Dynamic Pavement Loads And Road Wear: Scientific Questions The OECD DIVINE Project Is Intended To Answer

C.G.B. Mitchell
formerly of Transport Research Laboratory, United Kingdom

R.R. Addis
Transport Research Laboratory, United Kingdom

ABSTRACT

Earlier research has shown that dynamic pavement loads can increase road wear, but the scale of the effect is uncertain. The OECD DIVINE Project has been designed to include measurements, under laboratory conditions, of the possible reduction in pavement life caused by dynamic loads. Other experiments in the project are designed to determine the distribution of dynamic pavement loads along the road under mixed traffic; these will allow the laboratory test results to be applied to roads in service. Other tests will establish methods for rating the road-friendliness of heavy vehicles, and whether vehicles that are road-friendly are also bridge-friendly. The paper describes the underlying scientific questions the project is designed to address, and the consequential structure of the project.

INTRODUCTION

The loads which trucks impose on pavements and bridges have an important effect on the life of the infrastructure and therefore on total national road costs. There is also world-wide emphasis on increased productivity. Improvements in road freight productivity - through potentially higher payloads - have a large potential pay-off in reducing total vehicle operating costs and reducing transport costs, which typically represent at least 10% of gross national product in countries having advanced economies.

Pressure on existing road systems is known to be increasing. OECD transport research has found that dynamic pavement loading is currently increasing in OECD countries, leading to an increasing rate of road wear. The importance of this dynamic relationship is only just being recognised, as a result of increasing attention to infrastructure and vehicle operating costs brought about by:

- traffic growth
- pavement deterioration
- vehicle innovations, including configurations, suspensions and tyres, to enhance productivity.
- economic pressures

The DIVINE (Dynamic Interaction Vehicle-INfrastructure Experiment) Project is a co-operative international research programme into the dynamic loading of road pavements and bridges by heavy vehicles that was proposed in 1992 in the final report of OECD Expert Scientific Group IR2 "Dynamic loading of pavements". Planning of the project, by that Group, started in April 1992 and practical co-operative research began in October 1993. DIVINE involves some 17 OECD member countries, and includes specialists in vehicles, pavements, bridges, road management and transport policy. Inter-linked research projects are being carried out in nine countries, with co-ordination centres in Paris, Crowthorne (UK) and Melbourne.

The Project is designed to answer a number of scientific and technical questions. The four primary questions are;

1. Under controlled conditions, by how much do dynamic loads reduce the life of road pavements?

2. How do the results obtained under controlled conditions transfer to real road conditions with mixed traffic?

3. How should we specify and test heavy vehicles for road friendliness?

4. How much increase in pavement life should we expect from road friendly heavy vehicles in practice?

Two important but secondary questions addressed by the Project are:

5. Are vehicles that are friendly to roads also friendly to bridges?

6. Which computer simulation models of heavy vehicle dynamics are accurate and easy to use?

The answers to these scientific and technical questions are intended to allow policies on vehicle weights and dimensions, suspension standards, road construction standards and road maintenance to be considered on a more scientific basis.

The economic implications of the topic are considerable. It is estimated that in a relatively small country such as the UK, Heavy Goods Vehicle (HGV) traffic causes structural wear to the road system that costs about $1,300 million a year to repair. Road friendly suspensions could well enable 10 percent of this to be saved. Alternatively, if reductions in the potential of HGVs to cause road wear is used to increase the payload and hence the productivity of HGVs, the benefits for the economy could be even greater. In the UK, if average payloads could be increased by 1 percent, and the total distance travelled by HGVs reduced by 1 percent, the saving in vehicle operating costs would be of the order of $300 million.

This paper starts with a brief review of dynamic pavement loading and road wear. It will identify, in particular, the most significant uncertainties in assessing the effects of dynamic loads on road wear, and will then show how the OECD DIVINE Project has been planned to resolve these uncertainties.

DYNAMIC PAVEMENT LOADS AND ROAD WEAR

The dynamic loading of pavements and its effect on road wear was reviewed in the OECD Report "Dynamic loading of pavements" (OECD 1992) and, in greater detail, by Cebon (Cebon, 1985). Only the most significant findings will be summarised here, to identify the scientific uncertainties that existed at the start of the OECD DIVINE Project.

