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Manuscript title: The application of track deflection measurements made by the video gauge

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Abstract

This paper presents direct track deflection data measured by the Video Gauge (VG), (a Digital Image Correlation method) that is used to remotely determine track stiffness characteristics. Two cases are discussed. Firstly, the deflection performance of two novel ballastless trackforms are coupled with an analytical model to assess their stiffness properties for known train loads. Secondly, the performance of a bridge transition is evaluated under live train passages by the VG; the traffic loads are assumed based on train type to allow track stiffness interpretation from a number of train passes. A track deflection bowl is assessed to show the performance of the transition. The paper initially discusses the DIC technique and the importance and assessment of track stiffness. It then presents the VG deflection data, the global support stiffnesses and deflection bowls. It shows these novel methods to be consistent with other approaches of track stiffness evaluation. It concludes on how this methodology can be utilised in the railway industry for assessing trackbed performance of critical zones without the need for track possessions.

Keywords: Railway systems; Rail track design; Field testing & monitoring

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1. Introduction

In recent years Digital Image Correlation (DIC) techniques have allowed direct measurement of deflections of elements subject to dynamic loading using devices such as the Video Gauge. This technique has been used to evaluate track performance by assessing deflection under load (Gallou et al., 2017). The understanding of the deflection of railway track is important to Permanent Way Engineers as it gives an indication of the performance of the track system and identifies areas where there are potential issues, related to the performance of the track components and track quality .One parameter that can be assessed from dynamic deflection of the track under known load is track stiffness.

Global track stiffness of the whole track structure, is assessed as applied force to the rail divided by rail deflection. It varies with frequency, dynamic amplitude and position along the track. European guidance for acceptable levels of vertical track stiffness is not defined while current UK Railway Group Standards (GC/RT50210, NR/L2/TRK/2102 and NR/L2/TRK/4239) provide values for (a) target formation moduli for new track construction (45 MN/m^2) and for post renewal, (from 15 to 45 MN/m^2 (according to track category) and (b) optimum dynamic sleeper support stiffness, for existing track for different speeds (30 MN/m for line speed <50mph and 60 MN/m for line speed 50 to 125 mph). An optimum global track stiffness value of 45 MN/m and an optimum rail deflection of 2 mm was recently proposed (Wehbi and Musgrave, 2017).

There are various techniques available to measure track load and deflection performance to assess stiffness but many require access to the track to install extensive instrumentation and monitoring equipment. Such access can be difficult to obtain through possessions and has consequent effects on train services. The DIC technique can be undertaken remotely from the track and at worse only requires brief access to the track to install targets on the rails and sleepers to improve the target quality, in some cases targets may not be required. Such remote techniques offer potential advantages over current techniques, such as measurement of multiple points and track components at the same time, at higher capture rates and high resolution leading to a large deflection database of high accuracy offering substantial time and cost saving. The higher the train speed, the higher the deflection frequency of each axle. Thus, the video capture rate must be high enough to capture the actual maximum deflection.

This paper presents data from a DIC method of direct track deflection measurement under traffic loading using the Video Gauge and then uses the deflections measured to derive track stiffness characteristics. This is undertaken for situations where the load is known (for tests on novel track forms). It also presents data from live track, for particular types of train, where the loads are assumed (based on train type) to allow assessment of a track deflection bowl and the performance of a bridge transition. In the latter case the assumption is that if sufficient train passes are recorded, the deflection and load data will consolidate to a mean that will give sufficiently accurate data to allow track performance and stiffness to be appropriately assessed without the need for measured loading and track access.

To do this the paper initially discusses track stiffness, its measurement and the tools currently used. It then presents a model used for track stiffness calculation, followed by the data described above. It uses these data and the model to show how stiffness can be assessed from the V.G.

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Track stiffness and its Assessment

To assess track stiffness typically both load and deflection performance are required (see below). This data is then coupled with a model of track behaviour, such as the beam on elastic foundation (BOEF) to allow track stiffness to be calculated. Over a number of years global track stiffness has been assessed from data collected from various techniques (summarised and referenced in Table 1). For deflection this has included using a vehicle with a vibrating (known) wheel axle load, the RSMV-Rolling Stiffness Measurement Vehicle and the Portancemètre) and direct track instrumentation, including direct methods of measuring track deflection such as the linear variable displacement transducers (LVDTs), laser reflectometers, multi-depth deflectometres (MDD), remote video monitoring using PIV (Particle Image Velocimetry) and DIC, as well as by indirect methods such as geophones and accelerometers.

Detection of wheel loads to couple with deflection has been assessed from shear forces by means of strain gauges on the rail. Though, such devices need calibration against known applied loads which is difficult to achieve in the field.

Other devices for directly measuring local stiffness have been developed such as the TLV (track loading vehicle) and FWD (Falling Weight Deflectometer), recently developed into the RTST (Rail Trackform Stiffness Tester) to facilitate use on railways. The advantages and disadvantages of various track stiffness assessment methods are presented in Table 1.

The issues with many of the techniques in Table 1 is that instrumentation needs to be directly fixed to the track or requires a track possession.

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The Video Gauge

The Video Gauge (VG) is based on DIC principles and Video Extensometry and uses robust industry grade cameras that enable high resolution measurements of deflection via sub-pixel pattern recognition algorithms. Its practical advantages and high precision have been shown in the past as it has been widely used in material testing and infrastructure applications (Waterfall *et al.*2012). The VG was first introduced as a promising tool for rail application by Waterfall *et al.* (2015). The precision of VG for rail deflection measurements was tested by Gallou *et al.* (2016) where the dynamic deflections of a rail and rail joint were measured by the VG and compared to LVDT readings in the laboratory. An excellent correlation between the two techniques was found that validated its use for subsequent rail application in the field. Its applicability for the accurate assessment of rail deflection and rail joints under high speed traffic loading was published by Gallou *et al.* (2017).

The VG is advantageous over previous image based measurement techniques as far as the capture rate, the accuracy, resolution and the quality and quantity of data produced. It enables the measurement of multiple points (over 100) at a time at various perspective planes at sampling frequencies up to 300Hz and in resolutions of the scale of 0.001mm, comprising multiple cameras and allowing (post) data processing. Hence, high quality deflection data for a relatively long section of track, from a close distance can be collected quickly in a safe and cost effective way. Resolution is down to the quality of image target (depending on size and varying brightness) and the field of view (depending on lens choice vs distance to the object). For the VG, (when natural object features are not sufficient for pattern recognition) limited access is required to the track for marking of the rail web or mounting targets on sleepers to improve object target quality. The measurements themselves are being made remotely.

