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ERA technical note on work needed for closing TSI open point on bridge dynamics

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Contents

Abbreviations and acronyms

Table 1 : Table of abbreviations and acronyms

Abbreviation, acronym	*Meaning*
EC	European Commission
EN	European Norm
ERA, Agency	European Union Agency for Railways as defined in Regulation (EC) 2016/796 [2]
INF	Infrastructure (subsystem)
IOD	Interoperability Directive [1]
OPE	Operation (subsystem)
RST	Rolling Stock (subsystem)
TSI	Technical Specification for Interoperability

Reference documents

Table 2 : Table of reference documents and legislation

Ref	*Title*	*Version*
[1]	Directive (EU) 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system within the European Union (recast)	OJ L 138/44, 26.5.2016
[2]	Regulation (EU) 2016/796 of the European Parliament and of the Council of 11 May 2016 on the European Union Agency for Railways and repealing regulation (EC) No 881/2004	OJ L 138, 26.5.2016
[3]	EN 1991-2 Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges	2003/AC 2010
[4]	EN 15528 Railway applications. Line categories for managing the interface between load limits of vehicles and infrastructure	2021
[5]	EN 13848-6 Railway applications – Track – Track geometry quality – Part 6: Characterisation of track geometry quality	2021
[6]	EN 1990 Eurocode: Basis of structural design	2021

NOTE 1: The above legislation is in each case meant to include all the applicable amendments.

Introduction

To close TSI open points on Bridge dynamics, necessary investigations to formulate a European dynamic interface between railway bridges and rolling stock are needed. New methods must be further developed and should be compatible with the existing regulations in TSI INF, TSI RST, TSI OPE, EN15528 and EN1991-2 with a particular focus on the interface with existing infrastructure.

Using the ZBBD software that will be provided by CEN TC256 with the support of ERA, further research to evaluate the dynamic behaviour of the bridges during train passage using the DER method and the time step integration calculation (TSC) for a set of representative bridges together with the following representative train data is needed:

(i) Conventional and articulated Multiple Unit (MU) (for 200km/h - 160 km/h)
(ii) Conventional Double Deck MU (for 200km/h - 160 km/h)
(iii) Conventional and articulated high speed train with similar axle loads (for 320 km/h)
(iv) Loco hauled train pulled and pushed (Railjet for 250 km/h)
(v) Conventional high-speed train with power head (ICE 2 for 280km/h)
(vi) Freight trains with long and short wagons
(vii) 2 more train families (e.g., Talgo-ECx)

Considering previous research in this area (e.g. the DZSF funded project Bridge dynamic: Dynamic load model; the S2R funded projects IN2TRACK-2 and IN2TRACK-3), the next sections are describing in detail the expected foreseen developments in eleven research areas to be addressed to close TSI open points as well as fundamentally associated research activities.

1. Further development of spectral methods (DER, LIR)

1.1. Purpose

Undertake the research necessary for the further development of the train Signature technique and spectral methods (DER, LIR) to identify and address the limitations of the method including the known limitations identified below.

1.2. Background

The comparison of the Train Signatures of different trains has the potential to provide a very quick method for comparing the relative dynamic loading effects of different trains.

The formula for Train Signature was derived from the decomposition of excitation at resonance (DER method), as well as the Residual Influence Line (LIR) method. In the original studies describing the derivation of the method and from its application a number of limitations have been identified. These limitations potentially preclude the application of Train Signature and the spectral methods to current passenger traffic which has different train architecture characteristics to the characteristics of the first high speed trains.

An improved Train Signature technique has the potential to enable quick accurate comparisons of the relative dynamic loading characteristics of trains. Such a technique could enable the quick evaluation of the relativity of the load effects of a proposed train versus the load effects produced by existing train(s) which have been previously demonstrated to be compatible with existing bridges. For the verification of the proposed train / bridge compatibility to be valid (undertaken on the basis that the dynamic load effects from the proposed train are not greater than the dynamic load effects from existing trains), it is important that the revised Train Signature technique does not:

› underestimate the load effects of the proposed train; and
› overestimate the load effects of the existing trains that are operating.

It should be noted that one limitation may apply to one of the above trains but not to the other depending upon the train architecture characteristics of each train. This issue has the potential to make invalid the relative comparison of dynamic load effects from proposed and existing trains.

A revised spectral method should have the potential to enable the very quick determination of the maximum dynamic increment of static loading and maximum bridge deck acceleration for either an individual bridge or for use in parametric studies.

1.3. Envisaged activities

In addition to any identified activities to achieve this objective it is envisaged that the research undertaken should include:

(i) researching the background of the Train Signature technique and associated spectral methods, identifying the mathematical simplifications involved in their development, undertaking an engineering appraisal of the engineering and mathematical simplifications involved in the development of the techniques and determining the magnitude of errors in predicting load effects arising from the above simplifications in the Train Signature technique and spectral methods

(ii) updating the engineering and mathematical techniques used in the derivation of Train Signature and spectral methods to address the limitations, determining the magnitude of errors in predicting load effects arising from the revised methods and making recommendations for a revised Train Signature technique and spectral methods including guidance on limits of validity and likely maximum errors.

Where the revised techniques do not meet the accuracy requirements specified in Technical Requirements an alternative method is to be developed for comparing the relative dynamic loading effects of trains (dynamic increment of load and bridge deck acceleration); and computing the dynamic increment of loading and maximum bridge deck acceleration in bridges. A literature review of mathematical and dynamic engineering topics should be carried out to identify suitable approaches.

The revised method shall be suitable for determining these relative loading and absolute loading effects on an individual simply supported span, and on a range of simply supported spans with parameters representing the European bridge landscape.

1.4. Technical requirements

The update of the spectral methods, should reduce the following limitations:

a) DER method includes only dynamics at resonance;
b) Train Signature and DER method do not adequately describe the load effects from short trains;
c) Train Signature and DER method do not capture a critical case that occurs whilst a train is on a bridge before the whole length of the train has passed over the bridge, for example the case of a power car or locomotive with different axle spacings to the remainder of the train or where the train architecture varies throughout the train;
d) Train Signature and DER method are not suitable for comparing the load effects of trains on short span bridges or for excitation from short wavelengths;
e) terms neglected in the derivation of the Train Signature technique and DER method can be more significant than retained terms (e.g. 2nd or 3rd terms in Fourier series derivation);
f) Train Signature technique and DER method errors increase as the train length deviates from an exact multiple of the repeating vehicle length;

g) Train Signature technique and DER method were developed primarily from consideration of maximum bridge deck acceleration and the accuracy of the technique for determining displacements should be investigated and improved.

