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DYNAMIC INTERACTION OF VEHICLES AND BRIDGES

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ABSTRACT

Many studies conducted worldwide over a period of more than a decade have confirmed that large dynamic effects can be induced in bridges by the combination of heavy vehicles and uneven road profiles. In Australia, approximately 75% of the bridges have spans between 5 and 15 m. Many of these short span bridges have shown dynamic effects due to vehicle-bridge interaction that far exceed the provisions of the current Australian Bridge Design Code, and in some cases dynamic increments in excess of 100% have been recorded, even for heavily loaded events. The introduction of the new Australian Bridge Design Standard will see the design load for bridges increase to allow for heavier and more innovative vehicles in the future, and it is important to investigate vehicle-bridge interaction associated with these future vehicle types.

This paper presents results from computer-based dynamic models that were developed to investigate the complex problem of dynamic interaction between heavy vehicles and bridges in the presence of uneven road profiles. The models were used to investigate the influence of the main parameters governing dynamic responses of bridges to the crossing of heavy vehicles, such as bridge natural frequency and damping, vehicle mass and suspension characteristics, road profiles on the bridge approaches and deck, and vehicle speed. Results from parametric studies were found to be generally consistent with field measurements and experience. The work described in this paper is part of an ongoing program of research in Australia that is aimed at delivering recommendations to AUSTROADS with respect to the dynamic load allowance both for the design of new bridges and the assessment of existing bridges.

1. INTRODUCTION

Many studies conducted worldwide over a period of more than a decade have confirmed that large dynamic effects can be induced in bridges by the combination of heavy vehicles and uneven road profiles. In Australia, approximately 75% of the bridges have spans between 5 and 15 m, and during dynamic testing using heavy vehicles, many of these short span bridges have shown dynamic effects due to vehicle-bridge interaction that far exceed the provisions of the current Australian Bridge Design Code (Austroads, 1996). In some cases dynamic increments in excess of 100% have been recorded, even for heavily loaded events.

In Australia there is continuing pressure for current bridges built throughout the last millennium to carry a diverse range of heavy vehicle configurations and types as illustrated in Fig. 1. The introduction of the new Australian Bridge Design Standard (Standards Australia, 2000) will see the design load for bridges increase to allow for heavier and more innovative vehicles in the future. Thus, it is important to understand vehicle-bridge interaction and the effects of heavy vehicles on bridges to quantify the dynamic loading to:

1. Allow the safe and efficient evaluation of the capacity of old bridges to carry present vehicles.
2. Provide design standards for new bridges that will be consistent with vehicles and bridges of the future.
3. Provide guidelines for the maintenance of road profiles to avoid unnecessarily high dynamic loadings on bridges from vehicles.

This paper looks at the issues associated with vehicle-bridge interaction in Australia, presents the development of a vehicle-bridge interaction model which was created to study the interaction between vehicles and bridges, and presents the results of a preliminary parametric study.

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2. BACKGROUND

The dynamic response of bridges is the result of a complex interaction between the bridge, the vehicle/s that cross it and the road profile. Bridge design codes generally bundle this complex interaction into a single dynamic load allowance (DLA) or impact factor that is applied to the static effects of the vehicle/s. The Austroads[2] Bridge Design Code (Austroads 1996) follows this approach. It presents the DLA as a function of bridges natural frequency for frequencies between 0 and 7 Hz. These frequencies correspond to bridges with spans of 20 m or greater. In Australia, bridges with spans greater than 20 m represent less than 10% of existing bridges by number and less than 40% by area (National Road Transport Commission, 1996). Note that new bridges generally have longer spans.

Short span bridges were not included in the original international testing program that provided the basis of the DLA provisions in the Austroads Bridge Design Code. The considerable dynamic testing of bridges conducted in Australia and New Zealand over recent years has provided considerable data associated with both short and medium span bridges (Heywood, 2000). The medium span dynamic increment (DI) data is broadly consistent with the Austroads Bridge Design Code DLA provisions but the short span DI is often significantly larger than the extrapolation of the DLA to these higher frequencies. Fig. 2 summarises the test data and shows the relationship between bridge natural frequency, span and dynamic increment.