Some measurements of dynamic pavement loads had been made as early as the 1930s. Further measurements were made on more representative vehicles in the 1950s and 1960s, but these did not lead to policies on road friendly suspensions because there was no evidence of road wear caused by dynamic loading. Furthermore, road friendly suspensions were not readily available to encourage. Interest in the topic increased greatly from about 1975, particularly in Germany (Eisenmann, 1975; Hahn, 1987), North America (Whittemore et al, 1970; Ervin et al, 1983; Woodrooffe and Leblanc, 1986), Australia (Sweatman, 1983) and UK (Dickerson and Mace, 1981; Addis et al, 1986; Mitchell, 1987).

All the studies showed that dynamic pavement loads could be large fractions of the static loads applied to the road surface by heavy vehicles. They showed that dynamic loads tended to increase with increasing vehicle speed and road roughness, and that dynamic loading depended on the type of suspension used. The work in Germany also showed that the critical strains in pavements reflected the total static plus dynamic load applied to the pavement surface. The dynamic loads had predominant frequencies of 1.5 - 4 Hz if they were caused by the body of a vehicle bouncing on its suspension, or 10 - 15 Hz if it was caused by the axle "hopping" or "tramping" relative to the body of the vehicle.

Eisenmann (1975) developed a method to calculate the effect of dynamic pavement loads on road wear, but this has not been validated experimentally. It assumed that dynamic loads were randomly distributed along the length of a road and had a normal distribution of amplitudes, and that wear was proportional to the fourth power of the applied load. Hahn (1987) noted that most heavy goods vehicles had similar weights and suspensions, and travelled at similar speeds. He suggested that most heavy goods vehicles could well apply dynamic loads at similar points along a road. It was well established that a given vehicle making multiple passes over the same length of road at a given speed produced dynamic loads that repeated accurately from pass to pass, and there was some experimental evidence of a tendency for dynamic loads to concentrate at particular points along a road (Gyenes and Mitchell, 1992).

On the basis of this earlier work, the remaining issue was to quantify the effect of dynamic pavement loads on road wear. This required an experimental demonstration of the life of a typical pavement under a number of combinations of static and dynamic loads, in which it could be verified that the observed wear was proportional to the sum of the static and dynamic load components. Such an experiment could also confirm that the effect of the frequency of the dynamic load did not have a major effect on road wear. The need for this experiment became a key element of the DIVINE Project.

It was also important to determine whether dynamic loads under mixed traffic tended to cluster at particular points along a road in service. This could have a substantial effect on the life of a pavement. For an axle producing dynamic loads with a standard deviation of 25 per cent of static load (peak load 35 per cent of static), Eisenmann's method would predict an increase in road wear of about 37 per cent due to the dynamic loads (that is, by a factor of about 1.37). If the longitudinal loading pattern on the road were repeated exactly for every vehicle, this would imply an increase in road wear, at the point of peak loading, by a factor of about 3.3. Again,it was decided that this potentially important question should be addressed in the DIVINE Project.

As a result of the earlier work, it was widely recognised that road-friendly suspensions needed to equalise axle loads within bogie groups, and to generate small dynamic pavement loads. Good equalisation was difficult for some classes of suspension and needed much attention to detail design. Small dynamic pavement loads were achieved by suspensions with soft springs, appropriate levels of viscous damping, minimal coulomb friction and tyres that were not over -inflated. The European Union issued a directive (Commission of the European Community, 1992) that set criteria and a test procedure to measure these parametric characteristics. However, the validity of using such characteristics as a way of measuring road-friendliness was doubted by some workers, and the question of using complex road simulators, computer simulation or instrumented roads to measure the road friendliness of a vehicle was therefore included as an important issue for the OECD DIVINE Project to consider.