The revised Train Signature technique shall be capable of comparing the relative load effects of current and envisaged passenger traffic with maximum speeds of 160km/h to 400km/h and freight traffic for speeds up to 160km/h.

The revised methods shall be suitable for running on normal desktop PCs.

The revised DER method or an alternative shall be suitable for quickly checking:

- an individual train on an individual bridge; and up to
- multiple trains in a parametric study taking account of bridge parameters representing the European bridge landscape.

The revised methodology for determining Train Signature shall be checked by comparing the relativity of loading between critical trains using:

- the revised Train Signature Methodology; and
- TSC methods comparing the relative load effects using parametric studies with bridge parameters representing the landscape of simply supported bridges across Europe.

The maximum error in the revised Train Signature methodology for comparing Train A versus Train B shall be determined and if the maximum error is unacceptable for the intended purpose of comparing trains for train / route compatibility checks the methodology shall be revised and or guidance provided on how to take into account the error.

The revised DER method shall be checked by comparing the predicted load effects (dynamic increment of loading and bridge deck acceleration) against the results of a parametric study using TSC for current and envisaged passenger trains at speeds up to 400km/h for bridges parameters representing the European landscape of bridges.

The revised DER method shall be suitable for determining the dynamic increment of loading and maximum bridge deck acceleration from current and envisaged passenger traffic with maximum speeds of 160km/h to 400km/h.

1.5. Results

The following results are expected:

(i) a revised method for defining Train Signature and associated limits of validity;
(ii) revised DER method to combine static moment and deflection with dynamic DER results and associated limits of validity.

The above revised methods shall address the above known limitations and any other identified limitations:

a) a check of the results obtained using the revised methods against TSC results and commentary on the remaining differences and effects.
b) a check demonstrating that relevant critical trains can be detected (from variations and families - see section 4 below) by such an approach by comparison with TSC- results.

2. Definition of dynamic loading interface between vehicles and bridges

2.1. Purpose

Undertake the research necessary to define the dynamic loading interface between trains and bridges using a method that is easily understood by vehicle and bridge engineers and that enables engineers to easily understand the effect of varying train and/or bridge parameters on the interface.

2.2. Background

For static loading effects the static loading interface between trains and bridges can be defined by:

- the equivalent uniformly distributed load applied by the train to the bridge span for bending and shear load effects; and
- the load carrying capacity of a bridge in terms of the equivalent uniformly distributed load capacity for bending and shear load effects.

Alternatively, the static load effects of a train of vehicles can be categorized as being less than or equal to a defined static reference load model, for example the EN15528 Line Categories.

Similarly, the load carrying capacity of a bridge for a maximum speed of traffic can be compared to and defined by the corresponding EN15528 Line Category reference loading.

A similar simple technique is required for defining the dynamic loading interface between a train of vehicles and the dynamic loading capacity of a bridge (and to be suitable for describing the dynamic loading capacity of a set of existing bridges on a line).

The new technique could form the basis for defining the dynamic load carrying capacity of existing infrastructure and the vehicle parameters that are compatible with the existing infrastructure.

Previously a set of Multiple Unit Classes were developed for this purpose (see EN15528:2015) but these Multiple Unit Classes have not been used because:

- the Multiple Unit Classes do not cover all current and envisaged trains;
- the Multiple Unit Classes do not enable the relative effects to be understood of varying train parameters on the definition of the interface (e.g. a particular MU Class) including the effect of deviations from the limits of validity of the particular MU Class defined in terms of vehicle parameters; and
- the Multiple Unit Classes do not enable an easy understanding of the relative dynamic loading capacity of rail bridges for trains outside the MU Class.

2.3. Envisaged Activities

In addition to any identified activities to achieve this objective it is envisaged that the research undertaken should include:

(i) evaluation of the research undertaken in section 1, further research to describe the generic response of a bridge to a train of moving point loads and identification of the interface between train and bridge;
(ii) evaluation of the sensitivity of the resultant load effects in a bridge arising from varying train and bridge parameters from the research undertaken in sections 1 and 6;
(iii) distillation of findings into a form that is easily understood by vehicle and ‘static load’ bridge engineers and determining Dynamic Train Categories;
(iv) sensitivity studies to check accuracy of proposed method using dynamic analysis techniques based on an independent methodology (for example TSC); and making recommendations including guidance on limits of validity of proposed method and guidance on the application of the proposed Dynamic Train categories.

2.4. Technical requirements

The technical requirements identified in sections 1.4, 4.4, 6.4 and 7.6 shall apply in this section.

The new technique must be suitable for defining the dynamic load carrying capacity of existing infrastructure and the vehicle parameters that are compatible with the existing infrastructure.

The proposed method shall cover the following load effects generated in a bridge as the train passes over the bridge at speed:

- maximum bridge deck acceleration; and
- maximum dynamic increment of static loading for bending and deflection load effects.

Train / bridge mass interaction effects may be neglected.

The method proposed shall be:

(i) easily understood by vehicle engineers and ‘static load’ bridge engineers;
(ii) capable of being used for the investigation of the influence of train parameters on the interface;
(iii) capable of being used for the investigation of the influence of bridge parameters on the interface; and
(iv) capable of being used to define the interface for both passenger and freight traffic with detailed recommendations for the implementation of the method for passenger traffic.

The proposed solution should permit varying levels of train ‘dynamic loading intensivity’ to be specified and suitable steps in the magnitude of dynamic loading should be proposed with a set of corresponding ‘Dynamic Train categories’. It should be noted that a ‘one size covers all trains’ approach would be unnecessarily conservative (similar considerations to the static EN15528 Line Categories apply where a range of Line Categories are used to describe existing bridge load carrying capacity). For example different Dynamic Train Categories could be proposed excluding and including adverse multiples (within specified limits) of the various axle spacing distances in a multiple unit when compared to vehicle length, bogie pivot centres etc. or ranges of allowable axle spacings for a given coach length etc.). The Dynamic Train Categories may comprise of a set of Multiple Unit Classes or any other proposal (technical form dependent on results of research into methods for defining the dynamic loading interface between trains and bridges).

