DIVINE
An International Experiment to Investigate Dynamic Vehicle-Infrastructure Interaction

SUMMARY

The importance of vehicle dynamics in road design and management has only recently been recognised. This is because of the increasing attention to infrastructure and vehicle operating costs brought about by traffic growth, pavement deterioration and vehicle innovations to enhance productivity and economic pressures. In 1992, the OECD established Scientific Expert Group IR6 to initiate and undertake a co-ordinated international research programme to investigate the effect of vehicle dynamic loading on pavement deterioration and bridges, called the Dynamic Interaction of Vehicle and INfrastructure Experiment (DIVINE). DIVINE involves over 20 OECD member countries, and includes specialists in vehicles, pavements, bridges, road management and transport policy. The experiment consists of six inter-linked research elements being undertaken by researchers from more than ten countries. All the experimental work has been completed, most of the analysis work has been done and the draft reports are being prepared.

This paper describes briefly the research, outlining the primary research questions being addressed, the nature of the experiments being undertaken and some indications of the preliminary results.

INTRODUCTION

The Organisation for Economic Co-operation and Development (OECD) of which New Zealand is a member comprises 26 member countries primarily from the economically developed world. Its aims are to promote economic growth and employment in both member and non-member countries. Although many of the more publicised studies it conducts are related to socio-economic matters, it has a Science, Technology and Industry Directorate within which there is a Road Transport Research Programme.

In 1989, the OECD Road Transport Research Programme established a scientific expert group IR2 to review dynamic loading of pavements. This group completed its study in 1992 (OECD, 1992) and presented its report at a conference in Melbourne. It identified a number of major issues which were yet to be resolved and recommended an international co-ordinated research programme. In response the OECD established another scientific expert group, IR6 to undertake this research. This programme has become known as DIVINE (Dynamic Interaction of Vehicles and INfrastructure Experiment).

The objectives of DIVINE are to :-
(i) provide means for identifying and assessing road-friendly vehicles;
(ii) quantify the improvements in road and bridge life obtainable through the use of road-friendly vehicles; and
(iii) ensure that vehicle and suspension configurations that are found to be road-friendly are also bridge-friendly.

DIVINE involves over 20 OECD member countries, and includes specialists in vehicles, pavements, bridges, road management and transport policy. The experiment consists of six inter-linked research elements or projects being undertaken by researchers from more than ten countries with a total value in excess of US$2,000,000. This programme is now nearing completion. All the experimental work has been completed, most of the analysis work has been done and the draft reports are being prepared.

In this paper we will describe briefly each of the research elements, outlining the primary research questions being addressed, the nature of the experiments being undertaken and some indications of the preliminary results. It should be noted that any conclusions drawn in this paper are those of the authors and not of OECD Scientific Expert Group IR6.

ELEMENTS OF DIVINE AND THEIR LINKAGES

DIVINE consists of six inter-related elements of research which cover: accelerated pavement testing under dynamic loading, vehicle-pavement and vehicle-bridge testing which are being used to explore the question of the effect of dynamic loading on pavement life and bridge behaviour, and computer and laboratory simulation which are being used to develop and evaluate essential tools for measuring, understanding and predicting dynamic loading from heavy vehicles. The research is intended to answer four basic questions:

(i) Under controlled conditions, by how much do dynamic loads reduce the life of road pavements, and what influence do they have on bridge performance?

(ii) How do the results obtained under controlled conditions transfer to real road conditions with mixed traffic?

(iii) How should heavy vehicles be specified and tested for road friendliness?

(iv) How much increase in pavement life should be expected from road friendly heavy vehicles in practice?

To address these four points the research programme was designed to find parallel answers to each question, using different approaches and data sets, to ensure confidence in the results.

ELEMENT 1 - THE ACCELERATED PAVEMENT TEST

The primary aim of this research element is to quantify the effects of dynamic loading on pavement wear. Most previous approaches to this problem have been based on applying the fourth power law to the dynamic wheel forces in some way, for example, Eisenmann (1975). These approaches are largely theoretical and make a number of assumptions about the spatial distribution of the wheel forces and the corresponding pavement effects. The data from this experiment will provide a sounder basis for assessing these effects. The main research question to be addressed can be expressed as:

> *What are the relative performances and lives of a uniform pavement under two different and known magnitudes of dynamic loading?*

The experiment was undertaken at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) in Christchurch, New Zealand. CAPTIF consists of a 58 m long circular track contained within a 1.5 m deep x 4 m wide concrete tank so that the moisture content of the pavement materials can be controlled and the boundary conditions are known. An elevation view is shown in figure 1.