Finally, the question arose of whether vehicles that are road-friendly are likely to be bridge friendly. Normally the surface of a road or bridge is so much stiffer vertically than the suspension of a vehicle that the road surface can be considered rigid and the vehicle response to its profile involves no elastic interaction with the road. In these cases, vehicles that are road-friendly should apply lower dynamic loads to the bridge surface. This was shown to be the case by Mitchell et al (1991). However, some long-span bridges have fundamental bending frequencies in the range 1 - 4 Hz. In these cases there is the possibility of elastic interaction between the bridge and the vehicle, which could increase the dynamic loads applied to the bridge and the dynamic response of the bridge. In these cases it is possible that road-friendly suspensions, which have low frequencies and little friction, could prove to cause higher dynamic loads on some bridges than older types of suspension.

THE STRUCTURE OF THE DIVINE PROJECT

The DIVINE Programme comprises 6 research elements, each with connections to others. The elements are led by nominated experts in the particular field, and their responsibility is to ensure the correct conduct of the appropriate research element, leading to the integration of the results with those from other elements, and to the reporting of the results. Taken together, the six elements will provide an overall understanding of the topic that will be greater than the sum of the individual elements.

Research Elements 1, 2, 3 and 5 form a package that together attempt to answer the four primary questions noted earlier. Research element 6 addresses the specific effect of dynamic loading on bridge life and maintenance, while the more general question of how the observed effects of dynamic loading can be modelled is considered in Element 4. The six research elements are listed in Table 1, and described in detail in Section 4.

Self-funded research started during 1992. The first OECD-funded work in element 3 started in October 1993 and by May 1994 work was under way in all six research elements. Substantial progress has been made in most elements of the project and it is now possible to be confident that good quality scientific results will be obtained. It is still too early to predict the scientific results and policy implications of the Project.

Element 1 - Accelerated dynamic pavement test

Element 1 comprises an accelerated test to failure of a road pavement under two different patterns of dynamic loading. The research leaders of this element are experts in the field of accelerated pavement testing, from USA and Finland, and the test itself is carried out in New Zealand, under contract to OECD. Its purpose is to answer the question

> What are the lives of a pavement under two different known patterns of dynamic loading, as applied by a steel suspended axle and an air suspended axle.

In the test, being carried out on the University of Canterbury CAPTIF test facility, loading patterns are applied to separate tracks of a test pavement by a steel and an air suspension. The intention is to induce different, but known, dynamic load characteristics on each track. The dynamic load coefficient for the air suspension is less than half that for the steel at a given speed. Dynamic loads for the two suspensions are typical of those measured on the road. The estimated life of the test pavement under the air suspension is 1.8 times that under the steel suspension.

In addition to the test to failure, the structural response of the pavement, (as determined by the strains and deflections generated by the application of loads), is being measured at intervals, and the profile and structural condition of the pavement closely monitored throughout the test.

The test pavement comprises a bituminous bound layer 80 mm thick over an unbound granular base course of crushed rock 200 mm thick. The imported soil below the base is clay with a CBR of 10 - 12%. Following a comprehensive series of tests to establish the characteristics of both the loading and the pavement construction, (subsequently referred to as Zero Measurements), long term testing of the pavement began in October 1994. At 31st March 1995, 500,000 applications of load had been applied to each wheel track; although a 26 mm rut had developed in the wheel path of the steel suspension, compared to a 5 mm rut in the path of the air suspension, it is not thought that this was due to dynamic loading; rather, a local structural weakness has brought about the rut.

In addition to the results of the OECD test, the DIVINE Project will have available the results of a similar New Zealand test of a typical New Zealand pavement, tested to destruction under two different types of steel spring suspension which apply very different levels of dynamic loads. By comparison with many designs for heavy traffic, the pavement construction was relatively thin, comprising 80mm asphaltic concrete surfacing, and 200mm unbound granular base course, on subgrade of 10% CBR. The pavement was monitored throughout its life, and for the first time it has been shown that local rutting and cracking developed at points where high dynamic loads were being applied. Ultimately, failure occurred at one of the points of high dynamic loading. The patterns of rutting and cracking in the parallel tracks of the two wheels (arranged by loading arms of different radii) were different, proving that the areas of localised rutting