2.5. Results

The following results are expected:

(i) Recommendations for a method defining the dynamic loading interface between passenger and freight trains and bridges and associated limits of validity.

(ii) Set of passenger ‘Dynamic Train Categories’ and guidance on application for determining infrastructure capability and categorising vehicles and trains.

3. Economic evaluation of proposed Dynamic Train Categories (DTCs)

3.1. Purpose

The purpose of the economic evaluation is to identify an estimate of:

(i) the potential costs and timescales for the technical studies necessary to assess a section of line for each Dynamic Train Category; and
(ii) the likely number of bridges on a line that will require physical works to upgrade the bridge to meet each Dynamic Train Category and the associated costs and timescales.

3.2. Background

The current MU Classes need to be expanded to address their limitations.

Dynamic appraisals of individual bridges can be time consuming and costly and IMs are reluctant to implement new minimum dynamic loading requirements for existing lines without understanding the cost of the necessary studies and likely cost of required works to upgrade the lines to meet any new requirements.

To date no studies have been carried out to optimise the existing MU Classes (or similar) to:

- maximise their coverage of train parameters / minimise costs of implementation; and
- measure and maximise utilisation of current infrastructure dynamic capability for the dynamic bridge / train interface.

3.3. Technical context for economic evaluation

The technical basis of the studies shall satisfy the technical requirements for the other studies.

The economic technical bridge acceptance criteria for the studies shall comprise:

a) Where the DTC load effects do not exceed the published Line Category, e.g. D2 for the actual loaded lengths in a bridge (if not the bridge needs to be further investigated);
b) Where the DTC load effects exceeds actual bridge load carrying capacity (note the actual capacity of an individual bridge is likely to be greater than the published line capability e.g. D2); and
c) Bridge deck acceleration limit for existing bridges, for example:
    - 5m/s2 (0.5g) where resonance occurs;
    - 6m/s2 (0.6g) for vibrations not at resonance (e.g. inertial impact effects including repeated inertial impact effects from successive groups of axles in a train); and
    - 10m/s2 (1.0g) for zones of the track not exceeding 1.5m in length in the direction of the track).

3.4. Envisaged activities for economic evaluation

Step 1

Undertake a dynamic parametric analysis of bridge parameters representing the European bridge landscape with the proposed Dynamic Train Categories (DTC) to identify combinations of the bridge parameters span, mass and natural frequency etc. where the dynamic behaviour of bridges changes from satisfying the economic technical bridge acceptance criteria to requiring further investigation.

Review the data collected in section 6, data on existing bridges, particularly the data collected on the sample sections of line for 3 x 3 x 50 = 450 bridges to identify individual bridges that are compatible with the new DTC / require further investigation.

Step 2

For the bridges identified in Step 1 that require further investigation, carry out an individual bridge dynamic analysis with data describing the individual bridge.

It is anticipated that a reduced set of bridges requiring further investigation will be obtained that do not meet the economic technical bridge acceptance criteria.

Step 3

Adjust the DTC so that a range of DTC are available covering maximising flexibility for train parameters/associated largest potential requirement for infrastructure works through to less flexibility for train parameters/minimising the need for infrastructure works.

Step 4

Utilising the results of Step 2 and Step 3 undertake individual 3D dynamic analysis of the bridges requiring further investigation. It is anticipated that this will produce a reduced list of bridges that do not meet the economic technical bridge acceptance criteria.

Step 5

The results of Step 4 for each DTC will provide the technical basis for identifying for each DTC:

a) number and percentage of bridges that passed Step 1 (a very simple and low cost check)

b) number and percentage of bridges which required further studies to ‘pass’:

- where DTC dynamic loading was greater than line category and a review of existing detailed bridge records would be required (if available - if not also include the cost of undertaking a bridge recalculation);
- where Step 1 identified a bridge where DTC loading exceeded the published line category but further dynamic studies and or conventional further refined bridge recalculation studies were required to demonstrate the bridge was satisfactory (cost and time estimate for these studies to be provided)
- bridge deck acceleration limit criteria (cost and time estimate for these studies to be provided)

c) for the bridges that did not meet the economic technical bridge acceptance criteria identify the nature of likely physical works - strengthening and stiffening / reconstruction and cost and time estimate for these works

3.5. Results

A report describing the studies undertaken, the basis and limits of validity of the economic findings and the time and cost of technical studies and time and cost of physical works required for implementing each proposed Dynamic Train on average per 50 bridges (excluding brick and masonry structures) on a line.

4. Sensitivity studies on passenger and freight train parameters

4.1. Purpose

To identify the critical passenger and freight train parameters that have the greatest influence on train / bridge route compatibility regarding dynamic load effects in bridges and provide guidance on the design of passenger train architecture to optimize this interface.

The findings from this section will be used to inform the selection of critical real trains selected in other section, for example in section 5 and 7.

4.2. Background

A number of national standards specify that some passenger vehicle parameters such as the vehicle length or distance between adjacent axles across a coupling plane should not be close to a multiple of the bogie axle spacing.

Depending on bridge span/natural frequency etc. (or bridge element span/natural frequency etc. in the floor of bridge decks) it is known that critical loading frequencies produced by a train passing over the bridge at speed can be related to the different regular spacings of axles in a train. For example, vehicle length, spacing of axles in a bogie, ratio of pivot centres.

To reduce resonance effects in bridges it can be useful to break the regular pattern of axles along a train. For example, in coupled multiple units sets by making the end overhang of a multiple unit different to the corresponding distance for permanently coupled vehicles within one multiple units. How much different?

Often the axle loads vary along a multiple unit or freight train. It is not known what the effect of this variation is and the degree of conservatism in adopting the maximum axle load throughout the train for passenger and freight vehicle / route compatibility checks.

Some studies show there is a risk of freight trains generating resonance effects in some bridges where the assumed worst case critical bridge parameters may be unrealistic with this effect more likely for block trains.

In EN15528:2015 valid ranges of variation of geometric dimensions of vehicles are formulated for classification into MU classes. There are a number of individual trains with train architecture parameters outside these values.