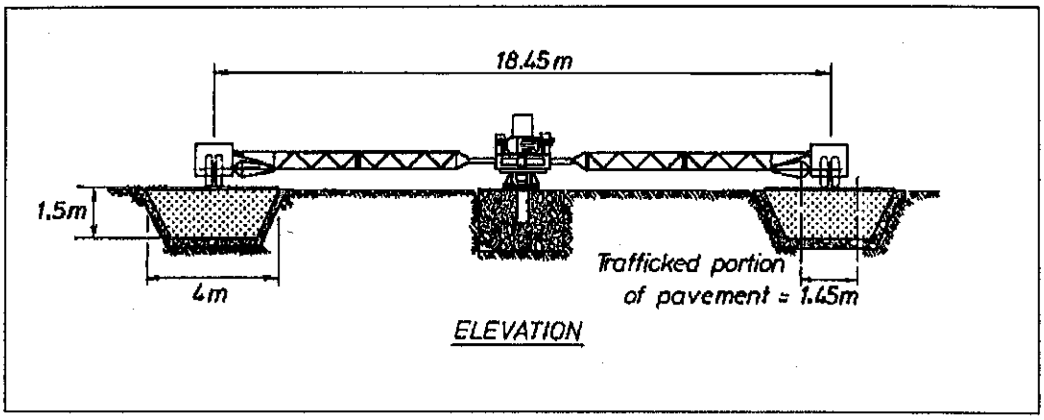

Figure 1. Elevation view of CAPTIF

A centre platform carries the machinery and electronics needed to drive the system. Mounted on this platform is a sliding frame which can move horizontally by 1 m. This radial movement enables the wheel paths to be varied laterally and can be used to have the two vehicles operating in independent wheel paths. At the ends of this frame, two radial arms connect to the Simulated Loading and Vehicle Emulator (SLAVE) units shown in figure 2. The arms are hinged in the vertical plane so that the SLAVEs can be removed from the track during pavement construction, profile measurement etc. and in the horizontal plane to allow vehicle bounce.

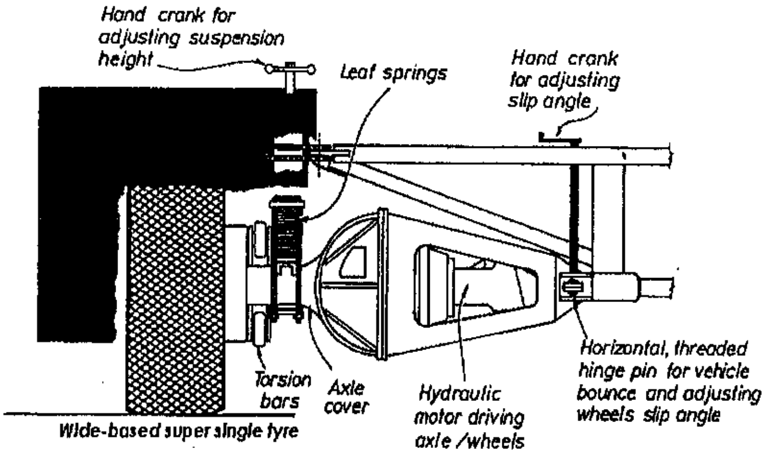

Figure 2. SLAVE vehicle unit.

Each SLAVE consists of an axle-wheel assembly with an attached hydraulic drive motor which is connected by a suspension system to a frame on which weights are hung. As much as possible these SLAVEs use standard heavy vehicle components. They can operate with wheel loads between 21 kN and 60 kN and at speeds up to 50 km/h. The "vehicles" can be fitted with air springs, parabolic steel leaf springs or trapezoidal multi-leaf steel springs, with or without shock absorbers. As the ratio of the sprung to unsprung mass is typical of real heavy vehicles and the suspensions use standard heavy vehicle components, the dynamic characteristics are very realistic in terms of the natural frequencies and relative magnitudes of the modes of vibration. The facility is housed within a building which, although not environmentally controlled, protects the pavement from rain (and snow) and direct sunlight.