The analysis of the experimental data from these bridge tests highlighted the influence of gross laden mass, road profile, vehicle configuration/suspension, speed and bridge natural frequency on the dynamic increment. There was a strong trend supporting a reduction in the DI with increasing mass, which is consistent with the international literature. This would lead to possible increases in load carrying capacity for older bridges provided that road profiles are maintained.

The considerable variability of the DI data is believed to be associated with variations in the road profile, test truck suspension and speed. It is clear that these parameters are important as the dynamic response of a bridge changes from vehicle-to-vehicle and the dynamic response of similar bridges varies from bridge-to-bridge. The dynamic response at one speed may be considerably different to that at other speeds. The critical speed varies widely. It may be as low as 20 km/h. For short span bridges, the critical speed tends to be between 40 and 80 km/h.

The test data shows the variability of dynamic increment on bridges and the influence of some of the parameters. Because of this variability and the expense of testing, a computer-based model was developed to study the influence of various factors on dynamic increment. The model and typical results are outlined in the following sections of this paper.

3. MODEL DETAILS

The vehicle model is an extension of the ¼-truck model developed by Prem et al (1998), consisting of a ¼-truck sprung mass with three independent axles – in place of the more usual single axle – to form a tri-axle group. The three axles traverse a simply supported single span bridge, represented by an equivalent ¼-bridge, in the presence of a road profile, as shown in Fig. 3. Either measured or artificially generated profiles can be included on the bridge and on its approaches. The model allows the user to study the interaction between the vehicles suspension, the road profile and the bridge, which deflects as the vehicle traverses the bridge.

3.1 Vehicle Model

3.1.1 General Description

The ¼-truck tri-axle group vehicle model consists of a sprung mass, and three (3) unsprung masses representing the vehicle body and the three individual axles respectively. The model has four degrees-of-freedom, one degree-of-freedom in bounce for the sprung mass (vehicle body), and one for each of the three unsprung masses (axles). The model features non-linear spring and damper elements in the suspensions. The axles are connected to the road profile through a linear spring and viscous damper that represents the tyre.

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[2] Austroads is the association of Australian and New Zealand road transport and traffic authorities.

3.1.2 Tyre-Road Contact

Contact between each tyre and the road profile is accounted for through the contact patch, with a fixed length moving average simulating the way the tyre envelopes small bumps and short, sharp, uneven features.

3.1.3 Air and Steel Suspensions

The suspension between the vehicle body and axle is modelled using two different types of non-linear spring, one that is based on the published models developed by Fancher et al (1980) representing a multi-leaf steel spring suspension Fig. 5(a), and one for an airbag suspension Fig. 5(b). The air spring model was developed from first principles assuming an adiabatic/isothermal gas compression/expansion thermodynamic process, which acts adiabatically for dynamic loads and isothermally for static loads. The isothermal feature allows the change in the air suspension stiffness with higher loads on the truck to be modelled, whereas the adiabatic feature accounts for the "stiffer" response from the air spring in the absence of heat transfer between the gas contained in the airbag and its surroundings when the excitation frequencies are higher (Prem et al, 1998).

3.1.4 Dampers

For both steel and air suspensions, a non-linear viscous damper has been added, similar to the one described in Prem et al (1998). The amount of damping in rebound (when the distance between the ends of the shock absorber is increasing) changes from low to high when a certain stroke velocity has been exceeded; in bump a single value of damping is used. This is consistent with the measured characteristics of shock absorbers reported by others, as discussed in Prem et al (1998).

3.1.5 Suspension Tests and Parameters

To tune and validate the parameters for the models, standard tests were applied. The responses from the model were analysed for natural frequencies and damping levels (bounce and wheel-hop modes) and compared with those published in literature (see, for example, OECD, 1997; Woodrooffe, 1996). For the sprung mass bounce frequency the pull-up method was used (Anon, 1992), requiring the chassis of the vehicle (sprung mass) to be raised 80 mm above the axle and released from this position. The subsequent oscillations are analysed to determine the natural frequency and damping of the body bounce mode. To check the wheel-hop frequencies and damping levels the axles were displaced from their equilibrium positions and the subsequent free-vibration was analysed.