4.3. Envisaged activities

In addition to any identified activities to achieve this objective it is envisaged that the research undertaken will include research to:

(i) identify the train parameters requiring investigation including regular train architecture and mixed train architecture, e.g. mixed conventional and articulated architecture and identify ranges of train parameters and valid combinations of ranges of train parameters for both passenger and freight traffic;
(ii) initially using travelling point force dynamic models investigate the influence of various train parameters for conventional (CB), articulated (AB) and single axle (SA) passenger train architecture configurations and similar variations for freight traffic for sample bridges representing the European bridge landscape. As an alternative to travelling point force models the output of sections 1 and 2 may be used;
(iii) Investigate the influence of varying critical passenger and freight train parameters on vehicle / bridge compatibility. It is anticipated that the outputs from these initial studies will inform the selection of critical passenger and freight trains and their associated parameters used in later stages of the studies and expand the scope of the studies to fully cover bridge parameters representing the European bridge landscape; and
(iv) Investigate the significance of other passenger and freight train parameters identified in section 7 regarding φ'' using mass interaction modelling techniques

4.4. Technical requirements

The studies undertaken shall evaluate the effect of varying train parameters on:

(i) maximum bridge deck acceleration; and
(ii) maximum dynamic increment of static load

experienced by bridges away from resonance and at speeds corresponding to a resonance condition (for example where a multiple of the loading frequency matching a natural frequency of a bridge).

In EN15528:2015 valid ranges of variation of geometric dimensions of passenger vehicles are formulated for classification into MU classes. The ranges of these parameters shall be checked, and the updated ranges used in the studies. Aligned with section 5 objectives, the vehicle parameters determining the dynamic behaviour are to be described. From this, tolerance ranges of the individual geometric dimensions of axle patterns are to be derived, as well as those of varying wheelset loads along the train and for other critical train parameters identified by the studies.

In addition to investigating the identified ranges of passenger train parameters, the studies shall also investigate for passenger trains:

p.1) MU formations (CB, AB, SA) and trains with mixed configurations CB, AB, SA;
p.2) pushed / pulled loco-hauled trains;
p.3) trains with power cars or locomotives at one or both ends
p.4) various patterns and magnitude of variation in individual axle loads from a constant level;
p.5) train formations of maximum 400m length comprising of 1, 2, 3 or 4 individual multiple units with varying coupling plane to adjacent bogie pivot distance compared to the general end of vehicle to adjacent bogie pivot point;
p.6) the effect of the length of repeating vehicles (and or pivot spacing in a vehicles) being an exact multiple of the bogie axle spacing including various percentage deviations;
p.7) the effect of variations in distance between adjacent axles between adjacent vehicles compared to bogie axle spacing including percentage deviations of this length being an exact multiple of the bogie axle spacing.

In addition to investigating the identified ranges of passenger train parameters, the studies shall also investigate for freight trains:

- f.1) one or two locomotives hauling the train of maximum length 400m with constant freight wagon axle loads of 22.5t (Line Category D4);
- f.2) a maximum length of 400m with constant freight wagon axle loads of 22.5t (Line Category D4) or with varying patterns of tare, partly loaded and fully loaded wagons (mixed traffic trains);
- f.3) block trains with uniform 4 axled freight vehicles or mixed traffic trains with varying length 4 axled freight vehicles – both with an overall length varying between 11.25m and 20m;
- f.4) comparison between 2 axled, 4 axled and 6 axled D4 freight vehicles;
- f.5) bogie axle spacings of 1.8m or 2m for bogies with two axles;
- f.6) the effect of variations in distance between adjacent axles across the coupling of adjacent vehicles compared to bogie axle spacing including percentage deviations of this length from being an exact multiple of the bogie axle spacing.

The Technical Requirements for section 7 and the outputs from section 6 shall be taken onto account.

For models that include mass interaction between the train and bridge to investigate the influence of train suspension characteristics and ranges in the mass of vehicle parts the Technical Requirements for section 7.6 and 8.4 ‘additional damping’ shall also be considered.

4.5. Results

Guidance on:

- (i) the critical passenger and freight train parameters that have the greatest influence on train / bridge route compatibility regarding dynamic load effects in bridges;
- (ii) the variation in maximum load effects in bridges resulting from varying a critical parameter within a typical range of values for the parameter;
- (iii) additional guidance on passenger train architecture and freight wagon design to optimise vehicle / bridge route compatibility.

5. Selection of relevant vehicles in train families

5.1. Purpose

The aim of the research is to investigate the uncertainty of the current methods used to choose relevant passenger and freight trains for detailed TSC calculation and develop an automatic method to detect the critical train configuration for bridge dynamic train / route compatibility checks.

5.2. Background

The design of one passenger train platform and the options available to customers can result in over 100 different train configurations and loading patterns. It is necessary to identify a minimum number of worst case train loading patterns for dynamic analyses to simplify train / route compatibility checks.

Due to computing capacities, TSC only allows a full calculation for some combinations. Currently only manual detection of critical trains is supported by ZBBD.

5.3. Envisaged activities

The research is to confirm the current process for selecting critical trains and refine the current detection method of relevant trains.

In addition to any identified activities to achieve this objective it is envisaged that the research undertaken will include:

(i) a review of current processes and the relevant findings from section 1, 2 and 4 and developing the criteria to set out the technical requirements for selecting relevant worst case individual trains;
(ii) using the findings of section 1 to carry out dynamic analyses to check the application of the criteria and undertaking a sample check of the findings using TSC;
(iii) finalizing the recommended methodology and criteria for selection of critical individual trains representing a train family;
(iv) advising the technical and programming requirements for updating the ZBBD software.

5.4. Technical requirements

(i) Explore whether it is possible to restrict the (pre-)calculation to one frequency line and minimum damping.
(ii) Explore what is the impact of the additional damping on the comparison of two trains according to the TSC method.
(iii) The recommendations shall be capable of easy implementation in the ZBBD software.

5.5. Results

The following results are expected:

(i) Recommendations for the methodology and criteria for the selection of critical individual trains representing a train family for passenger and freight trains.

(ii) Recommendations for the technical and programming requirements for updating the ZBBD software.