Pavement instrumentation which is used at CAPTIF (Pidwerbesky, 1989, 1992) includes: bison coil transducers for measuring vertical strains in the basecourse and subgrade layers of the pavement, h-bar strain gauges for measuring horizontal strains at the bottom of the asphalt layer in both the longitudinal and transverse directions and partial depth gauges for measuring the pavement layer deflections. As well temperature probes are used to monitor both the pavement and air temperatures. The vehicle instrumentation consists of accelerometers mounted on both the sprung and unsprung masses of each "vehicle" and displacement transducers to measure suspension displacements. As the "vehicles" are a fairly simple quarter vehicle structure, wheel forces can be calculated by combining the two accelerometer signals weighted by appropriate mass factors. Other measurement systems used at CAPTIF during testing are: a Falling Weight Deflectometer (FWD) which is used to monitor pavement condition by measuring the deflection response to loads applied by a falling weight, the CAPTIF Deflectometer which is a modified Benkelman beam which also measures pavement deflection response but to loads applied by the wheels of the SLAVE unit, a DIPStick profiler which is used to measure the longitudinal pavement profile, and a transverse profilometer. Recently a laser profilometer has been installed which supplements the DIPStick.

The pavement used consisted of 90mm of asphaltic concrete over 200mm of crushed rock basecourse on a silty clay subgrade. This was considered a thin and relatively weak pavement by European and North American standards though it is quite a strong pavement by New Zealand standards. The SLAVE units were loaded to 5 tonnes which is equivalent to a ten tonne axle load. Wide-based single tyres were used to maximise the separation between the wheel paths trafficked by the two SLAVE units. Based on the Transit New Zealand Pavement Design Guides and these axle loads, this pavement had a design life of approximately 400,000 rig cycles, with an equal probability of failure in both cracking and rutting modes. Some of the pavement models predicted a much shorter pavement life.

One of the SLAVEs was fitted with an air bag suspension with a shock absorbers which is a configuration which is generally regarded as "road friendly". The other was fitted with the two stage multi-leaf steel spring suspension which was part of the original CAPTIF design. This suspension is typical of what was in common use in New Zealand (and around the world) at that time, and is still used. These suspensions are robust, relatively light and low maintenance but also relatively "road unfriendly". Dynamic wheel forces are typically characterised by the dynamic load coefficient (DLC) which is the normalised standard deviation of the wheel forces. On this basis, the steel suspension vehicle produced dynamic wheel loads consistently three times or more greater than the air suspension vehicle.

The pavement was built to extremely high standards, with very strict quality control on thickness, compaction and moisture content. Considerable care was taken to ensure that the two wheel paths were as similar as possible. A 10 m long section of the pavement was extensively instrumented with the transducers described above.

At the start of the test a very comprehensive set of zero measurements was undertaken. These included measuring the wheel forces at a range of speeds and the pavement response to these wheel forces, recording the pavement profiles both longitudinally and transversely and the pavement deflection response using a falling weight deflectometer (FWD) and the CAPTIF deflectometer. Ramps were also used to induce specific types of dynamic load and the pavement response to these was monitored.

During the test the loading was interrupted at regular intervals and again measurements of dynamic wheel forces, pavement response and pavement condition were made. The interval between measurement sets was relatively short early on in the test and was increased as the test progressed and the pavement stabilised.

Relatively early on in the test programme a localised rut approximately 6 m long formed in the outer wheel path which was the one trafficked by the steel suspension. The formation of this rut commenced at about 30,000 load cycles and by about 150,000 load cycles had stabilised. From then on the increase in rut depth in this section was much the same as for the rest of the pavement. No satisfactory explanation for the formation of this rut has yet been developed.

Pavement cracking began at around 900,000 load cycles and increased through to the end of the test. The level of cracking was higher in the outer wheel part which was trafficked by the steel suspension. Pavement roughness increased steadily throughout the test but overall the changes were relatively small. The test was halted at 1,700,000 load cycles after 10 months of loading. At this point, apart from the localised rut mentioned above, the pavement had not reached the pre-determined failure criteria in either cracking or rutting. Although there was measurable pavement wear, its rate of increase was such that many further load cycles (perhaps 1,000,000 or more) would have been required to reach failure. Financial and time constraints precluded this.