It is therefore proposed that if VG can be used to assess deflection accurately, these data could be used to calculate track stiffness. This could be under a known load or by approximation of load from typical train types based on large data sets converging on a mean. Rail deflection depends on trackform condition, train speed and wheel spacing, as VG is able to evaluate deflections for each individual axle during a vehicle pass, it offers a greater understanding of track performance assessment, including any dynamic effects. Although the increase in train speed can affect the track deflection non-linearly this effect is limited as long as the speed is not approaching the critical speed (velocity of the wave propagation of the supporting track ground system), however, train speed can be assessed from the video where this may cause issues/variability.

2 Track stiffness: definition and an example of BOEF approach

Various models of track stiffness assessment have been proposed but global vertical track stiffness can be defined as

$$S_{system} = \frac{applied\ force\ exerted\ on\ top\ of\ rail}{rail\ vertical\ displacement} = \frac{Q(t)}{\delta(t)} \text{ or } S_{system} = \frac{Q(f)}{\delta(f)} \qquad \text{eq.1}$$

Where S is the track stiffness as a function of time or a function of the excitation frequency when assessed in the frequency domain. There are two approaches to track stiffness, a static one represented by its magnitude as direct relation of applied load and deflection and a dynamic one represented by its magnitude and phase, where phase is measured as deflection delay by comparison with force that is mostly related to ground vibration and damping properties (Li and Berggren 2010). Conventional calculations of track stiffness are based on the static approach of beam on elastic foundation (BOEF) developed by Zimmermann in the 1860s. This combines the rail flexural rigidity (EI), the rail-pad stiffness, the trackbed stiffness (ballast, subballast and subgrade) in a spring in series system. The governing differential equation that derives the solution for the rail deflection is (Powrie and Le Pen, 2016):

$$\delta(x) = \frac{Q}{2k_{system}L} e^{-\left(\frac{x}{L}\right)} \left(\cos\frac{x}{L} + \sin\frac{x}{L}\right) \qquad \text{eq.2}$$

where L is the characteristic length of the track, a parameter that defines how far from the point load, the deflection bowl extends along the rail, taking into account the flexural rigidity of the rail and the elasticity of the system, which is determined by:

$$L = \sqrt[4]{\frac{4EI}{k_{system}}} \text{ (m)} \qquad \text{eq.3}$$

k_{system} is defined as the series support system modulus, a combination of railpad modulus ($k_{railpad}$) and trackbed modulus ($k_{trackbed}$) given by:

$$\frac{1}{\mathrm{k_{system}}} = \frac{1}{\mathrm{k_{railpad}}} + \frac{1}{\mathrm{k_{trackbed}}} \qquad \text{eq.4}$$

The term modulus k (measured in MN/m^2) refers to the distributed support stiffness calculated from the sleeper spacing (c) and the discrete stiffness of the rail-pad, ballast, and subgrade defined as $k_{trackbed}=s_{trackbed}/c$ and $k_{railpad}=s_{railpad}/c$.

Therefore, for the point of application (x=0) of a wheel load and rail deflection measurement by combining the eq.1 and eq.2 the global static-stiffness is obtained by

$$S_{system} \left(\frac{\mathrm{MN}}{\mathrm{m}}\right) = \frac{Q}{\delta(0)} = 2k_{system}L \left(\frac{\mathrm{MN}}{m^2} m\right) \qquad \text{eq.5}$$

Figure 1a presents the calculated results using this BOEF approach for five typical track structures (of assumed trackbed stiffness ranging from 10, 30, 45, 60, 100 MN/m) for a CEN 56 rail, a standard railpad stiffness 150 MN/m and a typical axle load of 20 ton. The global track stiffness and the track moduli are calculated for each case. Figure 1b presents the calculated rail deflection for the various trackbed moduli ($k_{trackbed}$) from 10 to 80 MN/m^2.

These figures show that the rail deflection bowl is highly affected by the trackbed support system conditions, rather than the rail system properties.

3 Measurement of Track stiffness

This section presents field results and subsequent calculation of track stiffness from field trial data where deflections were measured with the VG. These trials can be split into two sets (1) where the load was known and (2) where the load has been assumed for a number of vehicle passes. The characteristics of the each set of data including site, train and measurement characteristics are summarised in Table 2.Train speed is determined in the time domain by determining the time between deflections under individual wheel loading separated by a known vehicle or trainset length from the VG data.

3.1 Site 1

3.1.1 Experimental technique

This data includes the measurement of the deflection of three track structures under controlled low speed train passage of known loading on conventional ballasted and two novel trackforms:

- Ballasted renewed track, reballasted with new track components
- IVES concrete ballastless modules with asphalt underlayment
- PORR slab system with asphalt underlayment

The IVES system constitutes individual prestressed concrete units of 250 mm depth, of 1 tonne weight separated by small gaps (to allow drainage), laid on 250mm of asphalt. The PORR slab system consists of 5.16 m x 2.4 m x 0.16 m pre-cast concrete slab panels laid on a 100mm asphalt layer. Deflections were measured at the extremity of the slab modules and in the rail above. A five sleeper length comprising 3.25 m of renewed ballasted track was also assessed. Measurements of both rail and sleepers/slab modules were undertaken simultaneously. The deflection of the asphalt layer below IVES was measured by using a steel rod fixed in the gap between the IVES modules. The train set consisted of a locomotive with three axles (16.3 tonnes per axle) and two wagons with two axles each (13.25 tonnes per axle) and was running at a range of velocity from 2 up to 20 mph. At least six train passes were recorded for each track form and multiple positions were measured for each trackform. The measurements were undertaken at a capture rate of 105 Hz, using two cameras, 2m away from the line, each providing an horizontal x vertical field of view of 1.4 m x 0.74 m. Figure 2 shows a view of the site and the locations measured.

3.1.2 Deflection results

An example of time- deflection plots of typical monitoring points for each trackform are presented in Figure 3a. The deflections due to the 2-axle wagon passage prior and after the 3-axle locomotive can be clearly seen. The resolution of the measurements was in a range between 0.005 and 0.02mm. Consistency of the results was found for each monitoring point under the passage of the six trains indicating the repeatability of the results (24 wheel passages at each point for a known load). The maximum deflections for each position were averaged for all wheel passages from all tests. Figure 3b presents a comparison of maximum deflections found for all track components due to the wagon's wheel load. The rail deflections found in ballasted track, IVES and PORR slab track are 1.26 mm, 1.85 mm and 1.26 mm respectively, whereas the deflections for the sleepers, IVES and PORR are 0.85 mm, 0.32mm and 0.31 mm.

3.1.3 Stiffness evaluation for known load

The rail deflection includes the effect of rail bending and the effect of the elastic layers (railpad and trackbed). The railpad and the asphalt layer below the slab track (IVES and PORR) provide the elasticity that the ballast and railpad provide in the ballasted track. The static stiffness of the railpad usually used with PORR and IVES are ≥ 22.5 MN/m (Vossloh, 2015).