TABLE 1

DIVINE Project Research Elements

Element no.	Title	Research organisation	Question addressed	Co-operating organisations
1	Accelerated dynamic pavement test	Test by University of Canterbury, NZ. Managed by IRL for Transit NZ	How much do dynamic loads reduce pavement life	ARRB, VTT
2	Pavement primary response	Tests by VTT, Finland and FHWA	What pavement structural response is caused by dynamic loads	Canadian NRC, TRL
3	Road simulator testing	Canadian NRC	Can a road simulator replicate on-road dynamics and be used to rate suspensions	FHWA, TRL
4	Computer simulation testing	TNO Road Vehicles Research Institute	How accurate and easy to use are computer simulation models of heavy vehicle dynamics	Canadian NRC, model owners
5	Spatial concentration of dynamic loads	TRL and LCPC	Do dynamic loads concentrate spatially on roads under mixed traffic	Canadian NRC, TNO
6	Bridge dynamic loading	EMPA and Queensland Univ. of Technology	Are road friendly HGVs bridge friendly	Canadian NRC, BPW, industry in Australia

ARRB = Australian Road Research Board;
BPW = Industry - Axle manufacturer (Germany.
EMPA = Swiss Federal Laboratories for Material Testing and Research;
FHWA = Federal Highways Administration (Turner-Fairbanks Highway Research Centre);
IRL = Industrial Research Limited, New Zealand;
LCPC = Laboratoire Central des Ponts et Chaussées (France);
NRC = National Research Council of Canada;
TNO = TNO Road Vehicles Research Institute (Netherlands).
TRL = Transport Research Laboratory (UK);
VTT = Technical Research Centre of Finland;

and cracking were caused by localised loading, not by localised weaknesses in the pavement (Figure 1). This suggests that dynamic pavement loads can cause localised rutting, cracking and premature failure of road pavements of this type.

Element 2 - Pavement primary response

This Element is designed to measure the structural responses of several pavements to known combinations of static and dynamic loads applied at the surface by instrumented heavy vehicles, to establish how the ratio of primary pavement response/applied dynamic load changes as the frequency of the dynamic load varies. Its purpose is to answer the questions:

Do the pavements respond structurally to applied dynamic wheel loads as well as to rolling static wheel loads?

How does the ratio of structural response/applied dynamic load vary as the frequency of the dynamic load varies?

The work is carried out on heavily instrumented test roads at the Virttaa site in Finland and at the Turner-Fairbanks Highway Research Centre in the USA and is led by the latter country.

In addition, it is expected that the results of the work will assist in extrapolating the results of Element 1, derived using single wheels on a half-axle, to multi-axle groups, and will also assist understanding of the effects of vehicle speed on the pavement response to dynamic loads.

In addition to measuring the structural response (strain, deflection, soil pressure) to wheel loads that are varying dynamically over a wide range of frequencies in response to the road profile, the response of the pavement to dynamic loads in narrow bands of frequencies is also being measured. Excitation of particular vibration modes of the test vehicles is induced by driving vehicles over artificial bumps on the road surface.

The results are linked closely to those of element 1, since if the structural responses of the pavement to measured dynamic loads are known, the life of the pavement under a defined pattern of dynamic loading (such as is available in Element 1) can be calculated. The results of Element 2 should also allow some investigation of the effect of suspension dynamics on pavement life by a single, or a few, vehicles of specified type. More generally, currently available pavement design programmes can be used to predict the structural response of the pavements used in elements 1 and 2 to known applied loading. This will increase confidence in the ability of such programmes to assess road wear in dynamic terms, perhaps leading in the longer term to their being used to assess road friendliness of vehicles.

Element 2 links to Element 3 through the frequency content of the dynamic loads applied by different vehicles or suspensions. Road friendly suspensions tend both to have lower frequencies for the fundamental modes of the sprung masses of a vehicle (body heave in particular) and to respond less in these modes. They also tend to respond as much or more than unfriendly suspensions in the modes of the unsprung masses (axle hop and axle roll). They should respond less at intermediate frequencies typical of bogie pitching modes, but the evidence on this is not definite. Element 2 provides evidence on whether the frequency of the dynamic loading has a significant effect on the pavement response it generates.