Analysis of the vehicle body oscillation from these tests for the steel and air suspension are listed in Table 1. Also listed in this table are results of axle hop tests conducted on the model. The model results compare well with published (OECD, 1997; Woodrooffe, 1996) and demonstrate the ability of the model to reproduce the key behaviour of air and steel suspensions. By changing suspension and damper characteristics it will be possible to model and evaluate the effect of suspension modifications, or, for example, air suspensions with failed dampers, vehicle behaviour and more importantly the effect of these suspension characteristics on bridges.

3.2 Bridge Model

In Australia short span simply supported bridges, such as those illustrated in Fig. 1 and Fig. 6 dominate the nations bridge inventory, as shown in Fig. 4. Thus the bridge model developed at this stage represents a simply supported single span, though it can be extended to model simply supported multiple span bridges. The model consists of a single degree-of-freedom linear model with the addition of transformations to account for the position of the vehicle on the span. The bridge is modelled as a mass on a linear spring with a linear viscous damper, as shown in Fig. 3. A method has been developed to calculate an equivalent mass, spring stiffness, and level of damping for the bridge – effectively creating a ¼-bridge analogue of the ¼-truck model – that is consistent with typical bridges based on measured natural frequency, percentage of critical damping and mid-span deflection.

3.3 Road Profiles

Measured road profiles or artificially generated profiles can be used in the model. The road profile is specified as an elevation versus chainage. The road profile before, on, and after the bridge can be specified, and the truck model passes over this profile. The section of road profile on the bridge accounts for any initial static deflections as well as deflecting under the dynamic loads imposed on the bridge by the vehicle. Fig. 7 shows a typical road profile recorded on the Camerons Creek Bridge.

Thus, the influence on vehicle bridge interaction of profiles on bridge approaches at the abutments and on the bridge decks can be studied.

3.4 Vehicle-Bridge Interaction Modelling

Both the bridge and the vehicle are modelled as interacting dynamic systems. The road profile causes dynamic wheel forces, which induces a dynamic bridge response which in-turn modifies the road profile. Thus there is an interaction between the vehicle and the bridge. Simulations can be performed with interaction between vehicle and bridge either enabled or deactivated.

To evaluate the effectiveness of the model and to demonstrate its capabilities, the model was used to simulate experiments that were conducted during the dynamic load testing of the Camerons Creek Bridge as part of the OECD DIVINE Project (OECD, 1997). During the testing of Camerons Creek bridge, road profiles were recorded, as well as dynamic wheel forces and bridge responses for a range of truck test speeds. Because the recorded results are based on a 6-axle prime mover and semi-trailer combination, two simulations were used to model the results. One model was used for the prime mover and one model for the trailer with the results superimposed to represent the passage of the truck over the bridge. Fig. 8 compares the bridge response from the model for a truck with steel suspension, and Fig. 9 for an air suspended truck. The results from the model compare well with the experimental results and show the ability of the model to simulate vehicle-bridge interaction. The model can also be used to simulate dynamic wheel forces and comparison of these wheel forces with the recorded wheel forces at Camerons Creek also shows that there is good agreement. Fig. 10 shows a comparison of results based on dynamic increment versus speed. The graph compares the results from the model using a tri-axle group with the experimental results for a 6-axle prime mover and semi-trailer. Again there is good agreement between experimental and modelled results.

4. PARAMETRIC STUDY

To begin the study into the influence of the various parameters which influence vehicle bridge interaction including: road profile, bridge type, vehicle suspension, configuration and mass a parametric study using the developed vehicle bridge interaction model was undertaken. The results from the study presented in this paper are based on the Camerons Creek bridge, use a variety of road profiles and vary the vehicle mass. Both air and steel suspensions were studied.

Fig. 11 shows the dynamic increment versus speed relationship for the steel suspended vehicles. For each profile: smooth, smooth with an initial bump, and measured profile, two truck masses were analysed (standard legal mass and 1.5 times the standard legal mass) with no change to the suspension parameters. In a similar analysis, the resultant relationships for the air suspension are shown in Fig. 12.

The results show the influence of road profile on the dynamic increment versus speed relationship for this bridge for both suspension types. The addition of a bump at the abutment considerably increases the dynamic increment compared to the smooth profile. The results for the actual measured profile (rough) are also significantly higher than those for the smooth profile as expected.