For the IVES track form, the global stiffness is calculated to be 36 MN/m. By using the deflections found and the known wheel load, the rail pad stiffness is back calculated. Then, by using the rail bending stiffness (for CEN56 rail), 0.65 m spacing of the fastening system and the BOEF equations as described in section 2, the effective rail pad stiffness calculated as 14.5 MN/m. It is observed that this value is lower than the specification. By using the 14.5 MN/m stiffness of the railpad the support stiffness of the asphalt layer below the IVES is calculated to be 51 MN/m. Table 3 summarises the track stiffness parameters back calculated for three track forms.

The global stiffness of the PORR trackform is directly calculated to be 53 MN/m. The stiffness of the railpad of PORR is back calculated to 27.1 MN/m which is within the specification. The support stiffness of the PORR, that actually represents the stiffness of the asphalt layer, is estimated to 62.3 MN/m according to the rail deflection (1.26 mm) and the calculated stiffness of its railpad (27.1 MN/m). Also the measured asphalt deflection 0.18mm corresponds to 14% of the overall deflection (1.26 mm) for the PORR slab track. (It should be noted that the thickness of the asphalt layer is different for the two track forms).

The global stiffness of the renewed ballasted track is calculated to be 53 MN/m. The rail pad stiffness is estimated to be 84.2 MN/m whereas the trackbed stiffness of 24.3 MN/m (trackbed modulus 37.4 MN/m^2); these are within expected values from the standards (see section 2).

3.2. Site 2

3.2.1 Measurement of deflections and stiffness in service

The second site was an assessment of the deflection performance of a transition zone on the approach to a bridge in live track, prior to and after major maintenance. The transition was needing regular maintenance due to uneven settlement of the substructure caused by variations in vertical track stiffness through the transition on to the bridge. Settlement variations can result in increased dynamic loads on the components and increased rail deflections during a train pass.

The field measurements described below include deflection measurements undertaken prior and after renewal. The maintenance activity included installation or a geocell web (to stiffen the transition track bed) and a sand blanket to provide drainage below the ballast. Initial measurements were conducted directly after manual tamping of the ballast which temporarily improved performance prior to the Main renewal.

3.2.2 Experimental technique

Rail and sleeper deflections through the transition were measured under high speed train passages (eight Intercity 125 and three Class 222 prior to renewal and two Intercity 125 after renewal) in live traffic with the VG (see train characteristics in Table 2). The measurements were undertaken at a sampling frequency 175 Hz using two cameras 5m from the track. A track length of 6.3m covering ten sleepers and the edge of the bridge was assessed. Each camera was recording both rail and sleeper deflections covering an horizontal x vertical field of view 3.5 m x 0.8 m. The anticipated resolution for the specific set up of the VG system is given as 1/100 pixel to 0.035 mm. Variations of the measurement resolution within a single image are principally down to the quality of the target the software sees. The resolution obtained has been calculated as the standard deviation of the measurements points when there is no load applied. This was found in a range of 0.016 mm to 0.042 mm for the various deflection points. At this site the applied load is assumed on the basis of the train type observed. The estimated static wheel load is calculated according to the published weight and number of axles of the vehicles. While this may not accurately reflect the actual weight of the train (by not taking into account the weight of passengers, fuel and the vehicle dynamic effects), it is assumed that over a number of passes that train weights will converge to a mean that will offer a way of using this deflection data (this will be subject to further work).

3.2.3 Deflection results

Typical graphical representation of the recorded deflection over time for two rail web positions is presented in Figure 4. Each deflection peak corresponds to an axle of an 11-carriage Intercity 125. Four peaks are distinct for each carriage (4 axles per car, 44 wheels over each point in total).Consistency was observed among the magnitude of peak deflections due to the wheel passages along each train passage and among the total number of trains. In most tests, maximum values were found due to the wheel load of the locomotive passage, whereas some differences in the intermediate carriages were observed that can be attributed to differences in the actual static passenger load or to wheel defects and dynamic forces. It is observed that the rail does not return to its original level between adjacent wheel spacings on adjacent coach, whereas between each bogie for each coach the rail deflection is fully recovered with small undulations due to the uplift of the rail ahead or behind the wheel passage. The maximum rail deflections for each position (averaged for all train passages), along the total measured track length of the transition zone are presented in Figure 5 for the two maintenance phases, (prior and after renewal).

As discussed above, the prior to renewal phase occurred after manual tamping and the deteriorated condition of the original transition was temporarily improved. The track deflection was found to be lower than 2mm for a 3m length on the approach to the bridge. The fact that after renewal the rail still deflected above 2mm adjacent to the bridge slab is attributed firstly due to the nature of the bridge substructure, where timber longitudinal beams support the sleepers off the end of the steel bridge beam.

Secondly, dynamic deflections are influenced by the effects of the high train velocity (125 mph). Literature often present track stiffness values or frequency values calculated from filtered deflection data after integration of velocity data measured by geophones to assess track quality. Since it is difficult to measure the dynamic load at a specific point of interest, it would be practical to target the deflection envelope, (as recommended by Webhi and

Musgrave, 2017), rather than using a back calculated track stiffness envelope or integrated frequency envelope to characterise the track quality for different train velocities. The measurements presented here include any potential sleeper voiding and dynamic effects that will influence the results within the BOEF model (see below). The methodology of real deflection measurements above could help track designers (Powrie & Le Pen 2016; Sharpe et al., 2002) design for an optimum deflection by selecting the appropriate combination of trackbed layers and railpad types that will correspond to an optimum stiffness of the track, as a system.

3.2.4 Stiffness evaluation for assumed load

From the deflection measurements over a track length of ten sleepers, the variance of the inferred track stiffness characteristics from one point to another, is shown in Figure 6. The global stiffness found by simply dividing the static locomotive wheel load by the rail deflections are shown in Figure 6a. The variability of the support system stiffness (Figure 6b), the support system moduli (Figure 6c) and trackbed moduli (Figure 6d) (evaluated by taking into account the effect of railpad and rail bending stiffness by using the analytical model described in section 2). A railpad of medium stiffness 200 MN/m is used with a rail section CEN 56 in the calculations. The increase of track stiffness after the maintenance activity is observed after the third sleeper whereas the stiffness values for first three sleepers near to the bridge remain low and is considered to vary with various dynamic loads, at various speeds.

This track stiffness calculation method is based on an assumption of linear elastic behaviour of the railpad and substructure (ballast and subgrade) and consequently may not represent realistically this site's performance; where significant voided sleepers may be present prior to renewal; less consistent behaviour is expected due to sudden change in track stiffness when passing from ballasted track to the bridge; where non-linear stress dependent responses and permanent settlements under dynamic loading may affect the track behaviour. To investigate this further a measured deflection basin from the data (as an indicator of the load transfer under a moving wheel load in the transition zone) for both renewal phases was investigated. The results show that the VG could be a suitable method of visualisation of change in track stiffness over a short distance of a critical zone and can be used to assess the subgrade deflection conditions in an area that needs to be assessed promptly. Additionally with more cameras a longer length can easily be assessed.

