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HYDRO-PNEUMATIC CRANE AND TRACTOR SEMI-TRAILERS: A COMPARATIVE STUDY OF THEIR DYNAMIC EFFECTS ON A SHORT-SPAN BRIDGE

Dr Rob Heywood

ABSTRACT

The dynamic response of the bridge over Coxs River (four 11.5 m spans) at Wallerawang, New South Wales, Australia to the passage of three test vehicles has been measured. The three test vehicles were:

1. a hydro-pneumatically suspended crane (AC205)
2. an air-suspended six axle articulated vehicle (BA) and
3. a steel-suspended six axle articulated vehicle (BS).

The hydro-pneumatically suspended crane performed well at Coxs River in terms of reducing the amount of allowance that should be made for dynamic effects. Its performance was particularly noteworthy when additional roughness was added in the form of a 300x25 mm plank across the road.

For the bridge over Coxs River, a dynamic load allowance of approximately 50% of the dynamic load allowance applied to general access vehicles is appropriate for the AC205 crane. This is equivalent to a reduction of approximately 10 to 15% in the calculated effects of the crane.

INTRODUCTION

The influence of heavy vehicle suspension on bridge performance has been investigated by the Australian Mass Limits Review (1996) and the OECD DIVINE (Dynamic Interaction between Vehicles and Infrastructure Experiment) international research program(Heywood & Cantieni, 1997). This research has illustrated the importance of road profile, vehicle suspension and their relationships with the natural frequencies of bridges in determining the magnitude of dynamic (and fatigue) effects induced in the worlds ageing infrastructure of bridges.

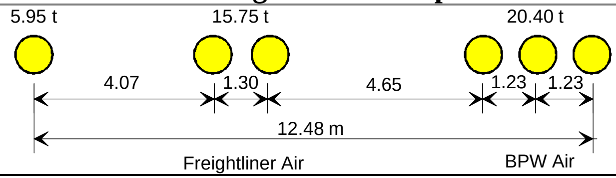
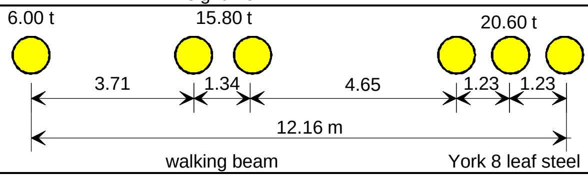
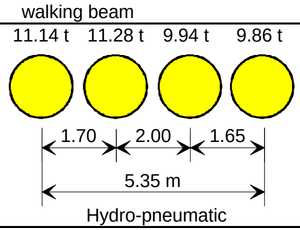
Recent developments in mobile crane technology has seen the introduction of hydro-pneumatic suspensions. Access for these highly productive cranes is limited by the strength of the bridge infrastructure. This paper investigates the hypothesis that these cranes can be permitted to carry heavier loads because they induce less dynamic effects in bridges. This has been investigated through a testing program by measuring the dynamic response of the bridge over Coxs River at Wallerawang, New South Wales, Australia to the passage of three test vehicles:

1. a hydro-pneumatically suspended crane (AC205),
2. an air suspended six axle articulated vehicle (BA) and
3. a steel suspended six-axle articulated vehicle (BS).

DESCRIPTION OF TEST VEHICLES

The axle configuration, dimensions, types of suspension and the axle loads for the three test vehicles are summarised in Table 1. The BA and BS test vehicles were six-axle articulated, over the rear axle, tip trucks. This configuration is the most common long-haul road transport vehicle used in Australia. The test vehicles are relatively short examples of six-axle articulated vehicles, thus maximising effects in short span bridges such as Coxs River.

Table 1: Test vehicle configurations and suspension types.

Vehicle Code	Vehicle configuration & suspension	Nominal Gross Laden
BA		42.1 t
BS		42.5 t
AC205		42.2 t

The BA and BS vehicles were loaded to their 42.5 t legal limit (steer = 6 t, tandem = 16.5 t and tridem = 20 t). The vehicles fitted with different types of suspension, the vehicles were configured with either air (BA) or conventional mechanical steel suspensions (BS).

Figure 1 Air suspension - BA trailer

In the case of the steel-suspended vehicle (BS), York eight-leaf spring suspension were used for the tridem group and a Hendrickson walking beam steel suspension for the tandem. Note that the steel suspensions used during these tests rely on damping from the coulomb friction of the steel leaves only. The general arrangement of the York type suspension is given in **Figure 2**

The suspensions were characterised in terms of natural frequency and damping (Sweatman et. al. 1994). Testing involved slowly driving the vehicle off 80 mm blocks and recording the dynamic response of the vehicle in accordance with the European Community (EC) drop test which defines a "road-friendly" suspension as one with a natural frequency of less than f = 2.0 Hz and damping coefficient greater than ζ = 20%. Test results indicated that the BA suspension was road friendly (tractor: f = 1.45 Hz, ζ = 20%; trailer: f = 1.4 Hz, ζ = 35%) whereas the BS trailer suspension was not (tractor: f = 2.75 Hz, ζ = 6%; trailer: f = 3.2 Hz, ζ = 10%). Tyres of the same size (11R22.5 and 700 kPa) and manufacturer were used on the prime-movers and tri-axle groups.