Some of the key outcomes are that the pavement lasted many times longer than predicted by the design guides and the pavement models which were used at the start of the test. Some of these models used measured material property data not just theoretical values. This was in spite of the fact that wide-based single tyres (which are generally believed to be significantly more road damaging) were used and that degree of lateral wander was limited. Likely reasons for this are that the pavement was protected from the influences of the weather including both direct sunlight effects and precipitation effects, and that the pavement construction was closely monitored and so construction variability was minimised.

Cracking was first observed in both wheel paths at about the same time. However, the level of cracking in the wheel path under the steel suspension was significantly higher. At the end of the test the total cracking in the outer (steel suspension) wheel path was 36% higher than that on the inner (air suspension). As well the standard deviation of the cracking was higher in the outer wheel path with many more locations (13 versus 5) exceeding the pre-defined failure criterion. If these rates of cracking increase are extrapolated the outer wheel path would reach the failure criterion at about 3,000,000 load cycles and the inner wheel path would reach it at just over 5,000,000 load cycles. There is, of course, no reason to expect that these rates of increase would remain constant throughout this period. It is also clear from this that continuing the test until failure in both wheel paths occurred was not practicable.

Surface roughness was also considered as it is a widely used measure of pavement condition in pavement management systems. Because of the relatively short section under consideration, the standard measures were not very effective. A number of different methods for quantifying roughness were investigated. For both wheel paths, the increase in roughness during the test was relatively small. For some of the measures investigated there was little difference in the rate of increase between the two wheel paths. For the roughness measures where there was a difference, in all cases the outer wheel path roughness increased more rapidly than the inner wheel path roughness.

ELEMENT 2 - PAVEMENT PRIMARY RESPONSE TESTING

The primary aim of this research element is to assess the level at which pavement primary response (that is, the strains in the pavement) reflect the dynamic nature of the applied loads. This is fundamental to understanding the mechanisms by which dynamic loads influence pavement performance and life. The principal research question can be formulated as:

> *How does the ratio of applied dynamic load to generated strain vary as the frequency and magnitude of the dynamic load varies?*

In addition, the results of the work assist in transferring the results of Element 1 to other situations, and aids in understanding the effects of speed on the pavement response to dynamic loads.

The test programme was designed to compare the strains generated in two typical pavement types under low-speed "static" and traffic-speed dynamic loads applied to the pavement by instrumented heavy vehicles. These types of load represent those which are used in the pavement design process, and those which occur in practice.

This element consisted of two series of experiments, one conducted at the Turner-Fairbank Research Center operated by the Federal Highways Administration in McLean, Virginia in the United States and the other conducted at Technical Research Centre (VTT) in Finland. In both cases, test sections of pavement were instrumented with strain gauges to measure the bending strains in the asphalt layer. Instrumented vehicles were then used to apply measured dynamic loads to these sections of pavement and the pavement response as measured by the strain gauges was recorded.

Rather than just use the random dynamic loads that would be generated by driving the vehicles across pavement, bumps of a controlled nature were used to excite specific forms of dynamic response from the vehicles. In the US experiments, a long bump (4m long) was used to excite the low frequency body modes of the vehicles. In the Finnish experiments both a long bump and a short bump which was intended to excite the unsprung mass modes were used. In the Finnish experiment two pavements were used, one of which was considered relatively thin and was of similar although not identical design to the pavement used at the CAPTIF facility in element 1.

Preliminary results from these experiments indicate a very good correlation between the dynamic wheel forces applied and the pavement strains recorded on the thicker pavement. This is true for both body bounce and axle hop modes of vibration. For the thin pavement, the correlation was not as good and there is some suggestion that tyre stress distributions and contact patch area were influencing the response. Further analysis is being done. This result is particularly relevant to New Zealand because, in this context, almost all our pavements would be classified as thin.

ELEMENT 3 - SERVO-HYDRAULIC SHAKER TESTING

The aim of this research element was to investigate whether servo-hydraulic shaker facilities could be used to simulate the on-road behaviour of heavy vehicles and hence be used to assess suspension "road friendliness". The two main research questions therefore were:

i. Can a road simulator replicate the dynamic motion and dynamic pavement loads produced by a vehicle on a road?

ii. What tests are appropriate for rating the road friendliness of a vehicle or suspension?