6. Identification of realistic combinations of critical parameters for existing bridges

6.1. Purpose

To identify realistic worst case combinations of critical parameters for existing bridges for use in parametric studies investigating train / bridge vehicle route compatibility.

6.2. Background

The use of the combined most unfavourable values for each bridge parameter in parameter studies leads to difficulties of demonstrating vehicle / bridge compatibility for route compatibility checks. Therefore, on the one hand, the critical parameters of bridges have to be identified. On the other hand, realistic combinations of bridge parameters have to be worked out (span, mass, stiffness, natural frequency, damping, wavelength v/n0) to avoid the need for superfluous follow up vehicle / individual bridge compatibility checks.

6.3. Envisaged activities

In addition to any identified activities to achieve this objective it is envisaged that the research undertaken will include:

(i) Extend the Network Rail structural form codes (to be provided by CEN TC256) to cover other European bridge types to enable bridge data to be analysed by structural configuration, structural details, material and combinations of material, number of tracks carried and bridge span and identify the bridge parameters to be collected (to include a photo of the elevation of the bridge and a photo or diagram illustrating the cross section of the bridge);
(ii) Assist railway administrations with the extraction of the required data from existing records such as databases and from individual paper examination reports and paper copies of bridge recalculations;
(iii) Across different countries identify three lines with maximum speed of 160km/h, three lines with a maximum speed of 200km/h and three lines with a maximum speed in the range of 250km/h to 300km/h. On each of these lines (sample routes) collect data for 50 individual bridges with a local line speed of 160, 200 or 250 to 300km/h respectively. For these 'sample routes' list the bridges and critical parameters. It should be noted that this data will be used in the future for the economic evaluation of future proposals for revised minimum requirements for existing bridges;
(iv) Analysis of the data by detailed bridge type (a proposition of a set of detailed bridge types based on an evaluation of the collected bridge data is expected) and maximum local line speed for:

- worst case for each parameter;
- worst case credible combinations of parameters (coupled values). For example it may be unconservative to assume that a bridge with the lowest natural frequency also has the lowest mass (t/m); and
- determine statistical distribution of critical parameters (taking account that each critical parameter is NOT fully independent of other critical parameters).

6.4. Technical Requirements

At minimum but not limited to:

(i) Data shall be collected across a minimum of five European countries from bridges on a variety of types of line and with varying maximum local allowable speed to represent the European bridge landscape of existing bridges.

(ii) The selected bridges shall cover a wide range of bridge ages and detailed bridge types. For bridges on lines with maximum speeds of 200km/h and above this shall include bridges on 'classic lines' and purpose built new lines.

Brick and masonry arch structures should be excluded from the data collection.

6.5. Results and deliverables

Recommendations for realistic worst case combinations of critical parameters of existing bridges for use in parametric studies investigating train / bridge vehicle route compatibility.

7. Revision of φ‘ and φ’’

7.1. Purpose

Undertake the research necessary to define for all current and envisaged rail traffic:

(i) revised limits of validity (by speed / type of train) of the existing formulae for φ‘ and φ’’ defined in EN1991-2;
(ii) revised formulae for φ‘ and φ’’ for bridges outside the revised limits of validity of the original formulae for φ‘ and φ’’; and
(iii) guidance on the total shortfall of the existing formulae for φ‘ and φ’’ for situations outside the revised limits of validity in (a) above for passenger traffic speeds up to 200km/h and freight traffic for speeds up to 120km/h.

7.2. Background φ‘

Comparison between the results of transient analysis of bridge response of a passenger train family with the corresponding EN Line Category enhanced by the dynamic increment φ’ defined in Annex C of EN1991-2 (or same dynamic increment in UIC776-1R) in the speed range below 200/160 km/h indicate that the dynamic factor φ'_{UIC} is not sufficient to cover all the dynamic effects.

Similar studies for freight traffic indicate that φ'_{UIC} can be insufficient.

The above cases include span lengths where the static load effects from the relevant EN Line Category in accordance with EN15528 exceed the static load effects from the individual real train loading – this conservatism in the EN15528 Line Category static loading for these span lengths is not sufficient to compensate for the shortfall in φ’ in comparison with the dynamic increment of loading determined from a transient analysis of the bridge response.

Similar studies indicate that (1+φ’) x the static load effects of a real train does not cover the dynamic load effects of the same real train determined from a dynamic analysis.

Recent CEN studies into the background of φ’ as described in ORE D128 Report 4 have identified that inter alia the derivation of φ’ did not fully take account of the effects of resonance due to the very short trains considered and very high damping values considered in the studies.

7.3. Background φ’’

Feedback from some railway administrations advises that some site measurements of the dynamic behaviour of bridges indicates that the actual dynamic increment of load from track defects may be less than the existing formula predicts.

The existing formula predicts very high values of φ’’ for very short spans.

The derivation of the formula for φ’’ appears to have been based on a small number of dynamic analyses.

Revised guidance is required on whether a dynamic analysis is necessary for a bridge exceeding the upper frequency limit of EN1991-2 Figure 6.10.

7.4. Envisaged activities φ‘

In addition to the identified activities to achieve this objective it is envisaged that the research undertaken will include:

(i) research into parametric study techniques and methods for presenting and evaluating extremely large numbers of calculated results and a review of the background to φ’ in ORE Reports D23, D128 and ERRI D214 studies and identification of limitations of original methodology used to derive φ’;

(ii) parametric studies to investigate the validity of existing formula for φ’ using:

- worst combinations of bridge parameters; and
- credible worst case coupled values of bridge parameters identified in section 6;

(iii) the research shall take into account dynamic bridge behaviour at resonance and away from resonance

(iv) the recommendations shall exclude the beneficial effects of the track in distributing the axle loads of a train and be compatible with the approach adopted in EN 1991-2 where the beneficial effects of the track in distributing axle loads is taking into account by modifying the determinant length used to calculate φ’.

(v) evaluation of findings, identification of revised limits of validity of the application of the existing formula for φ’ and identification of additional limits on bridge parameters to increase the limits of validity of φ’ for train speeds up to 160 km/h and 200 km/h. Such additional limits of validity could potentially comprise limits of validity on bridge mass, natural frequency, train speed divided by natural frequency and or a combination of critical bridge parameters;

(vi) proposals for a refined φ’ and associated limits of validity.