3.2.5 Deflection bowl as an indication of load transfer and track system behaviour

The deflection bowl due to the passage of the first wheel of a Class 222 above each sleeper for the prior to renewal phase is presented in Figure 7a whereas that due to Class 43 wheel passage in Figure 7b. Each line represents the deflection measured on every sleeper at a specific time for a specific position of the wheel load. By looking the area where the bowl extends we can see that the behaviour of track is consistent between sleepers G10 and G6 as the deflection over a sleeper extends over an area of two to three adjacent sleepers (giving a 2 m deflection bowl). This compares well to the data in Figure 1b. From this data the trackbed modulus was evaluated around 20 MN/m^2 based on the assumed train load, and is typical of that expected for ballasted track. The load transfer along the transition zone is however different when the wheel is above the area G4 to G1, with this situation to be improved after renewal (Figure 7c).

These findings indicate the requirements for a transition zone to have a gradual increase in the overall track stiffness through the length of the transition, where railpad stiffness variations or other structural elements could be used to compensate for stiffness magnitude variability. The deflection bowl diagrams are produced directly from the VG recorded data without any other input parameters and give realistic values (see section 2). This shows a potential of the VG system but does need further validation.

4 Conclusions

The applicability of the Video Gauge for the assessment of ballasted and ballastless track deflections and support stiffness characteristics remotely has been shown. Deflections below 2 mm were measured in ballastless and well maintained trackforms, whereas up to 5.5 mm were found in a transition zone adjacent to a bridge, leading to global track stiffnesses in a range of 18-75 MN/m with an average of 44-53 MN/m for well maintained and newly repaired track.

Variation in trackbed stiffness in a range of 4-36 MN/m was found between maintenance periods for the transition zone; 24.3 MN/m for the renewed ballasted track, whereas the support stiffness of slab modules with underlying asphalt was estimated to be 50-60 MN/m.

The above study leads to the following conclusions:

- Rail deflections, accurately assessed remotely by the VG, can be used directly for global stiffness derivation under a known wheel load.
- For estimated traffic load, the VG can be used to give reasonable estimated track stiffness properties without the need to fix complicated instrumentation to the track; hence, providing a visualisation of the performance of critical zones during service life and between maintenance periods by saving time, cost and the need for a full possession.
- Track system support stiffnesses and moduli for various positions can be determined by using estimated wheel load data and an appropriate model for the track behaviour such as the beam on elastic foundation.
- The deflection bowl for each point of wheel application can be derived directly through the real-time deflection measurements in absence of the wheel load data, indicating the load transfer in a critical zone. This allows the assessment of the dynamic response of the track as a holistic system providing useful information for both the superstructure and substructure through the analysis of multiple rail and sleeper deflections.
- The VG system can be used directly for track performance assessment where a rail deflection envelope is available; for critical zones that need to be investigated promptly this can be combined with an estimated track stiffness envelope.
- Variability of the maximum rail deflections and consequent track stiffness variance can be caused by variance of dynamic loading; further research is required to investigate and test the sensitivity of the above methodology for the derivation of absolute track stiffness values. An evaluation of deflections under various speed rates

over the same site for various trackbed conditions to determine the effect of the dynamic component to the stiffness range is recommended.

- The use of assumed train loads (averaged over many similar vehicle passes) coupled with remotely measured VG deflections seems to lead to calculation of reasonable approximations to track stiffness. Whilst this needs further validation it may offer a cheaper method of evaluating track stiffness in service. Especially where modern trains can monitor their own axle weight to complement the VG deflection data.

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List of notations

S_{system} is the global track system stiffness

Q is the applied wheel force exerted on top of rail

δ is the rail deflection

k_{system} is the track support system modulus

x is the distance from the force application point

L is the characteristic length of track

EI is the flexural rigidity of the rail

$k_{railpad}$ is the railpad modulus

$k_{trackbed}$ is the trackbed modulus

c is the sleeper spacing

$s_{trackbed}$ is the trackbed stiffness

$s_{railpad}$ is the railpad stiffness

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Table 1 Advantages and disadvantages of track stiffness measurement techniques

Measurement technique	Advantages	Disadvantages
LVDT (Fortunato et al., 2015)	High accuracy for high speed Direct deflection High capture rate (e.g. 500Hz)	Single axis (non- accurate results if movement in 2 axis) Less safe Need steel rods-additional non movable reference zero deflection frame
Laser deflectometer (Innotrack,2006; Fortunato et al., 2015)	High resolution to 0.001mm Direct deflection	High cost Ground borne vibration of the tripod may affect the accuracy Single point measurement
Multi-depth deflectometer (Mishra et al., 2014)	Direct deflection Measures permanent deformation	Requires fixed datum at depth Can be problematic to install
Geophones (Innotrack, 2006; Bowness et al., 2007; Le Pen et al., 2014)	Ground and subsurface layers motion (velocity) measured Resolution to 0.07mm	Initial noisy data need correction of signal, filtering and post processing to give accurate deflection values (need Inverse Fourier Transform and integration of velocity time history to absolute deflections) Single point measurement where each geophone is positioned High capture rate of raw voltages (e.g.500Hz) but not of actual deflection
Remote video monitoring (RVM) using PIV (Bowness et al., 2007)	Direct deflection Software comprising with multiple cameras Noise reduction Post process 2D OR 3D Remote monitoring apart from target positioning-Safe Easy set up	High resolution only when long sight e.g15m Small capture rate e.g. 30Hz Affected by ground borne vibration Only 1 sleeper or location can be monitored at a time
RVM using DIC (Murray, 2013; Thompson et al., 2015) and Video Gauge (Gallou et al., 2017)	All advantages of RVM using PIV High capture rate (e.g. 200Hz) High resolution to 0.001mm Multiple points at a time, enables measuring structures from <0.01mm wide to >1km long. Applicable in frequencies more than 200Hz by using expensive higher frame rate cameras Deflection bowl can be measured	Prone to alternating lighting conditions during outdoors recording.
Vehicle systems RMSV/ Portancemètre/TLV (Innotrack, 2006; Li and Berggren, 2010)	Dynamic track stiffness up to 50Hz and stiffness phase (deflection delay by comparison to force) Continuous measurements over long track length	Additional cost of transport to site and locomotive during measurements. Difficulty for widespread use.
FWD (Sharpe and Collop, 1998; Govan, Sharpe, Brough, 2015)	Indirect deflection of unclipped sleeper under a known falling mass Static support system stiffness without a live train wheel load	Assumptions of linear load distribution in depth to provide deflection of nearby track, uncertainty due to model dependency Neglects the uneven stress distribution below sleepers e.g due to voiding