Figure 3 Demag AC205 Hydro-pneumatic Crane

The AC205 crane featured hydraulic rams acting as the suspension and equalising elements. The oil content and gas pressure in the accumulators can be varied to permit suspension to be adjusted using bellows-type hydro-pneumatic reservoirs for good ride and handling performance at highway speeds.

Figure 4 Hydro-pneumatic suspension of Demag AC205 Crane

DESCRIPTION OF BRIDGE AND INSTRUMENTATION

The four-span, two-lane bridge over the Coxs River is located in the township of Wallerawang, west of Lithgow, New South Wales, Australia (refer **Figures 5 and 6.**). This bridge was constructed in 1945 using 670 mm steel "I" beams (24″ x 7.5″ x 95 lb/ft) supporting a 180 mm thick reinforced concrete deck. There is no shear connection between the deck slab and the steel girders. Relative movement between the girders and the deck slab was observed during proof load testing of this bridge. The bridge is supported on reinforced concrete piers and abutments and has a total length of 46.1 m with four simply supported spans of L = 11.65 m, 11.45 m, 11.45 m and 11.55 m. All spans are fixed at one end and have an expansion joint at the other end. The expansion bearings were constructed from steel and brass strips. Movement in these bearings was not evident. The width between kerbs is 6.5 m with a 1.2 m footpath which has been added to the western side of the bridge in recent years. This footpath has limited influence on the stiffness or the mass of the bridge.

As large loads are often carried over the bridge to the nearby power plant, the bridge has been strengthened by props positioned at mid-span. During the tests, the props were lowered to allow an investigation of the original structure (refer Figure 5.).

Using typical displacement time signals, the dynamic properties of the bridge were determined from the free vibration of the bridge after the passage of test vehicles. The frequency and damping of the first vertical bending mode was determined to be f = 10.2 Hz and ζ = 4.5%. This is a very high level of damping for a bridge. As a result, the dynamic response of this bridge is significantly smaller than bridges with similar natural frequencies (refer Heywood, 1995b).

The road profile was quite good as illustrated by **Figures 7 and 8**. An 300x25 axle hop plank (AHP) was added over pier 2 to simulate local defects such as a pot hole or poor joint.

Bridge Instrumentation

The bridge was instrumented to determine the vertical displacement at four points. Strain gauges and accelerometers supplemented the deflection data. For the vertical displacement measurements, inductive displacement transducers (Hottinger-Baldwin HBM W10 and W20) with a measurement range of ±10 mm and ±20 mm were installed on the underside of the bridges using a spring and wire technique. Three of the four displacement transducers were concentrated in span 2 immediately after the axle-hop plank (AHP) for vehicles travelling towards Lithgow (northbound). In addition, axle detectors were used to record the time when each axle entered or exited the bridge. The speed and direction of the test vehicles was deduced from this data.

The abbreviation used to identify a displacement measurement point is D(x,y). "D" means deflection measurement point, "x" identifies the span number and "y" the deck plank or girder number. Spans are numbered from Abutment A and girders/deck planks from the left. D(3,2). Strains follow the same format i.e. S(x,y).

Data Acquisition

Data was collected using a Blastronics BMX data acquisition systems. The system was triggered via the axle detectors placed at each abutment. The data acquisition system's pre-trigger recording system was used to record the response of the bridge prior to the test vehicle entering the bridge. The sampling duration was sufficient to allow the vehicle to cross the bridge plus a further allowance to measure the frequency and damping from the free vibration of the bridge.

The bridge and vehicle responses were recorded at a sampling rate s = 200 Hz except for speeds v < 30 km/h which were sampled at s = 50 Hz. The signals from the bridge and vehicle transducers were conditioned adjacent to the transducers before passing through a 50 Hz anti-ailasing filter

TEST PARAMETERS

Research has shown that the dynamic response of a bridge is sensitive to bridge natural frequency and damping, road roughness, vehicle speed, suspension type, vehicle mass and number of vehicles present on the bridge. Multiple vehicle effects and the influence of gross laden mass are not considered in this research. Since this research was carried on a single bridge, the influence of natural frequency and damping of the bridge could not be varied. The gross laden mass of the vehicle was also kept constant. The influences of the road roughness, vehicle speed and suspension characteristics were investigated by undertaking a series of tests incorporating the parameters set out below:

- vehicles
  - BA - six-axle articulated with air suspension
  - BS - six axle articulated with steel suspension
  - AC250 - 4 axle hydro-pneumatic suspended crane
- vehicle speed: crawl to 100 km/h at 5 to 10 km/h increments
- axle-hop plank (300 x 25 mm): with and without (fitted over pier 2)

The test vehicles were driven in both directions down the centre of the bridge. Close proximity to an intersection limited the speed in the southbound direction to 50 km/h.