This research was conducted at the National Research Council's Centre for Surface Transportation Technology in Ottawa, Canada which has a four post servo-hydraulic shaker facility. The test comprised three experimental phases. In the first, three instrumented vehicles, two rigid trucks and a tractor semi-trailer configuration were tested on a number of sections of public road with good, average and poor unevenness at several speeds. During these tests, the wheel forces, suspension deflections, the vertical accelerations of sprung and unsprung masses and the spatial position of the vehicle on the road were recorded. In addition the road profiles of the test roads were measured. These data were required, not only for this element but also fundamentally for element 4 and to a lesser extent for elements 2, 5 and 6 where the same tractor semi-trailer vehicle was used to provide dynamic loading.

The test vehicles were then mounted, in turn, on the servo-hydraulic shaker rig for the second phase of experimental work. The initial part of this was a series of tests to calibrate the vehicle instrumentation systems and to determine the vehicle parameters for use in element 4. Then the road profile data was used to provide shaker excitation signals to simulate the on-road tests which had just been completed.

The third phase of the experimental programme was a series of tests to evaluate various methods for rating suspensions (Woodrooffe, 1996). For these tests a purpose-built "pendulum" semi-trailer was used on the shaker rig. This trailer consists of a relatively light and long lattice frame structure with a sub-frame at one end to which different suspension bogeys can be fitted. The trailer is loaded so that the horizontal load centre coincides with the centre of the bogey. At the other end of the frame a normal fifth wheel pivot is fitted and this was restrained to prevent any vertical movement. Three different tandem suspensions were used for these tests, an air suspension (both with and without dampers), a steel suspension and a rubber walking beam suspension. (The air suspension was the same as that fitted to the semi-trailer in the first two phases). This trailer was then mounted on the shaker rig and subjected to a range of tests. These included low frequency anti-phase excitation of the two axles to evaluate the load equalisation performance of the suspension, sinusoidal frequency sweeps at various amplitudes with both axles in phase and out of phase, and drop tests at various heights which were variations on the EC standard test (EEC, 1992) which uses an 80 mm drop. These were done, one axle at a time, both axles together and the two axles phase separated to correspond to the vehicle travelling at 5 km/h over the ramp. As well road profile based excitations were applied. These consisted of three real profiles from the earlier road tests and three virtual profiles which were computer generated to have the same spectral content as the real profiles.

The results of shaking the rigid truck with excitations based on-road profile data were relatively good with a reasonable match between the response while on the shakers and the measured response on the road. For the tractor semi-trailer configuration, there were insufficient shakers to excite all the wheels of the rig and so the shakers were used to excite only the axle bogey on the semi trailer. These excitation, of course, differ from that which occurred on the road because the tractor wheels were not excited. Consequently the vehicle response also differed. This highlights the difficulties in using servo-hydraulic shakers to simulate on-road behaviour.

The tests with the "pendulum" trailer produced some interesting results. Quasi-static load equalisation is seen as important because, if a fourth power relationship between axle loads and pavement wear is assumed, poor load equalisation results in a significant increase in pavement distress. The tests showed, as expected, excellent equalisation with the walking beam suspension. The air suspension was not as good but significantly superior to the steel suspension.

The in-phase sinusoidal sweep produced the best results at the lowest amplitude tested (1 mm). The natural frequencies were clearly identifiable with the response peaks providing information on the damping. At higher amplitudes the results were less clear. The out-of-phase sinusoidal sweep did not excite the sprung mass resonances and so is of limited use for assessment purposes. As with the in-phase tests, the lowest amplitude gave the best response.

The drop tests with both axles in-phase produced the best results for calculated the sprung mass frequency and damping rates. Because the suspensions are non-linear, the values obtained are dependent on the magnitude of the drop used.

The tests using the air suspension with no dampers reinforced the importance of dampers to "road-friendliness". On average and rough roads, the air suspension without dampers generated higher dynamic loads than both the steel suspension and the walking beam.

The shaker trials using road profiles generated dynamic loads which were higher than those generated by the semi-trailer with the same suspension during road tests. This is because the tractor/trailer interaction tends to reduce the dynamic loads. However, the relative ranking of the suspensions was the same in both cases.