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Table 2 Sites and trains characteristics

Site	Type of line	Type of track form	Fastening system
1	Test track (Rail Innovation and Development Centre)	PORR IVES Ballasted renewed	Vossloh DFF300 Vossloh DFF304 Pandrol Fastclip FC clip
2	High speed (East Coast Main Line)	Transition zone prior and after renewal	Pandrol Fastclip FC clip

Site	Type of loading	Speed	Set car	Car length	Static wheel load magnitude
1	Locomotive + 2 Sea Urchin wagons	2 to 20 mph	Locomotive		81.5 kN
			Wagon	6.3 m	66.25 kN
2	Intercity 125 (11 cars)	Up to 125 mph	Locomotive Class 43 Bogie spacing Wheel spacing	17.8 m 10.3 m 2.6 m	87.8 kN
			Coach Mark 3 Bogie spacing Wheel spacing	23 m 16 m 2.6 m	52.1 kN
	Class 222 (5 cars)	Up to 125 mph	Carriage	22.8 m	56-68 kN

Table 3 Stiffness characteristics evaluated from VG data and known load using BOEF.

Site			1b		
Track form			**IVES**	**PORR**	**Ballasted renewed**
Symbol	**Description**	**Units**			
EI CEN 56	Rail flexural rigidity	$MN.m^2$	4.987	4.987	4.987
Q		kN	66.25	66.25	66.25
$s_{trackbed}$	Trackbed stiffness	MN/m	51.0	62.3	24.3
$s_{railpad}$	Railpad stiffness	MN/m	14.5	27.1	84.2
$k_{railpad}$	Railpad modulus	MN/m^2	22.3	41.7	129.5
$k_{trackbed}$	Trackbed modulus	MN/m^2	78.5	95.8	37.4
k_{system}	System modulus	MN/m^2	17.4	29.1	29.0
L	Characteristic length	m	1.04	0.91	0.91
S_{system}	Global system stiffness	MN/m	36.0	53	53
δ	Rail deflection	mm	1.84	1.25	1.25

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Figure captions

Figure 1. Results from BOEF for (a) various trackbed stiffness and (b) various support system moduli

Figure 2. (a) IVES track, (b) ballasted track

Figure 3. (a) Time-deflection plots of IVES, PORR and ballasted track under low speed train passage (b) comparison among maximum deflections.

Figure 4 Examples of time –deflection plots of rail web positions in the transition zone under the same passage of Intercity 125.

Figure 5. Comparison of rail deflections prior and after renewal

Figure 6. Comparison between renewal phases of (a) global track stiffness, (b) support system stiffness, (c) track system moduli and (d) support system moduli

Figure 7. Deflection bowl of the transition zone (a) prior to renewal due to Class 222 first wheel passage and (b) prior to renewal due to Class 43 and (c) after renewal due to Class 43