7.5. Envisaged activities φ’’

In addition to any identified activities to achieve this objective it is envisaged that the research undertaken will include:

(i) a review of the background to φ’’ in ORE Reports D23, D128 an ERRI D214 studies and identification of limitations of original methodology used to derive φ’’ and literature study. Identification of suitable train speed bands corresponding to typical varying standards of track maintenance, PSD values (spectral description) for general track vertical alignment quality according to speed band, typical discrete track defects according to speed band on the bridge and in the length of track on the approach to a bridge and typical wheel defects, for example degree of out of round wheels (oval) and wheel flats;

(ii) an initial comparison of dynamic effects generated in a bridge deck due to smooth track, track defects, wheel defects, track position errors and transition zones track platform-bridge using a comprehensive vehicle/bridge mass interaction model to identify sensitivity of results to various vehicle parameters in conjunction with a sample of parameters representing the European bridge landscape and identification of ranges of vehicle parameters to be used in detailed studies;

(iii) detailed parametric studies to investigate the validity of existing formula for φ’’ using:

  - worst combinations of bridge parameters; and
  - credible worst case coupled values of bridge parameters identified in section 6;

(iv) the research shall take into account dynamic bridge behaviour at resonance and away from resonance

(v) the recommendations shall exclude the beneficial effects of the track in distributing the axle loads of a train and be compatible with the approach adopted in EN 1991-2 where the beneficial effects of the track in distributing axle loads is taking into account by modifying the determinant length used to calculate φ''.

(vi) evaluation of findings and identification of revised limits of validity of the application of the existing formula for φ'' and make recommendations for additional limits on bridge parameters to increase the limits of validity of φ'' for train speeds up to 160km/h, 200km/h, 250km/h and 350km/h. Such additional limits of validity could potentially comprise limits of validity on bridge mass, natural frequency, train speed divided by natural frequency and or a combination of critical bridge parameters. Especially an extension of the of validity range with higher frequencies than the upper limit (fig. 6.10 in EN 1991-2) has to be evaluated;

(vii) if not previously carried out repeat parametric studies using a simple moving unsprung axle mass model following the vertical profile of the track including taking account discrete track defects located at critical location(s) to enable a comparison with ORE D128 report 4 studies;

(viii) proposals for a refined formula for φ'' and associated limits of validity.

7.6. Technical requirements φ' and φ''

The following trains shall be taken into account in the research:

(i) the six trains used in ORE D128 report 4 studies used to check the current formulae for φ' and φ'';
(ii) Train Types 1 to 12 listed in Annex D of EN1991-2 (Basis of fatigue loading);
(iii) a selection of the identified critical passenger trains; and
(iv) a selection of the identified critical freight trains including doubled headed 4 or 6 axled locomotives hauling either D4 wagons or E5 wagons; and
(v) a selection of freight trains representing 160km/h freight traffic.

Train speeds to take into account: the dynamic analyses shall be performed for train speeds of 50km/h and increase in steps of 5km/h up to the envisaged maximum speed of the vehicles for the particular train. The envisaged maximum speeds shall be a minimum of 20km/h greater than the maximum target speed for the type of vehicle set out in the INF TSI to allow for future developments in rolling stock.

Modelling of trains: A travelling point force model may be used to represent the trains for the studies concerning φ'. Mass interaction between vehicles and the bridge shall be taken into account for studies concerning φ''.

Structural configuration to be considered: Simply supported beam.

Span range: The ranges of spans and associated increment in span length shall be in accordance with the values set out in EN15528: 2021 for categorization of vehicles (EN15528 Table 1) for spans from 2m up to a maximum of 60m.

Bridge first natural frequency values: 5 values of natural frequency varying with span:

a) below the natural frequency limit in Fig 6.10 in EN1991-2;
b) at the lower natural frequency limit in Fig 6.10 in EN1991-2;
c) at the quarter point above the lower frequency limit between lower and upper frequency limit in Fig 6.10 in EN1991-2;
d) at the mid-point between the lower and upper frequency limits in Fig 6.10 in EN1991-2; and

e) at the upper frequency limit in Fig 6.10 in EN1991-2.

Bridge mass: 1t/m to 6t/m in 1t/m steps and 8t/m, 10t/m, 12t/m and 15t/m or a comprehensive set of mass functions m= f(span) covering 1t/m to 15t/m in total.

Additionally continuous beams and series of single beam bridges shall be taken into account with suitable bridge properties based on existing infrastructure. Bridge damping varying according to span for reinforced concrete bridges according to EN1991-2 and the revised recommendations for damping (see section 8).

Track and wheel defects:

d.1) PSD values for general track vertical alignment quality according to speed band for D1 and D2 wavelengths defined in EN13848-6; and
d.2) discrete track defects according to speed band on the bridge and in the length of track on the approach to a bridge including allowances for on-site rail weld misalignment, wet spots (voids under consecutive sleepers), worn insulated rail block joints, track position errors and interference areas in the transition zone track platform-bridge etc.; and
d.3) the sinusoidal track defects taken into account in the ORE D128 studies (Report 4) (to enable a comparison of the research undertaken in this section with the results of these studies); and
d.4) identification of typical wheel defects, for example degree of out of round wheels (oval) and wheel flats.

The formula for φ’ and φ’’ shall be suitable for easy application by bridge engineers without any specialist knowledge in bridge dynamics or dynamic analysis techniques.

The maximum exceedance of dynamic load effects from the critical trains determined from a dynamic analysis shall in comparison to the normal static based requirements enhanced by the existing formulae for φ’ and φ’’ (or the revised formulae for φ’ and φ’’) shall not exceed 5% for 99% of the individual combinations of parameters considered and for the remaining 1% of cases the exceedance shall not be greater than 10%. Where shortfalls in φ’ are compensated by conservatism in φ’’ and vice versa this shall be clarified.

7.7. Results

The following results are expected:

(i) revised limits of validity (by speed / type of train) of the existing formulae for φ‘ and φ’’ defined in EN1991-2;
(ii) revised formulae for φ‘ and φ’’ for bridges outside the revised limits of validity of the original formulae for φ‘ and φ’’ and associated limits of validity for the revised formulae; and
(iii) guidance on the total shortfall of the existing formula for φ‘ and φ’’ for situations outside the revised limits of validity in (a) above for passenger traffic speeds up to 200km/h and freight traffic for speeds up to 120km/h.