The pavements used in elements 1 and 2 have been chosen to make it possible to compare results from the different tests. Thus the pavement for the accelerated test in Element 1 has 80 mm bound bituminous material over a base course of 200 mm of crushed rock. The VTT pavements for element 2 testing have (pavement C) 80 mm bituminous surfacing over 150 mm base course and (pavement B) 150 mm bituminous bound material over 400 mm base course. The FHWA pavement for element 2 has 180 mm bituminous bound material over a 300 mm base course. It should be possible to compare between the CAPTIF test pavement for element 1 and the VTT pavement "C" and between VTT "B" and the FHWA pavement. The effect of the thickness of the bound layer can be examined by comparison between the two 80 mm pavements and the two heavier pavements. The instrumentation in all the pavements is similar.

The measurements at the Virttaa test site have been completed, using instrumented HGVs from Canadian NRC, TRL and VTT to provide dynamic loads over a wide range of input frequencies. Analysis of these results is a priority in the DIVINE project. Existing research results from the University of Munich and from TRL show that dynamic loads do cause structural responses in pavements, and this will of course assist in confirming the answer to the first question.

The University of Cambridge have estimated the effect of the frequency of dynamic loading on the structural response of a pavement, and Element 2 will therefore provide the first empirical information on this topic. The assessment of the road friendliness of suspensions would be improved if the relative consumption of road life by low frequency and high frequency dynamic loads of various amplitudes was known.

Element 3 - Road simulator testing

Element 3 consists of measurements of dynamic pavement loads for several vehicles on several roads with different unevenness profiles. It then replicates these road profiles on a road simulator (shaker rig) to check whether the laboratory shaker tests reproduce the dynamic motion and dynamic pavement loads measured for the same vehicle on the road with the same profile. Finally, if the road simulator can be successfully validated, it will be used to explore ways of using a road simulator to rate the road friendliness of a vehicle or suspension. This work is being led and largely done by Canadian NRC, with considerable assistance from FHWA and TRL.

Element 3 is designed to answer several basic questions:

> Can a road simulator replicate the dynamic motion and dynamic pavement loads produced by a vehicle when running on a road with the same profile as that used to excite it on the road simulator?
>
> Can a road simulator be used to rate the road friendliness of a vehicle or suspension, or be used to develop road or track tests to rate road friendliness?
>
> How much do the dynamic loads vary between vehicles, suspensions and road profiles?

There is already considerable data to answer the third question from previous tests in Germany, Australia and Britain, and limited data on the first from tests done by TRL.

In October 1993 three instrumented HGVs with very different overall and suspension characteristics (from NRC, FHWA and TRL) were used to measure dynamic pavement loads on three sections of road in Canada for which the profiles have been measured. By July 1994, the instrument calibration of the TRL vehicle had been checked and its stiffness and inertial characteristics measured on the NRC road simulator. It had also been used to measure the dynamic pavement loads induced by the three road profiles on the NRC road simulator and by two of the profiles on the Volvo road simulator. Analysis of all these measurements is well advanced.

Dynamic loads for the NRC and FHWA vehicles were measured on the NRC road simulator during summer 1994 and on the FHWA road simulator later in 1994. This series of tests is the most extensive ever undertaken to establish whether a road simulator does accurately replicate the dynamic motion of an HGV on the road. Because of the use of three different simulators, they should also discover whether results can be obtained that are independent of the road simulator used for the tests.

Element 3 will provide, among other results, measurements of the frequency content of the dynamic loads for several vehicles, suspensions and road profiles. These can be used with the results of element 2 to estimate the structural responses of road pavements to the different vehicles or suspensions, and for different road profiles. The lives of the pavements can then be calculated from the structural responses. In this way, road friendliness could be assessed in terms of pavement life, as well as the more conventional measure of dynamic pavement load.