In each case, the increase in truck mass led to a reduction in the dynamic increment, however the reduction due to the increased mass on a smooth profile is very small.

Air suspensions produce either similar or reduced dynamic increments when compared to equivalent steel suspension systems. Due to the stiffness of the air suspension being linked to truck mass, the reduction in dynamic increment due to increased mass is less pronounced for air suspension than observed for steel suspension.

This study will be expanded during the remainder of the project to incorporate other bridges, road profiles of varying roughness (IRI), and a wider range of vehicle masses. This work will lead to a basis to make recommendations for the dynamic increment versus speed relationship for the new Australian Bridge Design Standard.

5. MODEL APPLICATIONS

The vehicle bridge interaction model developed for this project has a wide range of other applications. These include:

1. Studying vehicle-road interaction.
2. Assist with the design of *"bridge friendly"* suspension systems.
3. A basis for a *Bridge Roughness Index (BRI).* A BRI could be developed, similar to IRI but designed to quantify the influence of road profile on bridge response. The BRI could then be monitored as part of routine network level roughness surveys to determine when unevenness levels on bridges and bridge approaches exceeded specified levels indicating that profile repair was required.

6. CONCLUSION

This paper has reviewed the development of a computer model, which includes the ability to study the effect of heavy vehicle suspension systems, vehicle mass, road profiles, and bridge behaviour on vehicle bridge interaction. Comparison of the model outputs with field test results from dynamic testing of bridges shows good agreement between the two results. The model is currently being used to conduct a parametric study which will allow recommendations to be made for appropriate dynamic increment values for the new Australian Bridge Design Standard. Dynamic increment is a measure of the increased effects of heavy vehicles on bridges due to dynamic effects over and above the static effects. To date the results of this study have shown that the road profile is a significant factor in vehicle bridge interaction and that dynamic increment values generally decrease with increasing vehicle mass. The model also has a number of other applications, which may be further developed in the future.

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TABLES & FIGURES

Table 1 Bounce and wheel-hop frequencies from the suspension tests.

Suspension Model	Body Bounce Frequency (Hz)	Body Bounce Damping (% of Critical)	Axle-Hop Frequency (Hz)
Air	1.55	17	10.6
Steel	3.2	7.1	11.7

Fig. 1 Triple road train crossing the Ward River, Central Queensland.

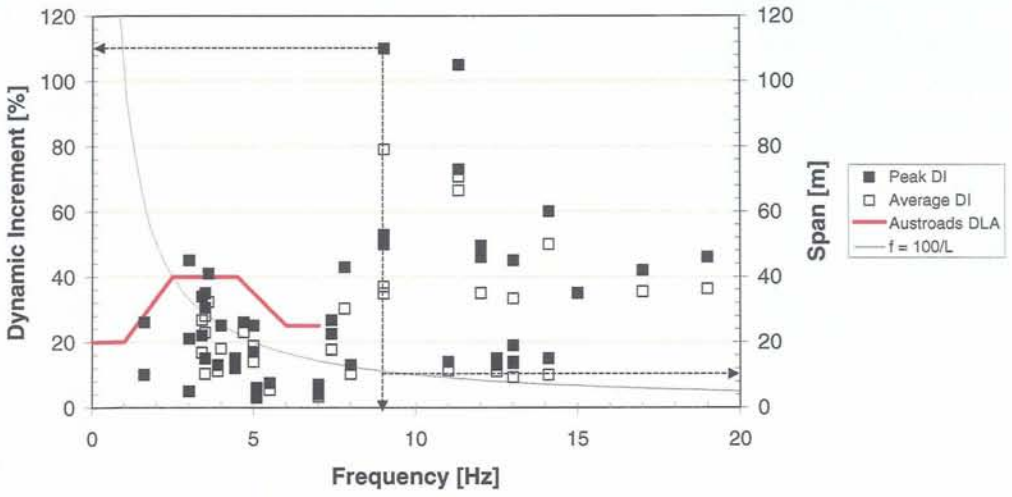

Fig. 2 Dynamic Increment Versus Frequency: All Materials - GLM 40-55 tonnes including Austroads DLA provision and relationship between frequency and span (Heywood, 2000).