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Figure 1a

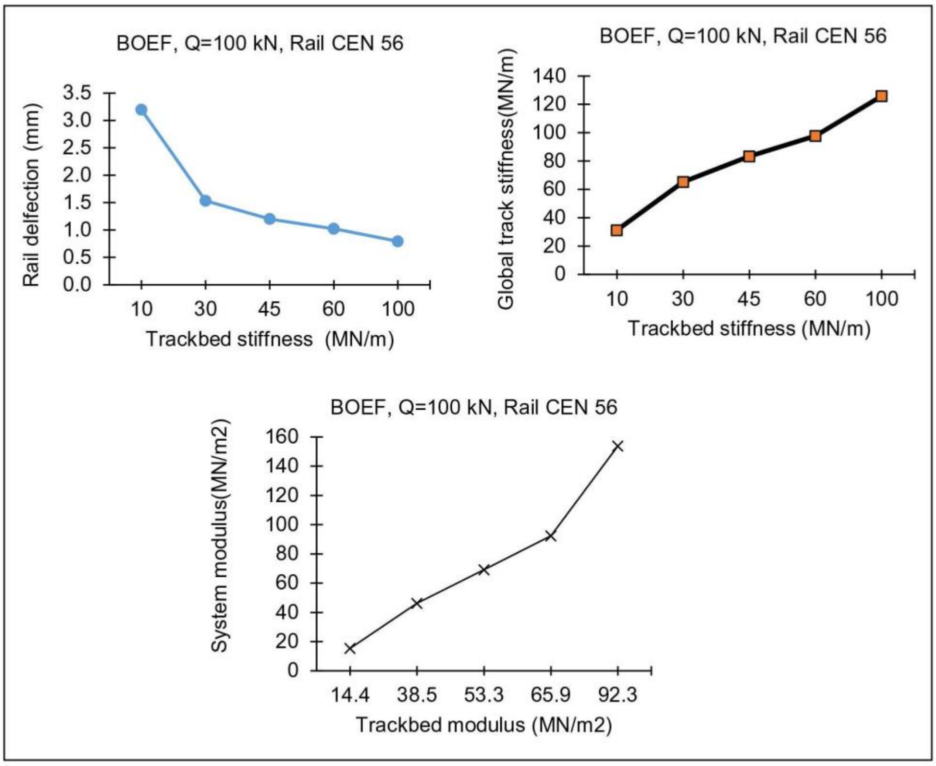

Figure 1b

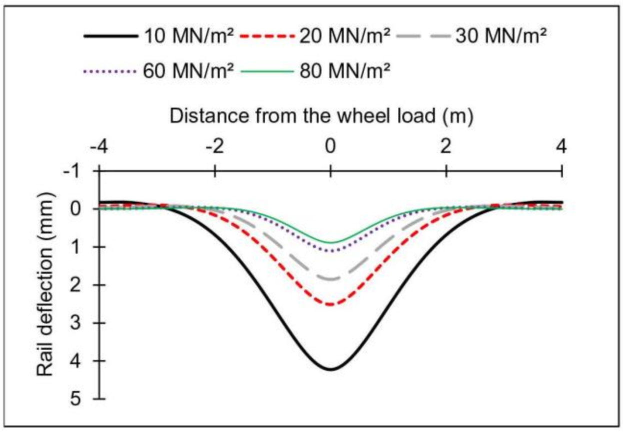

Figure 1.tif

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2a.jpg

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2b.jpg

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Figure 3a

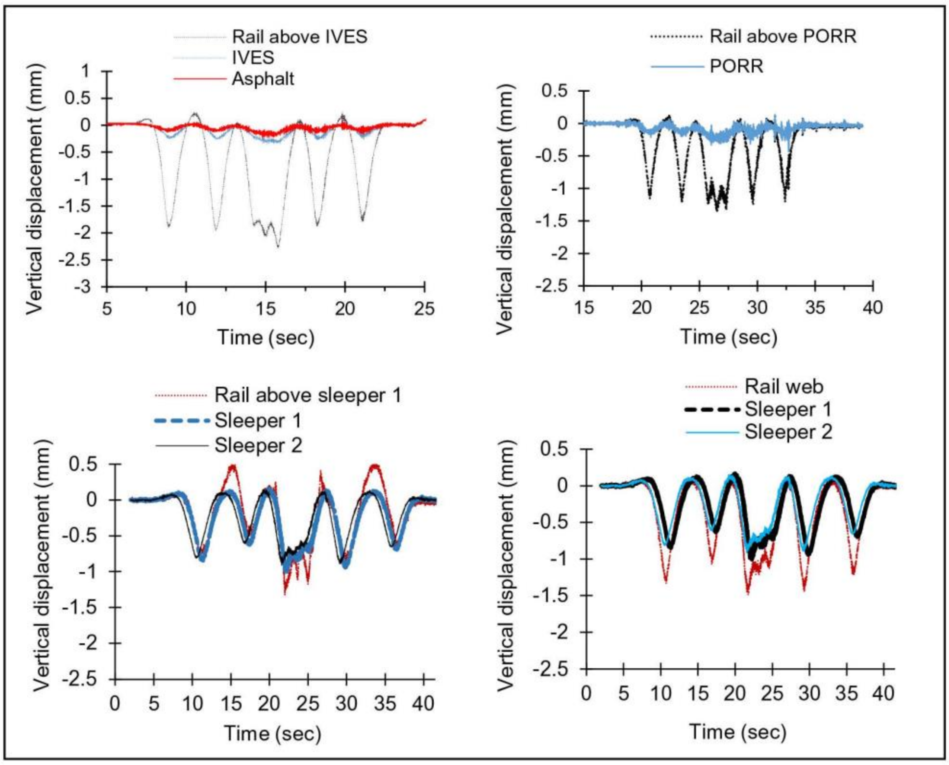

Figure 3b