8. Revision of damping

8.1. Purpose

Undertake research to enable guidance to be provided on damping values for existing bridges commensurate with the amplitude of vibration corresponding to limits adopted for checking vehicle / bridge compatibility (for strength, acceleration etc.) to develop an EC- compatible replacement/ rule.

8.2. Background

The value of bridge damping has a very significant effect on the maximum bridge dynamic response when a loading frequency of the train, or a multiple of, matches a natural frequency of the bridge.

Measurements of damping on what might be considered similar structures have widely varying values of damping.

Some in-situ measurements of damping might have been undertaken at such low amplitudes of deformation that significant damping effects may not have been mobilized. For example, damping from the track, end restraint of the bridge deck by the track or soil etc.

8.3. Envisaged activities

In addition to any identified activities to achieve this objective it is envisaged that the research undertaken will include:

(i) research into the factors that influence the magnitude of damping in existing railway bridges; and
(ii) collection and assessment of measurement data of damping of European bridges.

The measured damping values of existing bridges can vary very significantly for bridges that appear to be of a similar structural configuration. Reasons for such variations should be identified and recommendations made for more precise values of damping to be used in vehicle / existing bridge compatibility checks.

The assessment should include all relevant construction types such as single span girders, continuous girders, portal frames, tied arches or trusses. It should be checked if the damping can be expressed dependent from L_{φ} resp. L_{Φ}.

8.4. Technical requirements

(i) Include influences of track and track formation on the bridge damping (ballasted, unballasted)
(ii) Any recommendations for higher damping values shall be supported by both physical test results from existing bridges and supporting engineering rationale.
(iii) Generally conservative lower bound values of damping shall be specified. Extreme low values of damping from tests may be neglected where a valid justification for the exclusion of the test results is provided.

8.5. Results and deliverables

The output of this section shall include recommendations for values of damping to be considered in the assessment of the compatibility of vehicles with existing bridges.

9. Revision of BEAM model in parametric study

9.1. Purpose

Undertake the research necessary for expanding the application of current techniques developed for modelling simply supported beams in parametric studies to:

(i) cover other structural forms; and
(ii) incorporate more refined analysis techniques (not unduly conservative).

9.2. Background

There is a wide range of structural configurations of bridges that cannot be adequately represented by simple line beam models in dynamic analyses.

Comparison of site measured behaviour and 3D finite element dynamic models of the track and bridge shows that the distribution of axle loads by the track plays a significant role in reducing predicted dynamic effects in calculations. The work has shown that the track can distribute axle loads by more than the nominal 0.25 / 0.5 / 0.25 distribution set out in EN1991-2. The benefits of this effect should be quantified and alternative distribution models recommended to avoid the overestimation of dynamic effects in bridges.

9.3. Envisaged activities

In addition to any identified activities to achieve this objective it is envisaged that the research undertaken will include:

(i) identification of a range of structural forms to take into account including decks with combined longitudinal and torsion effects, skew decks, continuous span decks, portal frames, tied arch bridges, truss girder, plate floors, grillages of transverse and longitudinal members directly supporting the track and end trimmer beams of the floors of decks and identification of critical vibration modes in such structural configurations;
(ii) identification of advice on how to adjust existing parametric ‘simply supported span’ modelling to take account of these additional structural forms when undertaking vehicle / route train compatibility checks;
(iii) a check of the above recommendations using ranges of example bridges against dynamic analysis techniques using TSC dynamic analysis; and
(iv) evaluation of findings and producing recommendations and derivation of associated limits of validity for the proposed recommendations.

9.4. Technical requirements

The research shall consider a selection of the identified critical passenger and freight trains representing current and envisaged rail traffic.

The recommendations shall be suitable for determining:

- the maximum calculated dynamic increment of loading and comparing results with both load model LM71 (or SW/0 for continuous elements) x the dynamic factor or EN15528 Line Categories enhanced by the dynamic increment for real trains; and
- maximum bridge deck acceleration.

In addition, the study shall develop adjustments of the recently used single beam parametric study considering that:

a) recent parametric studies like ZBBD are based upon single track, single beam TSC.
b) other only- structural model related parameters may improve the results, e.g. bearing stiffness, track clamping.

c) more realistic load distribution than the currently used 3point distribution acc. EN 1991-2 can reduce dynamic load effects in bridges.
d) In the end, a fast compatibility check between RST and the whole Bridge Stock based upon simple methods is needed.

9.5. Results

The following results are expected:

(i) an evaluation of different model updates with the effect of improving the results and reducing uncertainties including revised recommendations for the distribution of axle loads by ballasted track and the contribution of the track in reducing dynamic effects in short span bridges arising from the combined response of bridge and track to variable loads (deck end partial clamping effects etc.);
(ii) a description of techniques for adjusting the dynamic analysis of simply supported beams to take into account other common structural configurations;
(iii) a technical specification defining a parametric study for new and existing bridges, that take the existing European bridge landscape into account including various detailed structural forms and associated ranges of parameters and coupled values of parameters to be utilised in the parametric study (also see section 6).

10. Acceleration limit

10.1. Purpose

Undertake the necessary research for specifying adjusted acceleration limit criteria for the evaluation of measured and calculated accelerations for both ballasted and unballasted bridge decks for:

- checking train / bridge compatibility for existing bridges; and for
- the design of new bridges.

10.2. Background

Existing structures often do not comply with the acceleration limit for the design of new bridges according to EN 1990.

With the deletion of the additional damping in the anticipated revision to EN 1991-2 the problem will increase.

It may be beneficial to take other parameters and behaviours into account when setting acceleration limits. For example: repeated impact vs. resonance condition, absolute value of deflection and/or frequencies of the acceleration in time domain, consideration of the affected length of track, number of cycles with exceedances, form of bridge superstructure and associated degree of ballast containment, RMS values in a certain frequency range in a defined time window and other behaviour.

The majority of previous research has concentrated on studies on ballasted decks.