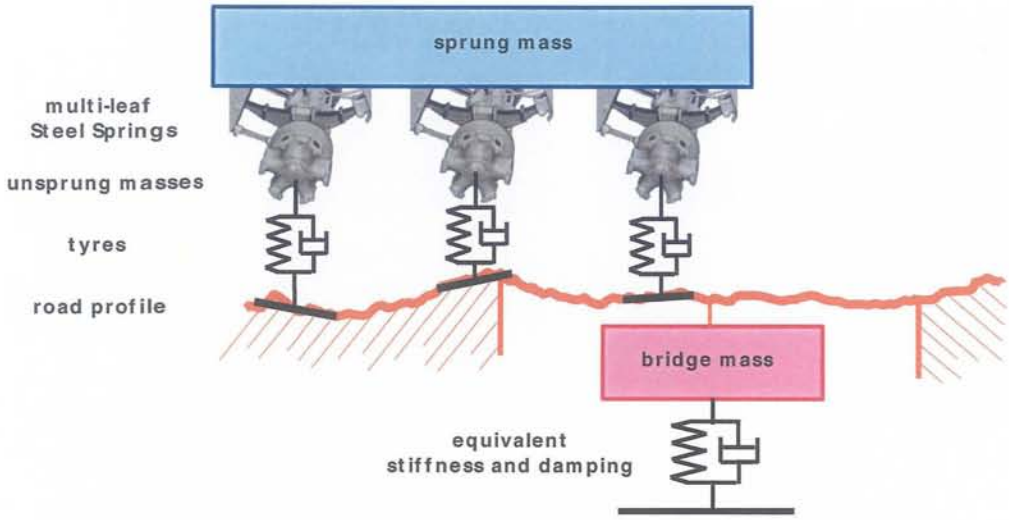

Fig. 3 Schematic of steel-spring suspension 3-axle ¼-truck model and corresponding "¼-bridge" model.

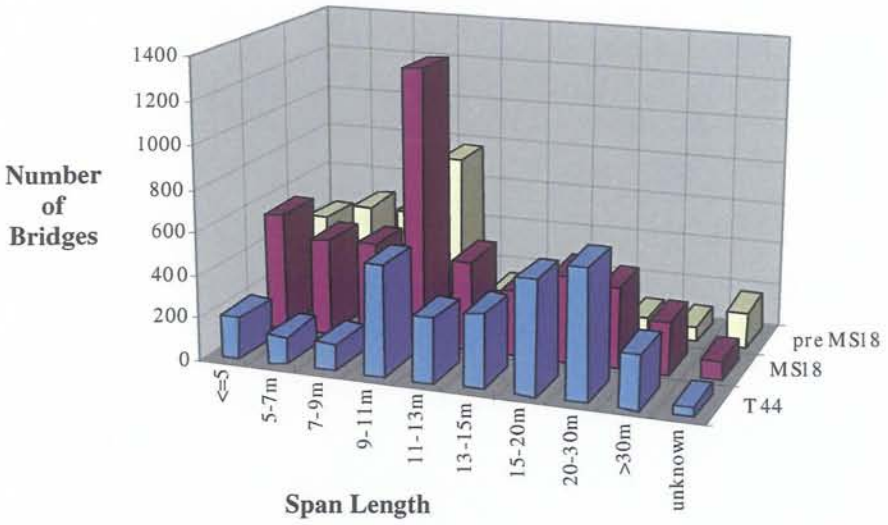

Fig. 4 Span lengths of bridges for the main design standards. Source: National Road Transport Commission (1996).

(a) Multi-Leaf Steel suspension.

(b) Air suspension.

Fig. 5 Typical suspension systems.

Fig. 6 Ringarooma Bridge, Tasmania.

