the bending capacity of the bridge it was able to carry the equivalent to 11 trains. This shows that concrete railway bridges can have a considerable reserve of extra load-bearing capacity.

Dissemination

Finally a seventh group worked on **dissemination**. A web page was set up, initially to act as an advert for the project,. where all guidelines and background reports are publicly available, see www.sustainablebridges.net.
The project has prepared four guidelines with the topics: “**Inspection and Condition Assessment “, “Monitoring”, “Load and Resistance Assessment”** and **“Strengthening and Repair”**. Traditional means of dissemination of the results (papers to Journals etc) have been used and, in addition, four workshops and training courses were arranged to gain feed back on draft versions of the guidelines. A final conference was held in Wroclaw, Poland, during October 2007.
Most groups have followed their original plans with only slight modifications in order to obtain a better over-all result. The project partners are proud that they have been able to fulfil the main objectives of the project and the railway partners have started to implement the results.

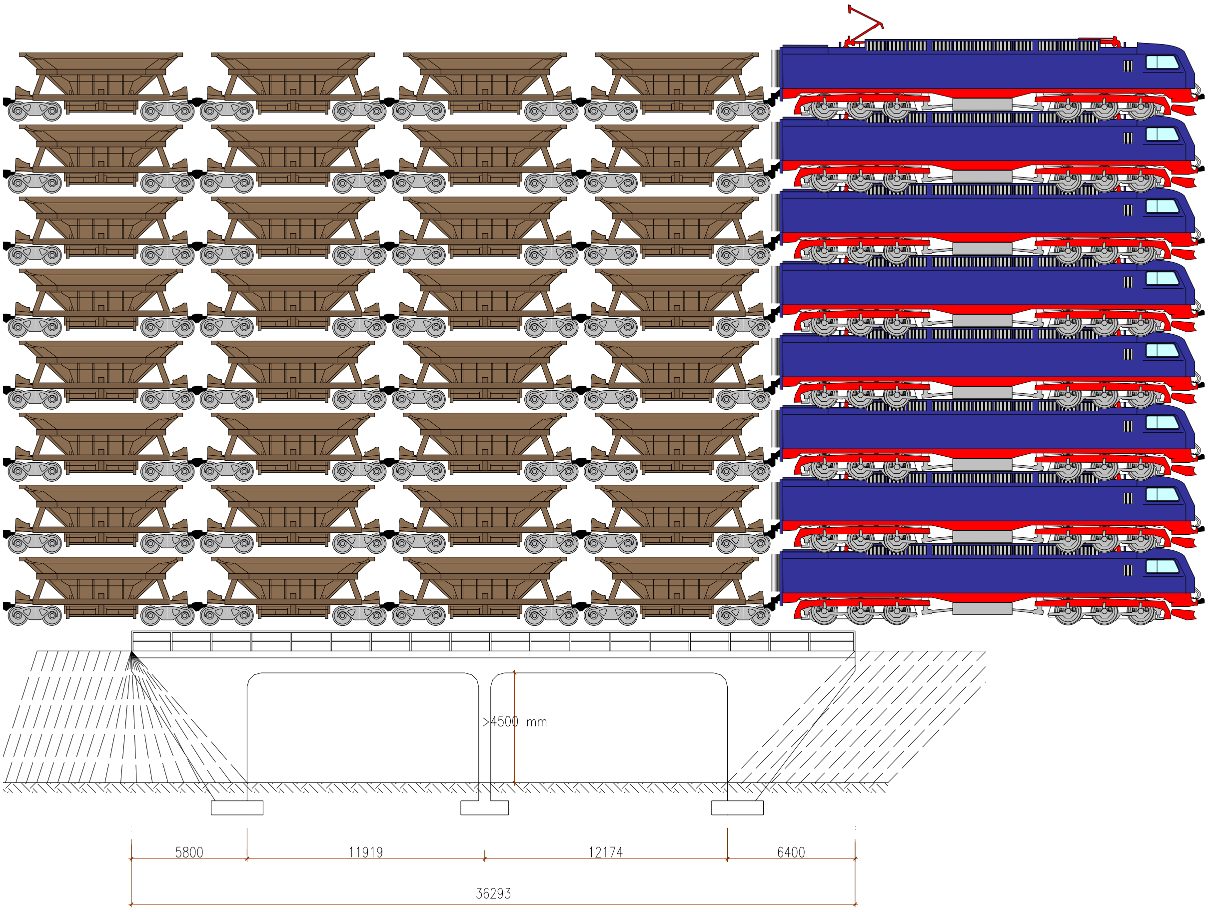

Figure 7. The failure test in figure 2 showed that the bridge without strengthening managed to carry not only one train, as it was designed to do, but eight trains on top of each other with an axle load of 250 kN. With strengthening it could carry 11 trains. This shows that concrete railway bridges might have a considerable reserve of extra load-bearing capacity.

Cost reductions

The project results will **reduce costs** by making it possible to increase the usage and extend the residual service lives of existing bridges. With more than 300 000 bridges, having a total value of the order of 50 billion Euros (10^9), a moderate 2% increase in load capacity, or residual life, would result in savings of the order of 1 billion Euros. The whole project cost will be returned with only ten ordinary bridges being saved/strengthened instead of being torn down and replaced by new bridges. The results will also be useful for road bridges, which more than double the value of the project.