Element 4 - Computer simulation testing

Element 4, which is being led by TNO Road Vehicles Research Laboratory, is concerned with the question:

> Are there computer simulation packages available that accurately model the dynamics of HGVs and which are relatively easy to use?

Work on this element began in May 1994. By July 1994, owners of computer simulation packages were being invited to participate in a blind trial to predict the dynamic pavement loads on the three Canadian road sections for the instrumented HGVs. These predictions will then be compared with the measurements to establish the accuracy of the package, and an assessment made of how easy the package is to use. At the time of writing, owners of the models had been provided with the necessary input information and results were awaited.

Element 5 - Spatial concentration of dynamic loads

Element 5, which was initiated by TRL, but is now being jointly led by LCPC (France) and TRL, is concerned with establishing to what extent dynamic loads concentrate spatially under mixed traffic. The information from this element is intended to be used to calculate the effects of dynamic loads on pavement lives in practice, and hence the economic value of making heavy vehicle suspensions more road friendly.

Its principal approach is to measure the concentration of dynamic loads under mixed traffic on a number (at present three) sections of roads with different roughness profiles. As back up methods of estimating the extent of spatial concentration, records of dynamic loads for different test vehicles at different speeds on the same length of road can be analysed to seek patterns of spatial concentration of dynamic loads, and similar analyses can be made of dynamic loads measured on the road simulator or calculated in Element 4. To date, these back up methods have given results for concentrations that are similar to those measured on public roads under general mixed traffic.

Measurements at one road section in the UK were completed in 1992 and show clear evidence of spatial concentration. Over a 20 metre length of road the cumulative axle load varies $\pm$ 20 percent about the mean and the sum of the 4th powers of the axle loads varies by a factor of more than three, with the wear at peak points being about twice the average for the section (Figure 2). During 1994, at a more comprehensively instrumented second site in UK, the dynamic wheel loads for about 30,000 axles had been measured at 24 stations along a 48 metre test section. Problems in the instrumentation have so far precluded a comprehensive and reliable analysis of these results.

In France, LCPC commissioned an 18 sensor measuring installation in May 1994 and by July 1994 had calibrated the in-road sensors. Measurements under normal traffic flow are now well-advanced. The installation differs in several important respects from the UK installations, and the results will complement those available from the UK site.

The results of element 5 are crucial to the interpretation of the results of elements 1, 2 and 3 in terms of pavement lives in practice and the economic benefits of road friendly suspensions. An important result from element 5 will be the extent to which road friendly suspensions affect both the magnitude and distribution of dynamic pavement loads in practice, and hence the life of the pavement. One output from the work will be an analysis of the experimental results to find the effects of road profiles, if any, on the spatial concentration of dynamic loads. The reduction of spatial concentrations, if they arise on all roads, could possibly be brought about by changes to vehicle design or to road profiles, and this may be preferable to accepting the substantial and deleterious effect on pavement lives that spatial concentration may cause.

Element 6 - Bridge dynamic loads

Bridges are important components of any pavement network; they are particularly important from the point of view of the DIVINE experiment because of the possibility of induced displacements and oscillations in the structure as a result of imposed dynamic loading. Although these are extremely unlikely in normal circumstances to lead to failure of the structure, its life may be reduced, with inevitable economic consequences, and there may be other consequences for vehicle and structure interaction.

In Element 6, led by Switzerland, research programmes carried out in Australia and in Switzerland are being used to address some of these specific problems, namely:

> Do vehicles that are friendly to road pavements cause any deleterious dynamic effects for long span, low frequency, bridges (Switzerland - EMPA)?
>
> What is the effect of road friendly HGVs on the dynamic deflections of short span bridges (Australia - Queensland University of Technology)?

The principal objective of the work is to improve understanding of the response of a variety of bridge spans to imposed dynamic loads. Instrumented vehicles were used to measure the instantaneous loads applied to a bridge, and were correlated with the resulting oscillations in the bridge itself.