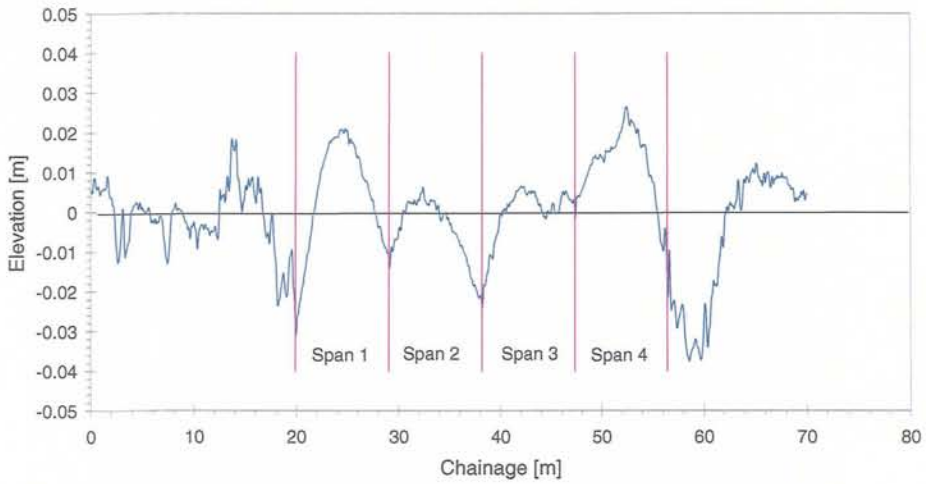

Fig. 7 Typical road profile (OECD 1997).

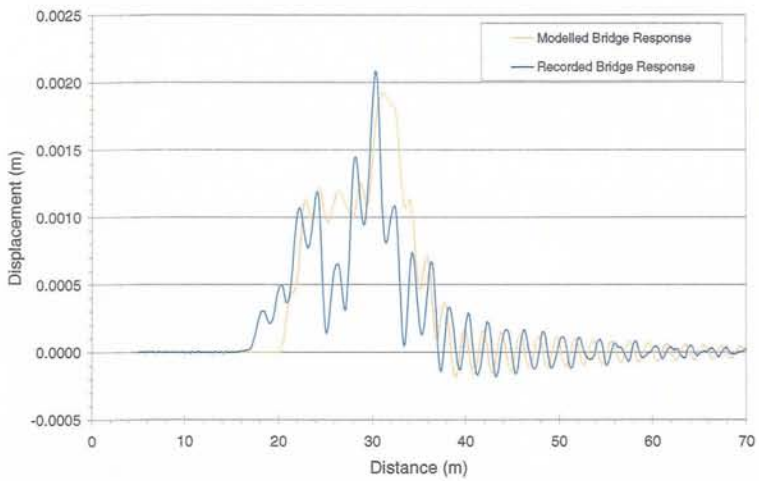

Fig. 8 Comparison of recorded field response and response from Vehicle Bridge Interaction Model (steel suspension).

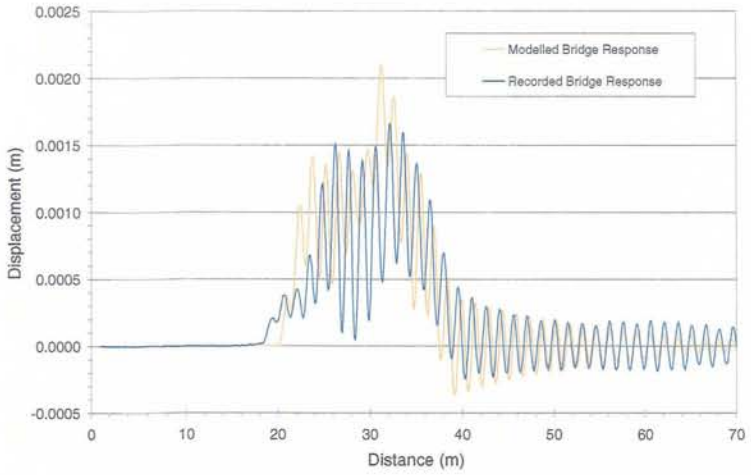

Fig. 9 Comparison of recorded field response and response from Vehicle Bridge Interaction Model (air suspension).