ELEMENT 4 - COMPUTER SIMULATION OF HEAVY VEHICLE DYNAMICS

The aim of this research element was to assess the usefulness of the various vehicle simulation programmes that exist in predicting the dynamic loads that heavy vehicles generate when travelling along roads. The research question then is:

Can computer simulation models be used to predict the dynamic loads generated by heavy vehicles?

This research project was co-ordinated by TNO in the Netherlands. The owners of 21 vehicle simulation programs were invited to participate at their own expense. Of these, eight agreed but only four actually participated.

They were provided with vehicle parameter data from the vehicles tested in element 3, together with the road profile data measured during the road tests in Canada. They were then asked to use their programs to calculate the resulting wheel forces. These results were then compared with the actual wheel forces measured in element 3. This comparison was on a statistical basis where the spectral content and DLC values were compared rather than the time domain wheel force signal. The owners of the programmes were then provided with the measured wheel forces and offered a second opportunity to adjust their model to see whether they could produce better estimates.

The four models varied in complexity from simple linear to full 3D non-linear. None of the models produced wheel force signals that matched those measured in any detail, but the better models were close statistically in that the power spectral densities of the wheel forces were very similar to those measured as were the DLC values.

Although the linear model did not perform well, as is to be expected because real suspensions behave non-linearly, one of the three non-linear models also did not perform well.

Detailed information on the spring and damper characteristics is considered critical to successful modelling of vertical response. Overall it appears that the value of modelling may be in using a standard reference vehicle models to evaluate issues such as road unevenness standards, and bridge approaches rather than in duplicating the behaviour of a specific vehicle.

ELEMENT 5 - SPATIAL REPEATABILITY MEASUREMENTS

The aim of this research element was to determine the extent to which the peaks and troughs of dynamic loading repeat spatially along the road under the real world situation of trafficking by mixed fleets of heavy vehicles. The importance of this issue is in determining the level of pavement wear which can be attributed to dynamic wheel loads. Eisenmann's (1975) method for calculating the contribution of dynamic wheel loads to pavement wear assumes that the loads are randomly distributed - that is, there is no spatial repeatability. Even a modest degree of spatial repeatability significantly increases the proportion of pavement wear than can be attributed to dynamic loads. Thus the results of this element are crucial to the interpretation of the results of elements 1, 2 and 3.

The pattern of dynamic wheel loads generated by a heavy vehicle depends on both the excitation (ie the road profile and vehicle speed) and the vehicle response (ie suspension behaviour). For the same vehicle at the same speed on the same road this is highly repeatable. However, although in normal traffic the excitations for different vehicles are very similar as the road profile is essentially the same (lateral position may introduce some small variations) and the speeds usually fall within a relatively narrow range, there is much more variability in vehicle response as not only suspension stiffness and damping have an effect but so do load magnitude and distribution, and axle spacing.

The experiments were conducted in the United Kingdom and in France. In both cases, Weigh-in-Motion (WIM) sensors were embedded in sections of public road and the accumulated loads of the heavy vehicle fleet passing over these sensors was recorded. Instrumented vehicles (two of those used in element 3) were used to calibrate the sensors. If the spatial distribution of wheel loads was totally random then over time the accumulated loads on each of the sensors would tend towards the same mean. If there was a trend towards spatial repeatability some sensors will accumulate higher loads than others.

Preliminary results from the UK (Gyenes and Mitchell, 1992) indicated that peak loads on some sensors might be as much as 20% higher than the mean load. In analysing the French data, an impact factor which, for gross vehicle weights is calculated as the ratio of the sum (for all axles of the vehicle) of the axle WIM weights to the statically weighed gross vehicle weight (O'Connor et al, 1996) was used. It was found that for tractor axles there was no difference in impact factor between air and steel suspensions but for tridem axles on trailers, the steel suspensions had maximum impact factors which were 11% higher than air. At this test site which is a very smooth pavement, impact factors of up to 1.1 were obtained for the fleet as a whole. This again indicates a degree of spatial repeatability.

ELEMENT 6 - BRIDGE RESPONSE TESTING

The failure, or removal from service, of a bridge frequently has effects that are noticeable at regional rather than local levels. Bridges also provide a limit to the axle loads and gross laden weight permitted. The prediction and prevention of failure have considerable economic benefits to the owner, the user, and the surrounding region. For these reasons, an understanding of the response of bridges to the dynamic loads applied by heavy vehicles is essential.