BRIDGE RESPONSE

Typical bridge responses

Samples of the dynamic response of the bridge recorded during the passage of the three test vehicles are presented in **Figure 9 through Figure 11**. In all cases, deflection D(2,3) has been chosen as it consistently proved to be the largest deflection. Comparisons indicate that deflections associated with the crane are significantly greater than of the other two test vehicles. This reflects its small wheel-base.

Crawl Speed Response

The maximum strains and deflections recorded during the passage of the AC205, BA and BS vehicles are summarised in **Figure 12 and Figure 13**.

The response of the bridge (both deflection and strain) caused by the crane at crawl speed is 1.5 to 2 times larger than the response caused by the BA and BS vehicles. This is due to the load configuration of the vehicles (*Table 1*) as there is little dynamic effect at slow speeds. On average, the crane induced effects that are 1.6 times that of the BS vehicle and 1.7 times that of the BA vehicle at crawl speeds.

Maximum Dynamic Response

The maximum dynamic deflections and strains recorded (all speeds, without axle hop plank) for the test vehicles travelling in a northerly direction over the Coxs River bridge are presented in **Figure 14 and Figure 15**. These results show:

- the response due to the crane at maximum speed is 1.2 to 1.8 times larger for the crane than for the BA and BS vehicles. On average, the crane effects are 1.64 and 1.35 times the maximum effects introduced by the BA and BS vehicles respectively. Thus the performance of the crane relative to the BA and BS vehicles is better at speed that at crawl.

- the difference in responses due to the steel suspended and air suspended vehicle is greater at speed. The relative improvement is 6% against the BA vehicle and 17% against the BS vehicle over the speed range tested.

Dynamic increment

The maximum dynamic response of a structure to the passage of a vehicle is a function of many parameters. These can be sub-divided into stationary effects and dynamic effects:

Stationary effects:
- vehicle mass,
- axle configuration and distribution of mass and
- span length & bridge configuration.

Dynamic effects:
- road profile
- speed
- natural frequency & damping of bridge
- natural frequency and damping of vehicle and
- the interactions between the above.

The response of a bridge to a stationary vehicle (A_{stat}) can be determined using well established structural analysis procedures. A_{stat} includes all the stationary effects listed above and thus forms the basis from which the dynamic effects are considered. The dynamic increment ϕ compares the maximum dynamic bridge deflection A_{dyn} and the maximum static deflection A_{stat} in accordance with the definition presented in Figure 11).

The tests were undertaken with and without a 300 x 25 mm axle hop plank in place over the pier immediately before the span of the bridge being tested (**see Figure 16**). The axle hop plank causes the axles to oscillate (or hop) with greater amplitude. These two groups of tests are discussed below.

The graphs of dynamic increment (ϕ) versus speed (v) without the axle hop plank (AHP) in place are presented in **Figure 17**. The maximum ϕ's are associated with the BS vehicle. For some speeds the ϕ for the AC205 are smallest and other speeds the BA vehicle generates the smallest ϕ. It should be noted that the AC205 crane could not achieve the same speeds as the BA and BS vehicles due to the proximity of the intersection.

The dynamic increments for the Coxs River bridge are all less than the Austroads Bridge Design Code (1992) recommended values for the dynamic load allowance (DLA) which is 25% for bridges of this natural frequency.

The addition of the axle hop plank (AHP) causes the dynamic increment (ϕ) for the BA and BS vehicles to increase but to hardly change the ϕ associated with the AC205 crane. It would appear that the extra short-wavelength roughness has been absorbed by the crane without additional excitement being evident in the bridge.

Maximum Dynamic Increment

Figure 19 and Figure 20 show that the maximum dynamic increment due to the steel suspended vehicle is much greater than the maximum dynamic increment of both the crane and the air suspended vehicle.

Table 2: Comparison of Maximum Dynamic Increments (fmax) without AHP

Transducers	AC205	BA	BS	Crane/BA	Crane/BS
D(2-2)	14%	16%	29%	0.9	0.5
D(2-3)	10%	13%	26%	0.8	0.4
D(2-4)	7%	14%	30%	0.5	0.2
D(4-3)	4%	11%	21%	0.4	0.2
Average (deflections)				0.6	0.3
S(1-3)	7%	9%		0.8	
S(2-2)	11%	19%	37%	0.6	0.3
S(2-3)	13%	12%	26%	1.1	0.5
S(2-4)	3%	17%	40%	0.2	0.1
S(3-3)	12%	12%	26%	1.0	0.5
Average (strains)				0.7	0.3

On average, the dynamic increment (ϕ) associated with the AC205 crane is 1/3 and 2/3 of ϕ for the BS and BA vehicles respectively.