In April - May 1994 EMPA, in co-operation with Canadian NRC, successfully measured the dynamic wheel loads and bridge deflections for three long span bridges. The bridges had fundamental frequencies of 1.6, 3.0 and 4.7 Hz. They were loaded by the 45 tonne Canadian NRC instrumented truck, fitted either with all steel spring suspensions or all air suspensions (except for the steer axle, which remained steel sprung). A large amount of analysis remains to be done, but it does appear that the air sprung HGV caused larger deflections of the 1.6 Hz bridge than did the steel sprung truck. Whether this is significant for the design loads for long span bridges is not yet known.

In Australia, measurements of dynamic wheel loads and bridge deflections were made for two short span bridges loaded by a 6 axle HGV fitted with either all air suspensions or all steel suspensions. Dynamic coupling between the air suspension and one of the bridges was marked at one critical speed when the vehicle was excited by a short bump on the bridge abutment. At other speeds the dynamic increment to the deflection was relatively small.

Because the response of a bridge structure to dynamic loading is somewhat different to that of a pavement structure, the results obtained on one are not transposable to the other. The important link between them, however, is the need to be able to assess short-term effects on the structures, so that the consequences for the whole-life economics of each can be calculated. Important decisions on the need for maintenance, and future funding of that maintenance, may then be made more accurately.

CONCLUDING DISCUSSION

Research in all six elements of the DIVINE Project is under way and progressing well. From the detailed results given in section 3 above it can be seen that most of the research elements are already producing significant results that will contribute substantially to existing knowledge. Many of the results being obtained will be measurements and analyses that have never been made before. They have considerable significance for an understanding of the interaction between heavy vehicles, road pavements and bridges, and it is hoped that the final report of the DIVINE Project will enable the highway engineering community to undertake extensive changes to the design of road pavements, their maintenance, and the regulation of heavy vehicles. The economic implications of the scientific results that are emerging are very considerable.