The aim of this research element was to investigate the extent to which the dynamic response of vehicles interacts with the dynamic behaviour of bridges. The issue raised here is that most bridge design codes make some allowance for the dynamic characteristics of the vehicles. Typically if the bridge's natural frequency is between 2-5 Hz then it must be built stronger to allow for the fact that typically heavy vehicles have had natural frequencies in that range. However, the advent of softer suspensions has meant that the natural frequencies of the sprung mass resonances of vehicles has reduced. A good air suspension would typically have a body bounce resonance with a natural frequency of the order of 1.5 Hz. For this reason there was some concern that bridges which have spans with natural frequencies of 1-2 Hz might be adversely affected by these heavy vehicles. The early work in this element raised the issue that perhaps short span bridges with natural frequencies corresponding to the axle bounce modes of heavy vehicles, that is between 9-15 Hz, might also be adversely affected. The more "road-friendly" suspensions typically reduce the level of activity in the sprung mass modes and increase the amount of activity in the unsprung mass modes.

The experiments were conducted in two countries; the medium span bridges were investigated in Switzerland, and the short span bridges were investigated in Australia. In both cases the approach was very similar, instrumented vehicles were run across the bridges and both the vehicle loads applied and the bridge response was recorded. The simultaneous measurement of dynamic wheel forces and bridge responses has provided valuable insights into the influence of truck suspensions on bridge response.

In the case of the medium span bridges, that is, bridges with a natural frequency of 1-3 Hz, some increased dynamic response from the bridges was observed but it was relatively low and well within normal design practice. In the case of the short span bridges, it was found that in some instances, very high levels of dynamic response occurred under loading by "road-friendly" suspensions. The primary cause of this appears to have been the roughness of the bridge approach which excited the axle hop resonances of the vehicle. As other elements have also illustrated, suspension damping was an important factor here, but there is also an indication that ensuring bridge approaches are kept smooth will reduce the loading impacts.

OUTCOMES, BENEFITS AND IMPLEMENTATION

While the DIVINE project will contribute substantially to the means by which road maintenance costs may be reduced, even greater benefits may be possible in some countries through improved productivity of road freight operations. World-wide, the annual costs of operating freight vehicles far exceeds the costs of building and maintaining roads (vehicle operating costs have been estimated to be up to 30 times road costs). For example, the average annual operating cost of a 6-axle vehicle in Australia is $225,000, which should be compared with the annual average road track costs of $15,000 for the same vehicle.

Experience in many countries has shown that reduced transport costs tend to be passed on to consumers in the form of lower prices for goods. The implementation of such productivity improvements clearly depends on national policies in respect of road funding, road user charges, size and-weight limits and vehicle regulations.

The three key factors arising from the DIVINE project that may affect policy considerations are:

reduced road wear (and hence road maintenance costs),
improved productivity with a neutral effect on road costs, or
reduced road costs and increased productivity.

The DIVINE Project is strongly orientated towards the latter objective. Increased payloads and productivity could be brought about by a mix of transport policy options selected to best suit the regulatory and economic environment in each country. Components of these policy options include:

higher gross weights for road-friendly vehicles, perhaps brought about by additional axles rather than higher individual axle weights; this may involve increased use of tridem groups in place of tandem groups.

consideration of increased axle group weight on road-friendly tandem and tridem groups.

scientifically-based means for measuring and assessing the road-friendliness of heavy vehicle suspensions (including the dynamic and load-sharing performance of suspensions).

Vehicle related options could be supported by new strategies for pavement design, reconstruction and maintenance; these might be required to produce pavements that induce less dynamic loading and are less sensitive to its effects, and could result in stronger, more even pavements on designated freight routes. Structural and surface (evenness) uniformity should be emphasised in pavement design and construction cost/performance "trade-offs". The DIVINE project provides further support for the characterisation and measurement of highway condition, and to enhance the pavement management systems on which all OECD member countries are increasingly reliant.

DISSEMINATION

The concluding DIVINE seminar is scheduled to be held in Ottawa on 12-13 June 1997, immediately prior to the International Road Federation (IRF) World Conference being held on 16-20 June 1997 in Toronto. Two further seminars are planned to be held, one in Europe and one in the Asia/Pacific region in October 1997 (probably in Australia).