DISCUSSION

The traffic loads applied to bridges are considered to be the effects induced when the vehicle is stationary on the bridge plus an allowance for dynamic effects. This dynamic load allowance (DLA) is usually expressed as a fraction of the effects induced by a stationary vehicle. In the case of the AUSTROADS Bridge Design Code (1992) the DLA varies between 20% and 40% as a function of the fundamental natural frequency of the bridge. The DLA is applied at the strength limit state and the serviceability limit state. It is also applied to single and multiple vehicle events.

One method of reducing the level of distress experienced by bridges is to reduce the dynamic components in the bridge response. Although these cannot be eliminated entirely, they can be significantly reduced by a combination of good suspension, smooth road profiles and speed. The OECD DIVINE project and the Mass Limits Review undertaken by the National Road Transport Commission in Australia investigated the hypothesis that softer (air) suspensions induce smaller loads and hence reduce damage to the road and bridge infrastructure.

A model for the relative damaging effects induced in bridges by vehicles fitted with traditional mechanical suspensions and air suspensions has been developed as part of the Mass Limits Review and is published as part of Technical Supplement 2 (Heywood, 1995a). This study was based on the results of the test program conducted for the OECD DIVINE project, the laws of physics and a significant measure of engineering judgement. It concluded that vehicles fitted with highly damped air suspensions were likely to result in reduced damaging effects except for short span bridges on average to rough roads. This was because dynamic resonance between groups of air suspended axles and short span bridges was observed at axle-hop frequencies f = 8 to 15 Hz or span = 15 to 8 m.

The bridge over Coxs River has its fundamental natural frequency in this axle hop frequency range but it does not dynamically couple with axle-hop vibrations because of its high level of damping. At Coxs River, this damping is associated with the reinforced concrete slab sliding over the girders during the passage of vehicles and thus acting like a large leaf spring. Consequently the dynamic response was smaller than that desired for this test.

The AC205 crane induced approximately 1.6 times the effects associated with the BA and BS test vehicles at crawl speeds. This is as expected and is consistent with structural engineering theory.

The dynamic increment ϕ associated with the crane was similar to that of the air suspension when the road was in its natural state. The addition of the axle hop plank (300 x 25 mm) to the road profile did not influence the ϕ associated with the AC205 but caused significant increases in ϕ for the BA and BS vehicles, thus providing evidence to support the notion that the hydro-pneumatic suspension of the AC205 is very effective in smoothing out short imperfections in the road profile. For the Coxs River bridge, the AC205 seems to be at least as good as the BA suspension.

The AC205 operates with large tyres which give the impression of being soft and suggesting that the axle-hop frequencies of the crane would be lower than those associated with heavy commercial vehicles. If this is true there will be less likelihood of dynamic coupling between the Coxs River bridge and axle-hop of the AC205. It is also noted that the axle spacing between the axles of the AC205 are unequal. As a consequence the vibrations of the axles are likely to be out of phase with each other in the axle hop frequency range. In addition, the overall softness of the hydro-pneumatic suspension means that the AC205 has the ability to smooth out many features in the road profile without inducing large dynamic wheel forces. It is suggested that these factors combine to result in the AC205 inducing smaller dynamic effects in the Coxs River bridge.

Unfortunately the expected performance for bridges with different natural frequencies and damping due to the passage of the AC205 cannot be extrapolated with confidence from a single bridge test, especially one with unusually high damping. The frequencies evident in the axle motions are necessary to gain a basic level of understanding of the dominant frequencies evident in the dynamic wheel forces. Once these frequencies are known, those bridges where quasi-resonance effects are likely can be identified. Further testing / dynamic modelling of bridges with these natural frequencies would provide valuable information in determining the bounds for the dynamic effects induced by cranes such as the AC205.

The results of this test do however suggest that the dynamic response of most bridges to the AC205 will be on a par, if not better, than air suspended vehicles. The evidence of the Coxs River test indicate that the AC205 induces approximately 1/3 of the dynamic effects by conventional mechanically sprung commercial vehicles. If this can be demonstrated to be true across the bridge system then there is a strong argument to recommend that the DLA used in association with cranes like the AC205 be smaller, say 50% smaller, than those used for general access traffic. This would lead to reductions in the calculated effects induced in bridges by this style of crane by 10 to 15%.

CONCLUSIONS AND RECOMMENDATIONS

The experimental results have been presented for the passage of the following three tests vehicles across the bridge over Coxs River at Wallerawang:

1. a hydro-pneumatically suspended crane (AC205)
2. an air-suspended six axle articulated vehicle (BA) and
3. a steel-suspended six axle articulated vehicle (BS).