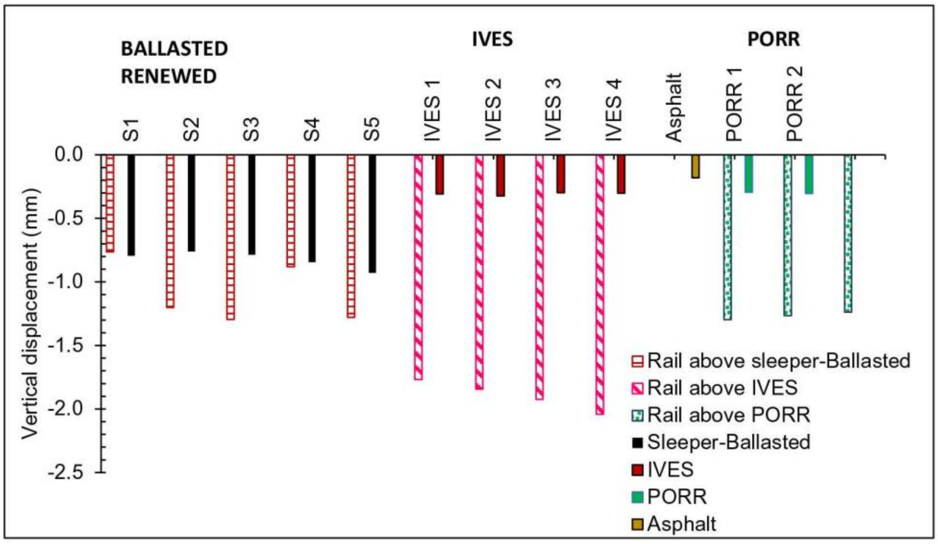

Figure 3.tif

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Figure 4

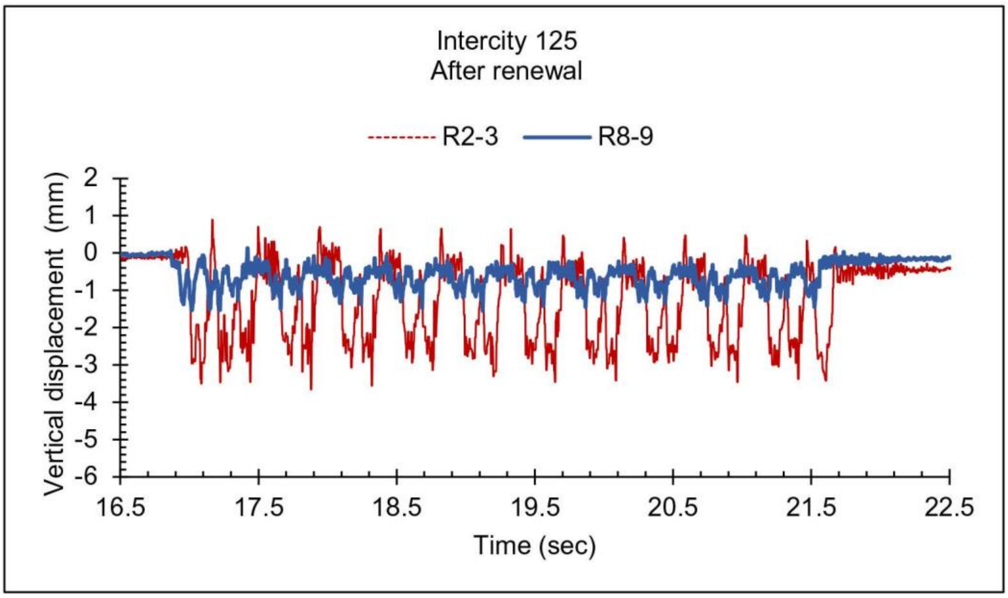

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Figure 5

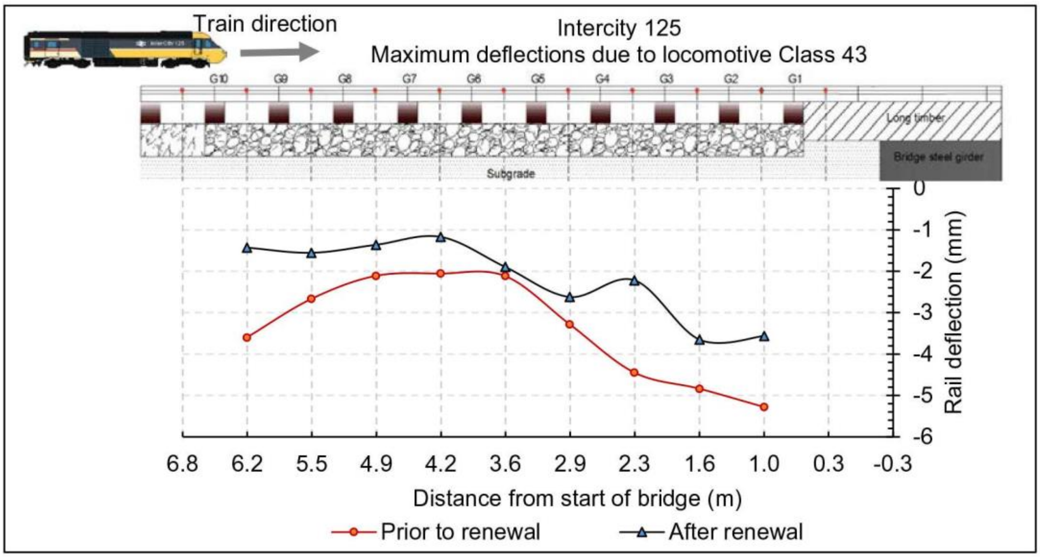

Figure 5.tif

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Figure 6a

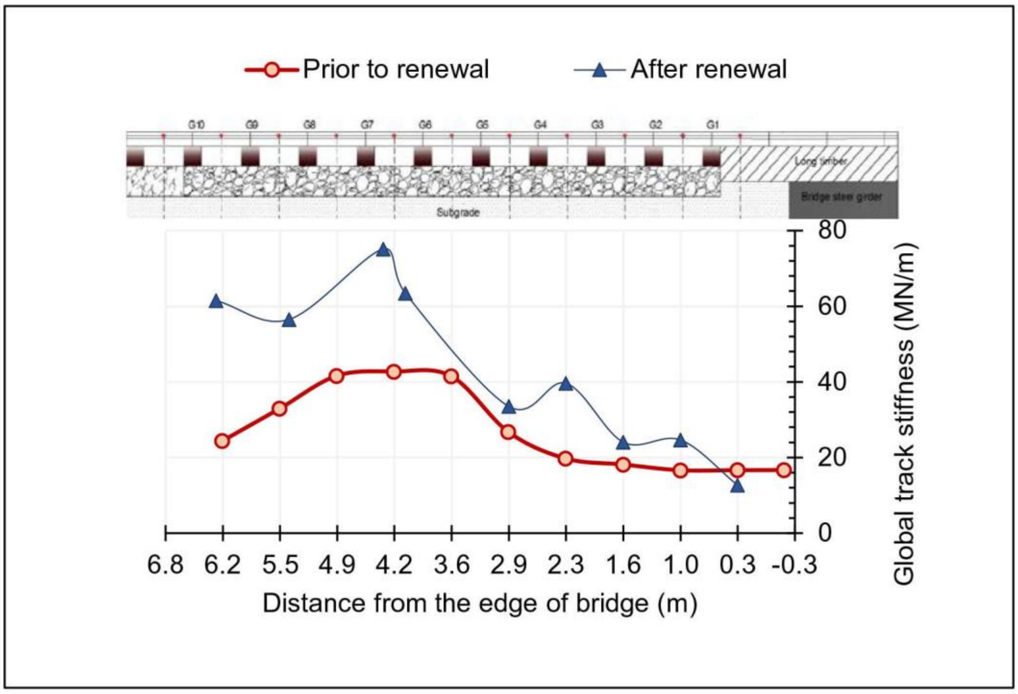

Figure 6a.tif

Figure 6b

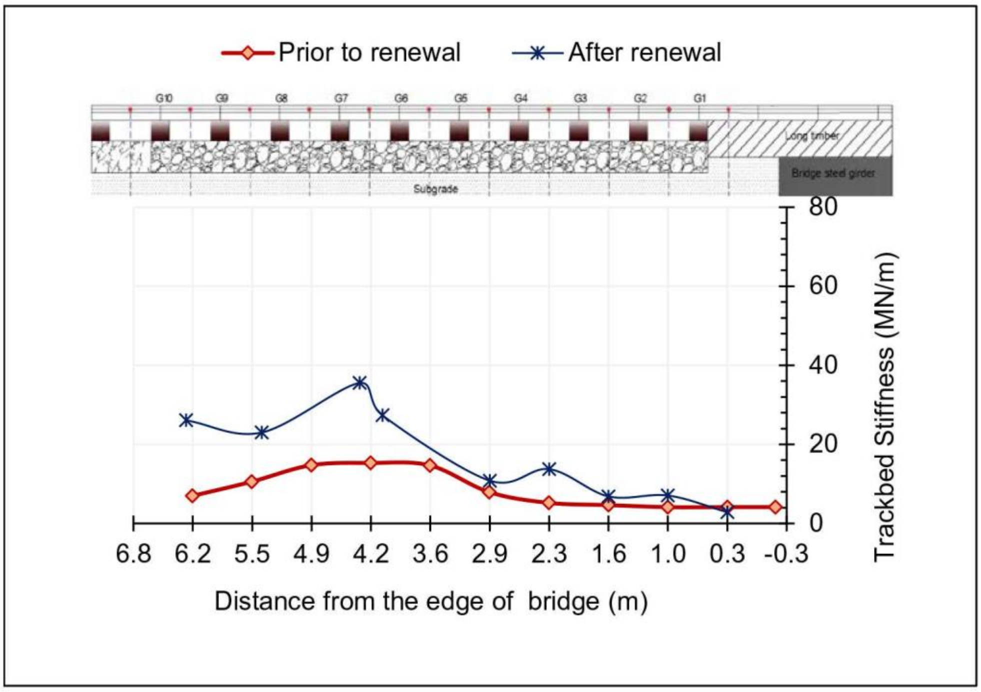