Reference groups have been established in Australia, New Zealand and Japan to encourage the dissemination of the DIVINE results in those countries, to translate research into practice and to receive feedback from industry, highway agencies and other interested parties. The Australasian group has issued two "DIVINE Down Under" newsletters. Groups are also being organised in Canada, Europe and the USA.

CONCLUSIONS

The OECD DIVINE experiment was designed to address a number of important questions that arise in the field of the interaction of dynamic loading and road infrastructure. The objectives of each element, the outputs and the benefits are summarised. The experiment was carried out through world-wide co-operation and with the support of national governments and industries. The potential benefits to infrastructure owners, vehicle operators, and road users are considerable.

Pavement design and construction techniques should emphasise uniformity and rely on statistical quality assurance schemes to ensure that heavy vehicle dynamic loads do not substantially reduce pavement life and increase maintenance costs.

Three techniques for assessing the road-friendliness of suspensions have been evaluated and shown to reflect the on-road performance of vehicles fitted with these suspensions. The capital cost and complexity of the three methods vary substantially, as does the level of detail produced. However, all three methods are practical.

Details of the suspension (spring and dampers) are critical to modelling vertical response. Models can reproduce dynamic wheel loads to a certain degree of accuracy, based on the inputs to the models and the accuracy of the measured data.

There is a degree of spatial repeatability in dynamic loads. For the relatively smooth test site in France the level was approximately 10%, that is, the peak loads by location were 10% higher than the mean load. Further analysis is still required to determine whether this needs to be taken into account in pavement design.

Bridge design and management should incorporate information gained from this research regarding the potential effect of vehicle dynamics. Bridge and vehicle dynamic modes do couple together. For short span bridges the unevenness of the bridge approach together with the suspension damping are very important in controlling the impact on the bridge.

ACKNOWLEDGEMENTS

The DIVINE program was funded by member nations of the Organisation for Economic Co-operation and Development both through direct financial contributions and through in-kind support in the form of researchers, equipment and facilities. In New Zealand, this support was provided by Transit New Zealand, the University of Canterbury, Industrial Research Limited and the Public Good Science Fund. The authors are very grateful to all these organisations.

REFERENCES

COUNCIL OF THE EUROPEAN COMMUNITIES (1992). Annex III of the Council Directive 92/7/EEC amending Directive 85/3/EEC on the weights, dimensions and certain technical characteristics of certain road vehicles. Council of European Communities, Brussels.

EISENMANN J. (1975). *Dynamic wheel load fluctuations - road stress*. Strasse und Autobahn 4.

GYENES L. AND MITCHELL C.G.B. (1992). *The spatial repeatability of dynamic pavement loads caused by heavy goods vehicles.* Proceedings 3rd International Symposium on Heavy Vehicle Weights and Dimensions, Cambridge, UK. Eds D. Cebon and C.G.B Mitchell, Thomas Telford, London.

HAHN, W. D. (1985). *Effects of Commercial Vehicle Design on Road Stress - Vehicle Research Results.* Institut fur Kruftfahrwesen: Universitat Hannover.

O'CONNOR, T., O'BRIEN, E.J., and JACOB, B. (1996). *An experimental investigation of spatial repeatability.* Vehicle-Infrastructure Interaction IV, San Diego, June 1996. Engineering Foundation: New York.

OECD (1992). *Dynamic Loading of Pavements*. OECD Road Transport Research, Paris.

PIDWERBESKY, B.D. (1989) *Evaluating the Dynamic Interaction of Vehicle Characteristics and the Road Condition,* Proceedings of 3rd IRTENZ International Heavy Vehicle Seminar, Christchurch, August.

PIDWERBESKY, B.D. (1992) *Dynamic Response of Flexible Pavements to Tyre Types, Loads and Pressures.* Proceedings of 4th IRTENZ International Heavy Vehicle Seminar, Auckland, March.

WOODROOFFE, J. H. F. (1996). *Heavy Vehicle Suspensions: Methods for Evaluating Road-Friendliness.* Road User Research Report C-96-4. Prepared for National Research Council Canada, Centre for Surface Transportation Technology. RUR, Ottawa.

John de Pont, Industrial Research Limited.
Bryan Pidwerbesky, University of Canterbury.