For the bridge over Coxs River, the average of the maximum dynamic increments (ϕ) for 9 bridge deflections and strains corresponding to the AC205 crane was approximately 1/3 and 2/3 of the ϕ associated with the BS and BA vehicles respectively. Its relative performance improved further when additional roughness was added in the form of a 300x25 mm plank across the road.

Additional information / research is required before reductions in the recommended dynamic load allowance can be made for the bridge infrastructure. It is recommended that the following hypothesis be investigated:

That the dynamic load allowance used when evaluating the effects of hydro-pneumatically suspended cranes such as used on the Demag AC 205 crane be taken as 50% of the dynamic load allowance specified by the AUSTROADS Bridge Design Code for general access vehicles. i.e.

$$DLA_{AC205} = 0.5 \cdot DLA_{AUSTROADS\ BDC}$$

The methodology would involve at least the following:

1. the collection of data regarding the frequencies of the dynamic wheel forces of the AC205 crane,

2. the interpretation of this data to identify bridges which are likely to be susceptible to the particular frequencies evident in the dynamic wheel forces and

3. the measurement of the dynamic response of some selected bridges to the passage of the hydro-pneumatically suspended cranes such as the AC205. There is a possibility that this could be done in association with other bridge testing / research activity. The test program should include other known vehicles and preferably other cranes with traditional suspensions.

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AUTHOR BIOGRAPHIES

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Dr Heywood is a recipient of the WH Warren Medal (Institution of Engineers, Australia) and the Babcock Australia, Institution of Engineers Australia Centenary Scholarship.

Dr. Heywood's interests centre on improving the efficiency of transport by considering heavy vehicles, bridges and roads as inter-related elements in the transport system. Recent highlights include the development and application of instrumentation to assist in the evaluation of bridges, the development of the next generation AUSTROADS Bridge Design load, participation in the OECD DIVINE (dynamic interaction between bridges and vehicles experiment) international expert group, identifying damaging features in road profiles, and the development of bridge health monitoring technology.

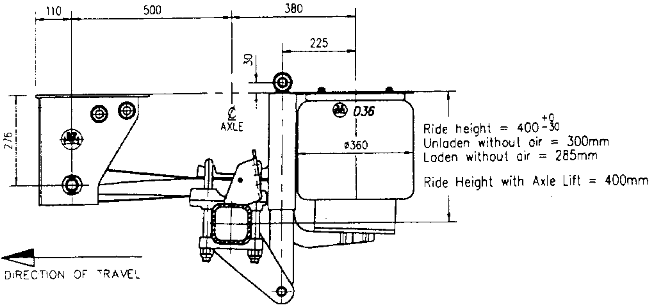

Figure 1 Air suspension - BA trailer

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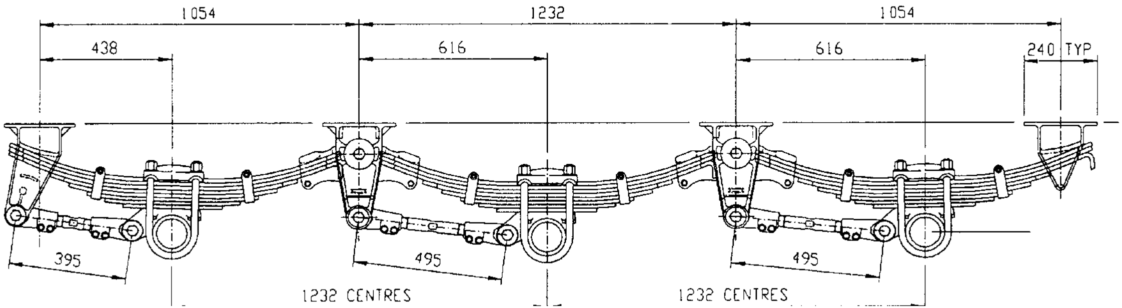

Figure 2 Steel suspension - BS trailer

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Figure 3 Demag AC205 Hydro-pneumatic Crane

The AC205 crane featured hydraulic rams acting as the suspension and equalising elements. The oil content and gas pressure in the accumulators can be varied to permit suspension to be adjusted using bellows-type hydro-pneumatic reservoirs for good ride and handling performance at highway speeds.