Previous research has shown that limits on bridge deck acceleration are necessary to avoid the following risks to track stability:

- flow of ballast from between adjacent sleepers at depth;
- increasing rates of settlement of a sleeper into the ballast at a rate which cannot be managed by normal track maintenance cycles;
- non-linear behaviour of the ballast providing vertical support to the sleeper;
- reduction in lateral resistance of the sleeper to lateral loads and consequential risk of track buckles;
- with track where there is no lateral support to the track, lateral flow of ballast emptying the ballast between sleepers; and
- for situations where there is lateral support to the ballast adjacent to the sleeper ends, surface flows of ballast.

Previous research has generally been undertaken by applying sinusoidal vibrations and various frequencies to for example a 3m section of track in a steel box potentially replicating repeated cycles of a bridge deck at resonance. A limited number of tests have also been carried out with single pulses of acceleration applied to the same section of track potentially replicating a bridge deck experiencing repeated impact loading where the frequency of passing groups of axles does not match a natural frequency of the bridge. These tests also identified that a number of the above adverse phenomena occurred including unmanageable rates of track settlement, non-linear ballast behaviour and surface ballast flows.

10.3. Envisaged activities

In addition to any identified activities to achieve this objective it is envisaged that the research undertaken will include:

(i) review of previous research into the dynamic behaviour of ballast and bridge deck acceleration limits;
(ii) dynamic particulate modelling of track and ballast to enable the fundamental dynamic behaviour of ballast relevant to this section to be identified;
(iii) comparison of modelling with physical tests to verify modelling;
(iv) using verified modelling of ballast, a range of simulations is to be carried out for investigation, including identification of critical cases and potential enhancements to the bridge deck acceleration limits;
(v) physical testing to validate recommendations for revised bridge deck acceleration limits; and
(vi) checking whether the revised limits are acceptable with respect to adverse effects on wheel / rail contact forces, the risk of wheel unloading and the risk of derailment.

10.4. Technical requirements

The revised recommended limits on bridge deck acceleration shall be sufficient to manage the risks identified above and any other risks identified.

It shall be noted that no partial safety factor will be applied to the revised acceleration limits in their use according to EN1991-2 and EN 1990. Therefore, the recommended criteria shall include an appropriate safety margin (to be determined as part of the research). For example, if it is found necessary to limit acceleration to 9m/s2 and the uncertainty in the derivation of the limit and associated application criteria warrants a partial safety factor of 1.5 then the recommended limit for acceleration should be set at 9 / 1.5 = 6m/s2.

For ballasted track the ERRI D214 studies identified that bridge deck acceleration should be limited to circa 7.0m/s2 and application of a partial safety factor of 2.0 resulted in the published limit of 3.5m/s2. Some railways use a reduced partial safety factor for existing bridges where key bridge parameters are better known.

The studies shall include the derivation of the appropriate value of partial safety factor for incorporation in the recommended acceleration limits as described above. It should be anticipated that a number of parameters, behaviours and considerations apply to the derivation of the partial safety factor and that fault tree analysis or other techniques will be necessary to determine an appropriate overall partial safety factor to be incorporated in a deck acceleration limit.

The work shall also take into account the effect of revised deck acceleration limits on wheel / rail contact forces and shall avoid the risk of wheel unloading and or derailment.

10.5. Results

New regulations for bridge deck acceleration limits for:

(i) The recalculation of existing bridges;
(ii) The acceptability of site measured deck acceleration on existing bridges; and
(iii) The design of new bridges.

11. Revision of limits of validity of static vehicle / bridge compatibility checks

11.1. Purpose

Undertake the research necessary for specifying revised criteria (train and bridge) that set out when it is necessary to undertake a dynamic analysis check in addition to the normal static based requirements for checking the compatibility of rail vehicles with existing bridges and new bridges.

11.2. Background

The current requirements in the INF TSI, EN1991-2 and EN15228 regarding when a dynamic analysis is necessary in addition to normal conventional checks for static loading enhanced by a dynamic factor for design or the dynamic increment for real trains are based upon:

- theoretical studies undertaken primarily with high-speed trains comprising of power car hauled light coaches as opposed to multiple units with distributed traction and regular heavier axles;
- historic in-service experience with a very limited number of trains operating at speeds of above 160km/h up to 200km/h; and
- vehicle / route compatibility checks for trains introduced around the year 2000 in a very limited number of countries.

More recent studies have identified that there are currently either operating or envisaged a much wider range of train architectures and there are increasing business needs for trains with heavier regular axle loads.

11.3. Envisaged activities

In addition to any identified activities to achieve this objective it is envisaged that the research undertaken will include:

(i) evaluation of the findings from the other sections of this technical note and other industry knowledge; and
(ii) identifying and evaluating relevant experience from train / route compatibility checks undertaken across Europe.

11.4. Technical requirements

Normal static based requirements for allowing for dynamic effects shall be taken as:

(i) for the recalculation of existing bridges (using real train loading or Line Categories set out in EN15528) the enhancement of static load effects by the dynamic increment of real train loading set out in Appendix C of EN1991-2; and
(ii) for the design of new bridges the enhancement of Load Model 71 (and for continuous elements SW/0) by the dynamic factor set out in 6.4.5 of EN1991-2.

The outputs from this section shall be valid for:

- all bridges and all known vehicles (passenger and freight etc.); and
- the maximum exceedance of dynamic load effects (bending moment, deflection) from the critical trains considered in comparison to the normal static based requirements defined above shall not exceed 5% for 99% of the train/bridge parameter combinations considered and in the remaining 1% of cases the exceedance shall not be greater than 10%.

11.5. Results

The following results are expected:

(i) a Europe-wide harmonized definition of the limits of validity of static compatibility checks according to Table C.1/2 in 15528:2021.
(ii) recommendations for revising EN 1991-2:2010.
(iii) recommendations for revising the INF TSI.

The following additional outputs are also expected:

(iv) as an alternative to the recommended requirements being valid for all bridges and all known vehicles, recommendations should be provided on minimum coupled bridge parameters that are valid for all known vehicles for design assuming a minimum value of alpha of 1.0 in accordance with EN1991-2 and for the recalculation of existing bridges both for:
    - Passenger traffic at speeds up to 160km/h
    - Passenger traffic at speeds up to 200km/h; and
    - Freight traffic at speeds up to 120km/h.
(v) a harmonized regulatory proposal for the Route Compatibility Check of vehicles.