Figure 6b.tif

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Figure 6c

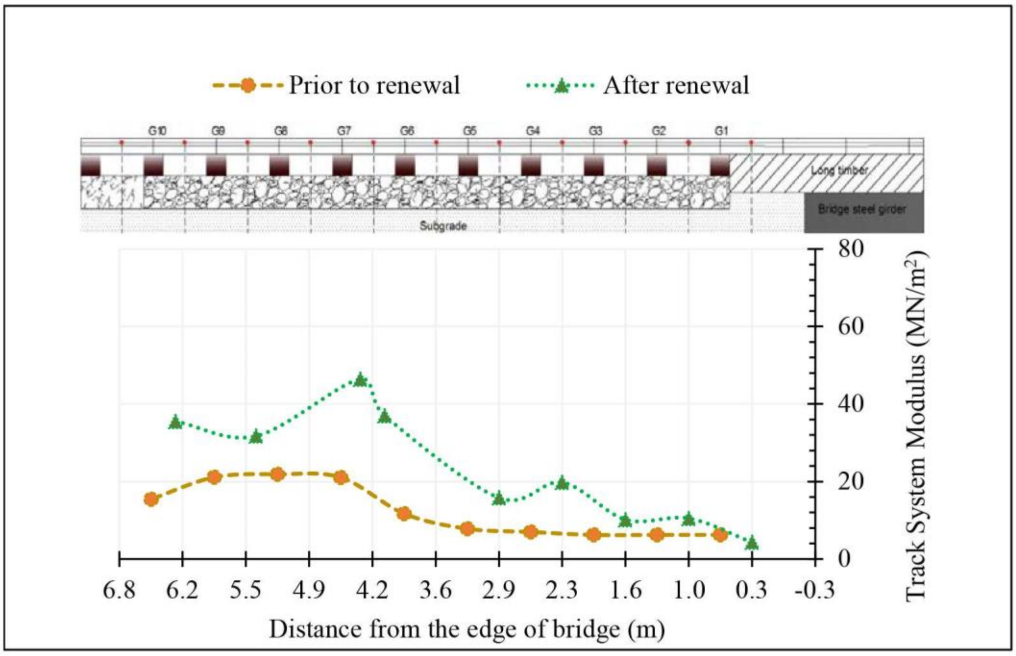

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Figure 6d

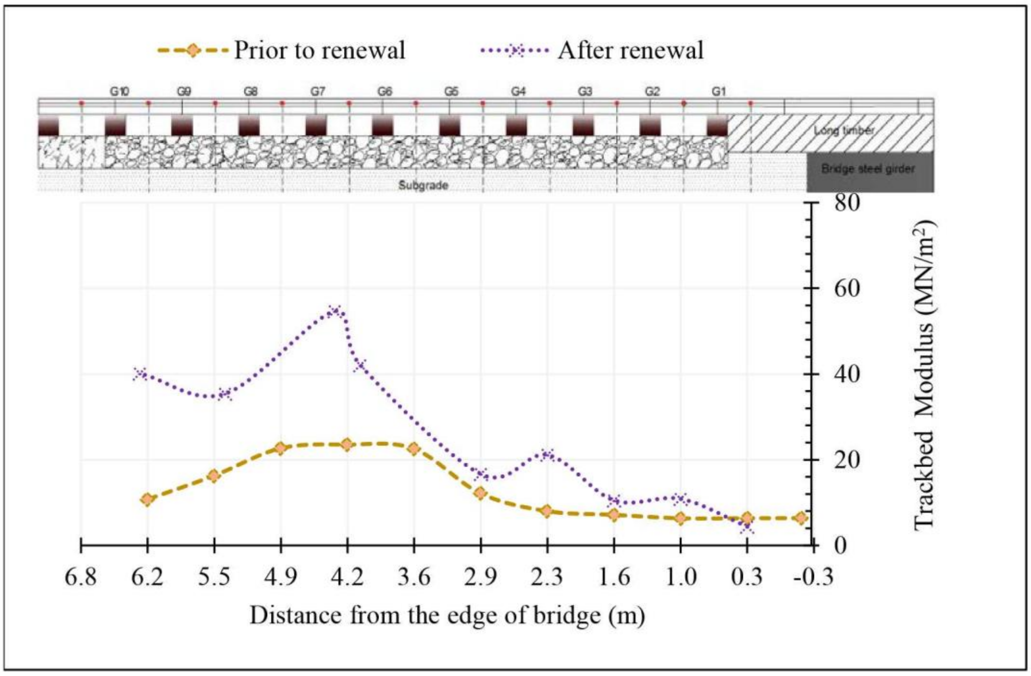

Figure 6d.tif

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Figure 7a

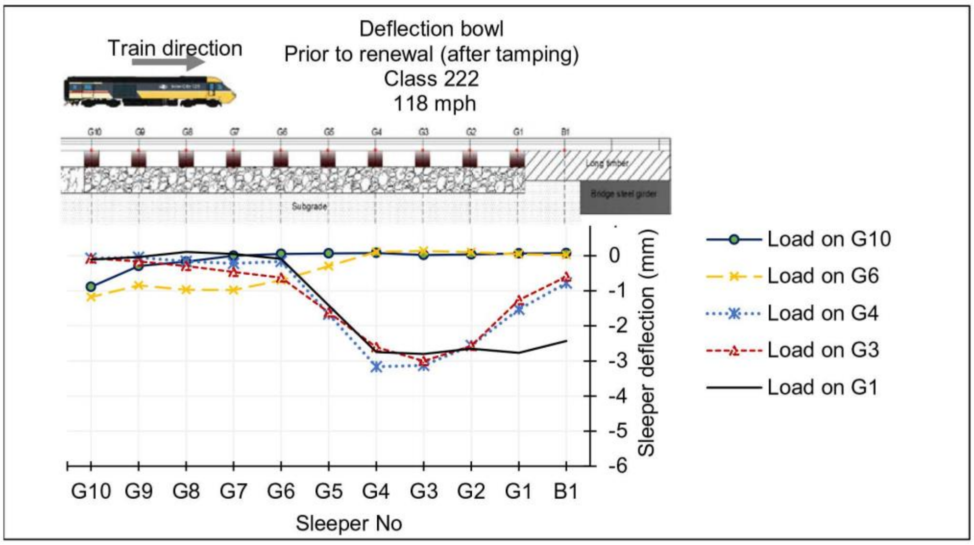

Figure 7b

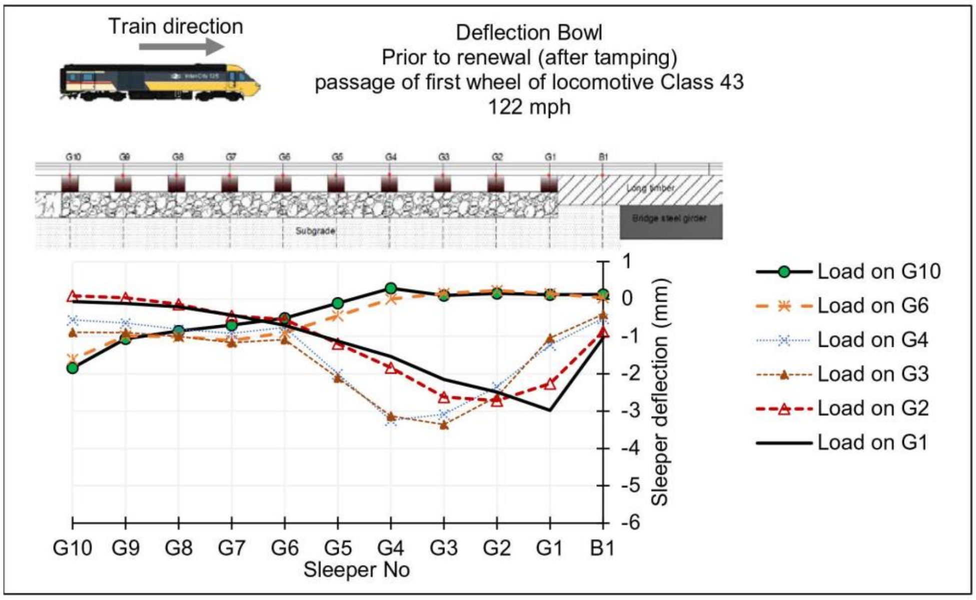

Figure 7.tif