Figure 4 Hydro-pneumatic suspension of Demag AC205 Crane

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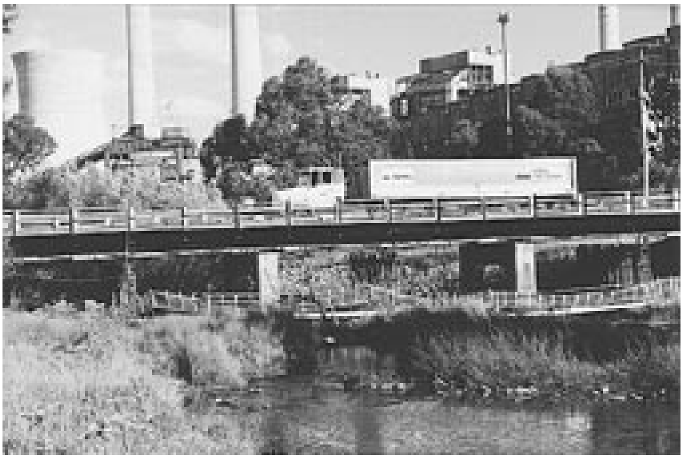

Figure 5 Test vehicle (BS) crossing the Coxs River Bridge, Lithgow, NSW

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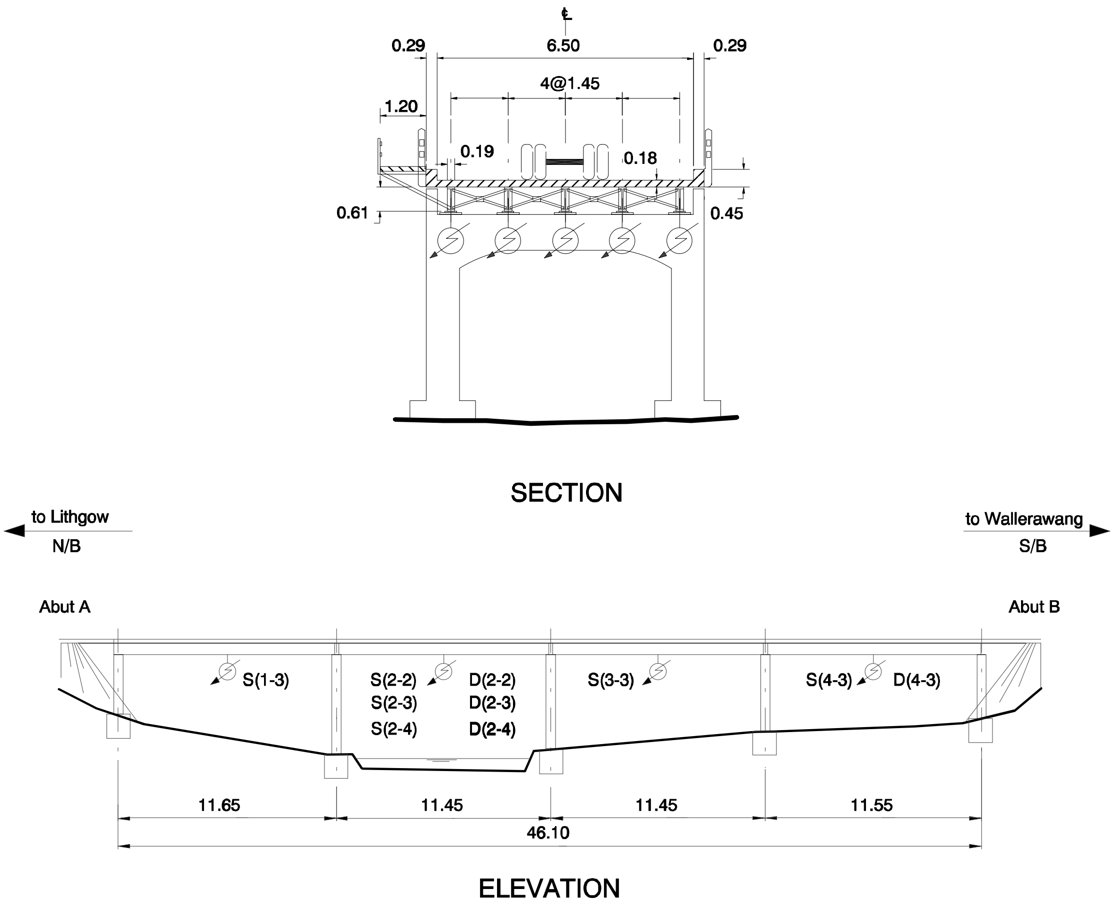

Figure 6 Coxs River - Geometry and Instrumentation layout.