In conclusion, all the three specific goals for the project have been met, i.e. increased bridge capacity and life length and enhanced methods for maintenance, repair and strengthening.

2. Dissemination and use

Figure 8 below gives a structure of the deliverables and Table 1 presents a list of the deliverables.

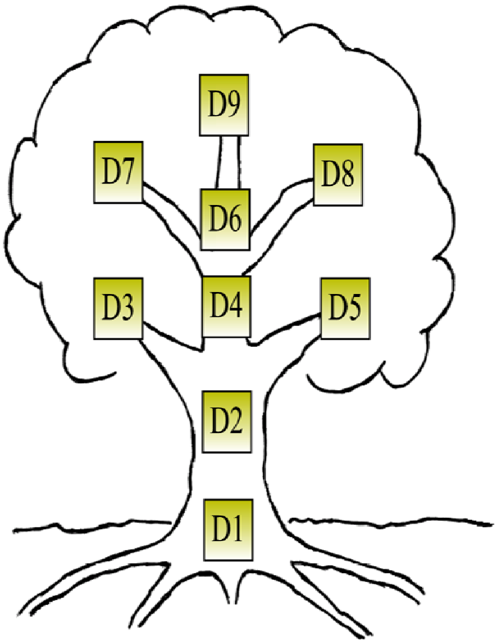

Figure.8. The deliverables are interrelated in the following organic way:
- D1 (Start up and Classification) - Background material for the programme
- D2 (Guidance and Review) - Guides and reviews the project (Railway partners)
- D3 (Condition Assessment and Inspection) - Research and Guidelines
- D4 (Loads, Capacity and Resistance)- Research and Guidelines
- D5 (Monitoring)- Research and Guidelines
- D6 (Repair and Strengthening) – Research and Guidelines
- D7 (Demonstration – Field testing of Bridges) – Demonstrates results from D3-D6
- D8 (Demonstration – Monitoring on Bridges) – Demonstrates results from D3-D6
- D9 (Training and dissemination) – Workshops, Final Conference and Reports

Table 1: List of deliverables

Number	Work Package and Deliverable name	Year
WP1	**Start up and classification**	
SB-1.1	Detailed Work plan for WP 1	2004
SB-1.2	European Railway Bridge Demography	2004
SB-1.3	European Railway Bridge Problems	2004
SB-1.4	Railway Bridge Research	2005
SB-1.5	Legislative and Regulatory Issues that could prevent Advances…	2005
WP2	**Guidance and Review**	
SB-2.1	Comments to Working Plans	2006
SB-2.2	Assessment of Progress	2007
SB-2.3	Reports from General Assembly meetings	2007
WP3	**Condition Assessment and Inspection**	
SB-3.1	Actualised Work Plan	2004
SB-3.2	Inventory on condition assessment methods	2004
SB-3.3	Condition Assessment Procedures	2005
SB-3.4	Steel bridges. Stress measurements	2005
SB-3.5	Combination of radar data of different polarisation	2004