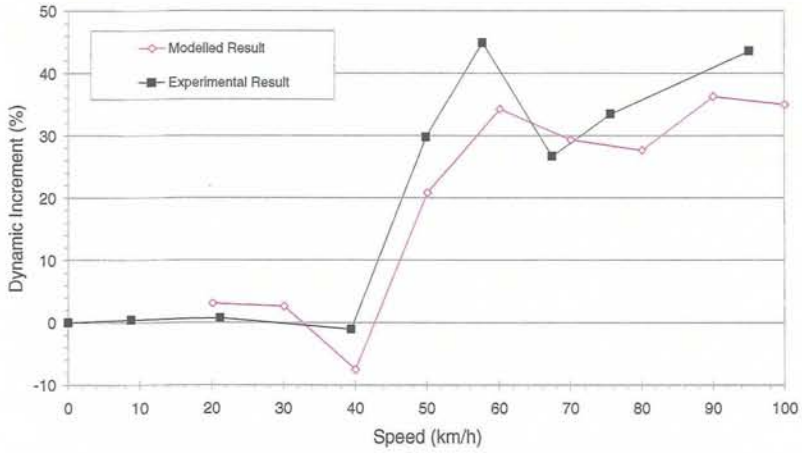

Fig. 10 Comparison of dynamic increment versus speed based on recorded test results and results from Vehicle-Bridge Interaction Model.

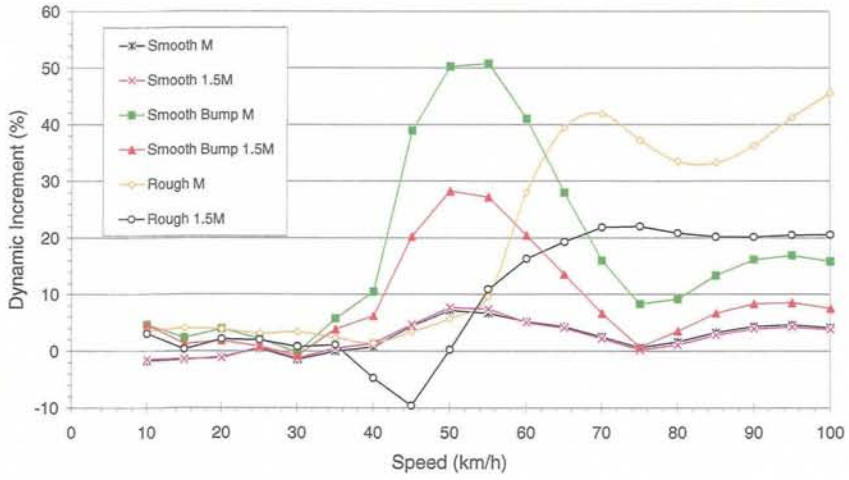

Fig. 11 Dynamic Increment Result for Steel Suspension.

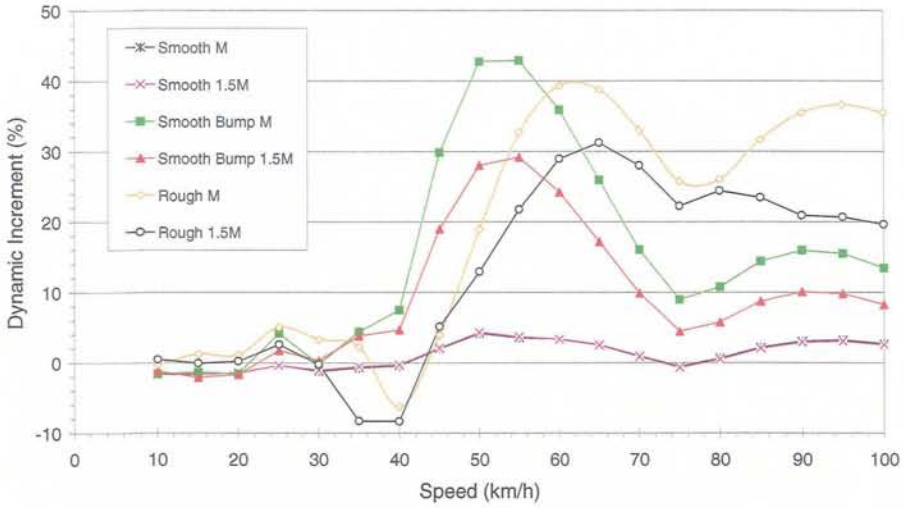

Fig. 12 Dynamic Increment Results for Air Suspension.