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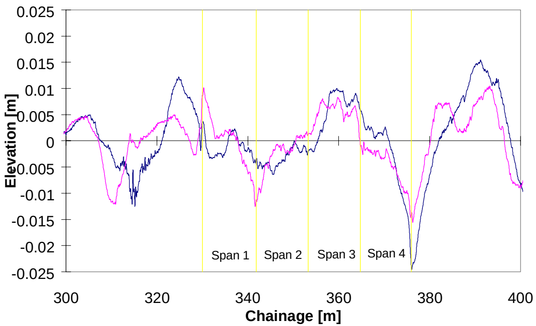

Figure 7 Profile across Coxs River Bridge, filtered to exclude wavelengths greater than 32 m

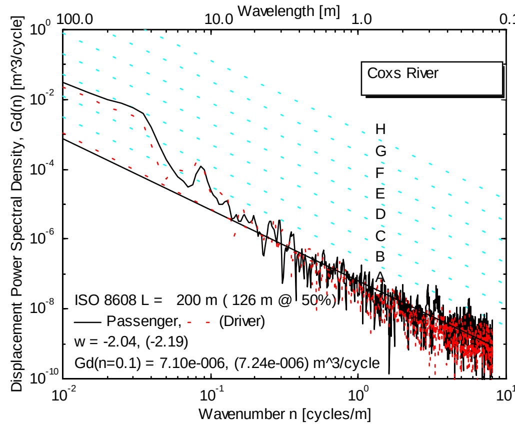

Figure 8 Power spectral density vs spatial frequency of the road profile (ISO 8608, 1995)

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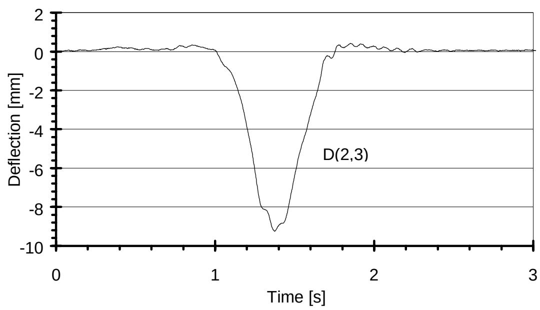

Figure 9 Coxs River Bridge, mid-span deflections for the AC205 crane, v = 82 km/h (northbound direction)

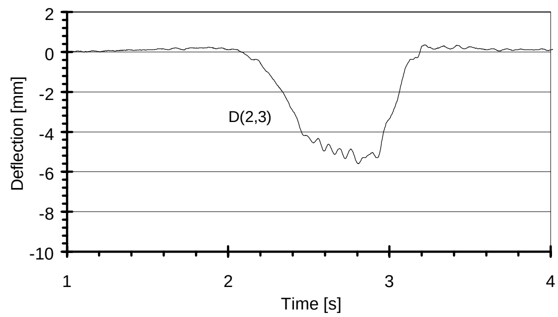

Figure 10 Coxs River Bridge mid-span deflection D(2,3) for the BA vehicle, **v = 77 km/h (northbound direction)**

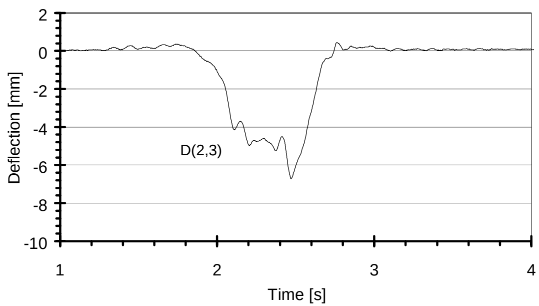

Figure 11 Coxs River Bridge, mid-span deflection D(2,3), BS, v = 96 km/h (northbound direction)

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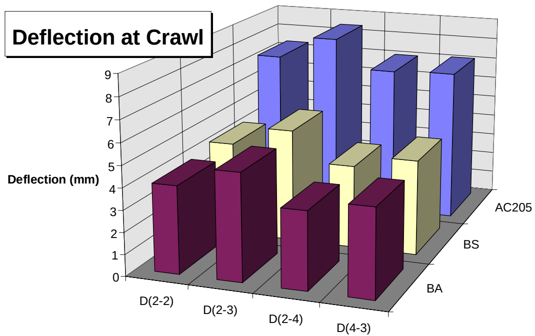

Figure 12 Comparison of Deflections at Crawl Speed

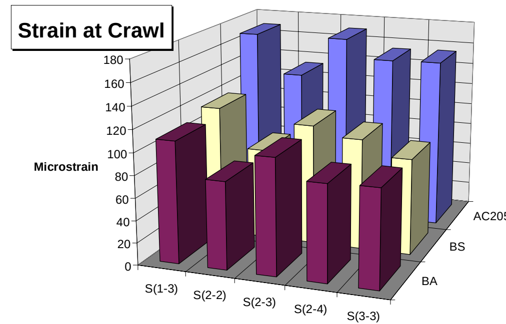

Figure 13 Comparison of Strains at Crawl Speed

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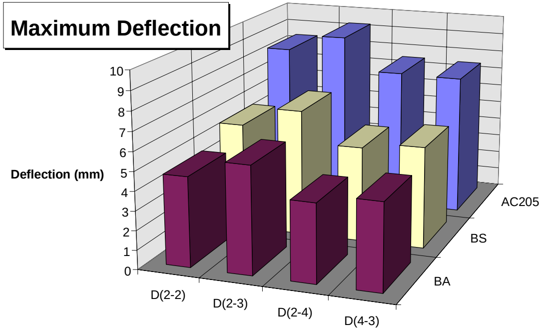