SB-3.6	Scanning system for concrete surfaces	2006
SB-3.7	Impact-echo system for crack depth measurement	2007
SB-3.8	Radar tomography	2007
SB-3.9	Electrochemical methods for corrosion	2006
SB-3.10	Steel bar corrosion. Review and lab tests	2007
SB-3.11	FE modelling of concrete attacked by corrosion	2007
SB-3.12	Steel bar corrosion. LIBS	2006
SB-3.13	Foundations. Non destructive test (NDT) methods	2005
SB-3.14	Embankments. Cross hole tomography	2006
SB-3.15	Guideline for Inspection and Condition Assessment, SB-ICA	2007
SB-3.16	NDT-toolbox (annex to D3.15)	2007
SB-3.17	Demonstrations of measurements	2007
WP4	**Loads, Capacity and Resistance**	
SB-4.1	List of contents for guideline	2004
SB-4.2	Guideline for Load and Resistance Assessment, SB-LRA	2007
SB-4.3	Background document for loads and dynamic effects	2007
SB-4.4	Background document for safety and probabilistic modelling sub-group	2007
SB-4.5	Background document for concrete bridges	2007
SB-4.6	Background document for metal bridges	2007
SB-4.7	Background document for masonry arch bridges	2007
WP5	**Monitoring**	
SB-5.1	Monitoring instrumentation techniques	2007
SB-5.2	Guideline for Monitoring (incl. S1-S4), SB-MON	2007
SB-5.3	Prototype – crack sensor sheet - optical fibres	2007
SB-5.4	Prototype – fibre optic grating sensor	2007
SB-5.5	Prototype - MEMS	2007
SB-5.6	Prototype – shaker for vibration tests	2007
SB-5.7	Prototype – wireless communication network	2007
SB-5.8	Prototype – smart data processing	2007
SB-5.9	Prototype – TOF fibre optic sensor	2007
WP 6	**Repair and Strengthening**	
SB-6.1	Guideline for use of Repair and Strengthening Methods, SB-STR.	2007
SB-6.2	Background documents	2007
SB-6.3	Field testing	2007
SB-6.4	Quality Assurance	2007
WP7	**Demonstration – Field Testing of Bridges**	
SB-7.1	Detailed Implementation Plan	2006
SB-7.2	Riveted steel bridge, France	2007

SB-7.3	Concrete bridge, Sweden	2007
SB-7.4	Masonry arch bridge, Poland	2007
WP8	**Demonstration – Monitoring of Bridges**	
SB-8.1	Detailed implementation plan for demonstrating basic monitoring system	2007
SB-8.2	Demonstration of bridge monitoring	2007
WP9	**Training and Dissemination**	
SB-9.1	Programme of the book “Railway Bridge Damages”	2004
SB-9.2	Overall Project Guide :“Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives”	2007
SB-9.3	International Conference “Sustainable Bridges” – book of proceedings	2007
SB-9.4	Dissemination activities	2007
SB-9.5	Project Web Site	2007

Knowledge and know-how created in the project will be used by rail authorities, consultants and contractors. Through the active participation of rail authorities from several countries there will be a natural flow of know-how. The knowledge has also been disseminated to a wider audience through training programs, workshops, conferences and a web site.

Below is an overview of the post project completion plan for the use and dissemination of the knowledge and know-how:

- the current market for methods to assess, monitor and strengthen existing railway bridges will grow

- the actual practical applications and industrial impacts from the project outputs have been demonstrated through tests on real bridges and will continue to be disseminated

- the technical and economic potential for exploitation has already been presented in training programs, workshops and at conferences. A well attended final conference was held in October 2007 to summarize and disseminate know-how from the project.

- there are no patentable results

- hands on experience has been given in training courses

- contacts with potential users exist on many levels. The active participation of rail authorities in several countries in the project guarantees that customer requirements have been addressed

- publications and conference presentations resulting from the project will continue to be encouraged.

- the website www.sustainablebridges.net is publicly accessible and permits the downloading of all the main deliverables and most of the detailed background reports from the project.

The coordinator, Mr Jan Olofsson, can be contacted by mail at Skanska Sverige AB, Teknik, SE-405 18 Göteborg, Sweden; by phone +46 31 77 11 319 or by email Jan.Olofsson@skanska.se