Figure 14 Comparison of Maximum Deflection

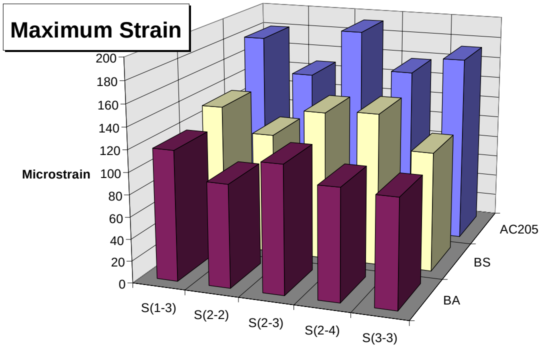

Figure 15 Comparison of Maximum Strains

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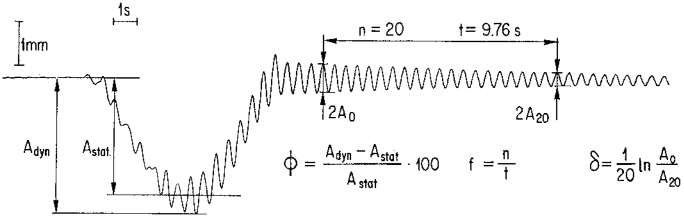

Figure 16 Time history with the definitions of the dynamic increment ϕ [%], the fundamental frequency f [Hz] and associated damping decrement δ (or, in percent of critical: $\xi = \delta/2\pi$). (from Cantieni, 1983)

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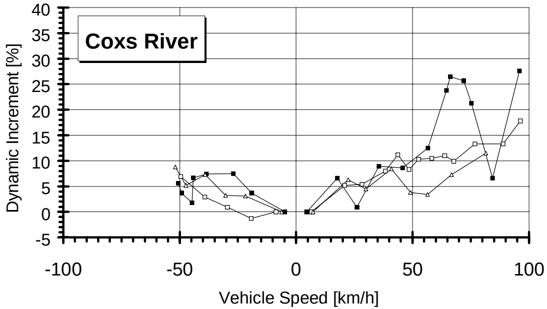

Figure 17 Dynamic increments vs. speed for Coxs River Bridge, deflection D(2,3) (+ve northbound, -ve southbound). .

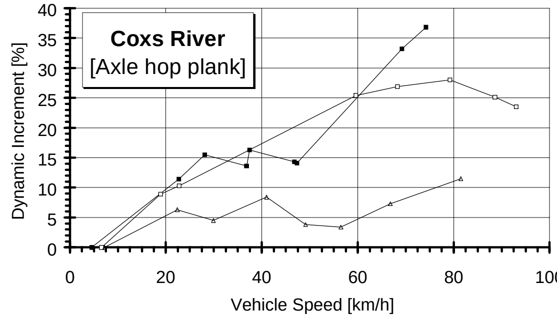

Figure 18 Dynamic increment vs. Speed for Coxs River Bridge with axle hop plank, deflection D(2,3).

Solid squares: steel suspended vehicle, open squares: air suspended vehicle, open triangles: hydro-pneumatic crane

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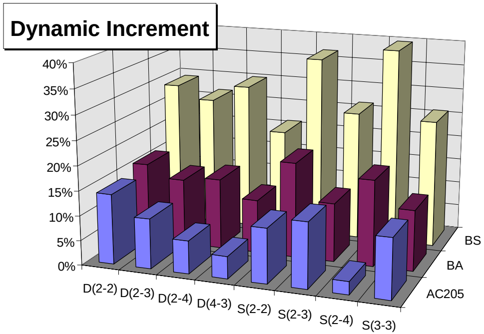

Figure 19 Comparison of Maximum Dynamic Increments

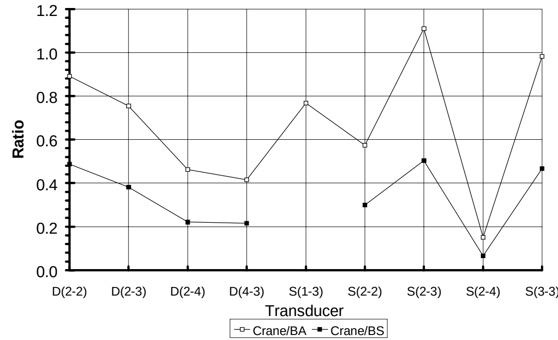

Figure 20 Ratio of Maximum Dynamic Increment (ϕ) due to the AC205 Crane to the Maximum Dynamic Increment due to the BA & BS Vehicles.

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