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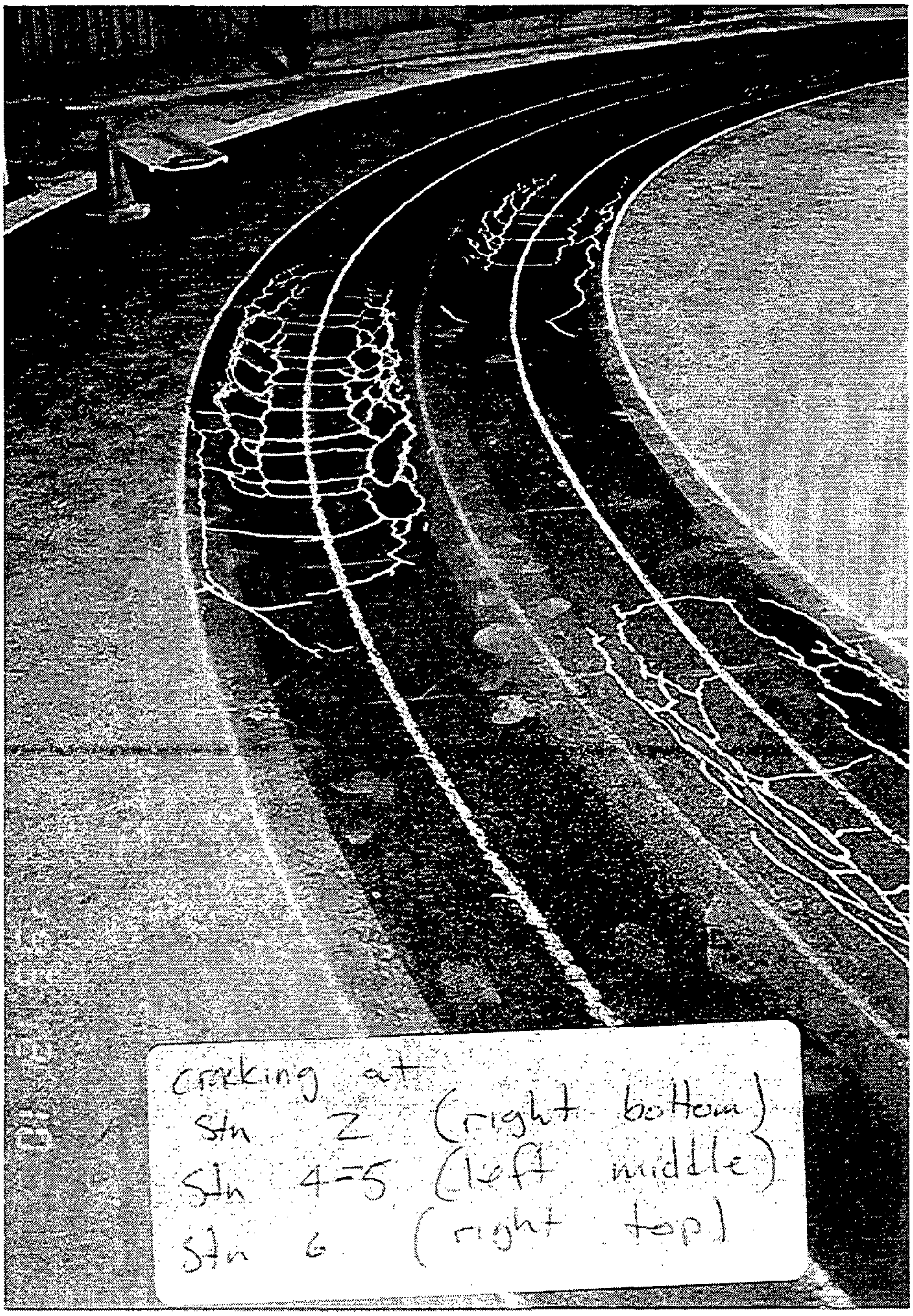
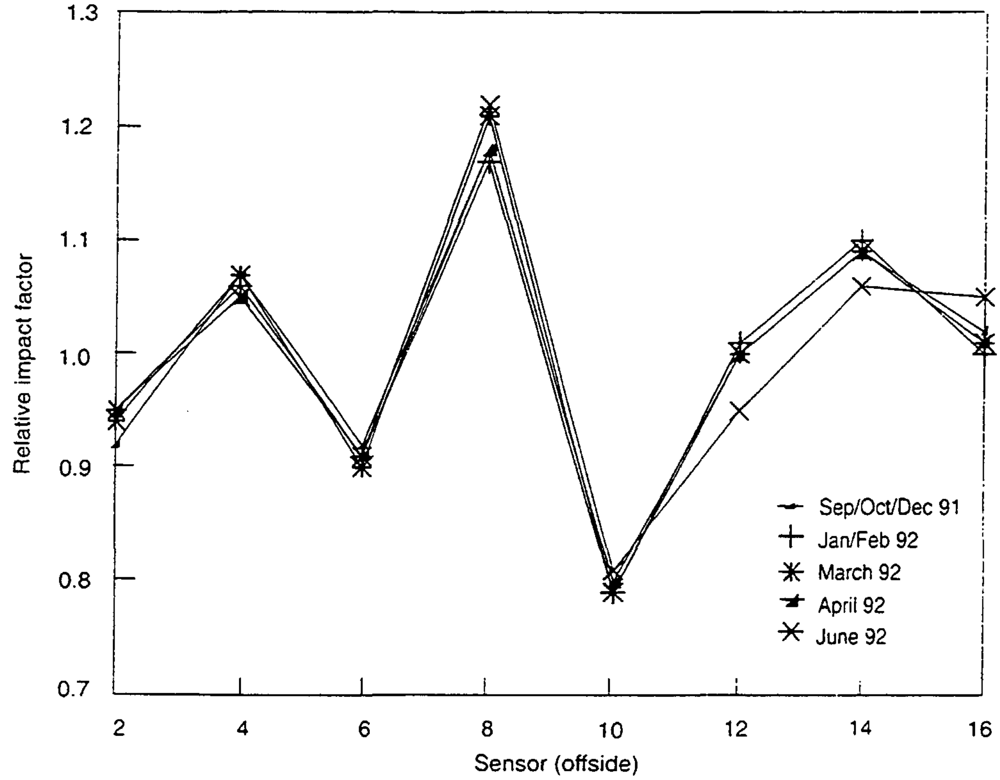
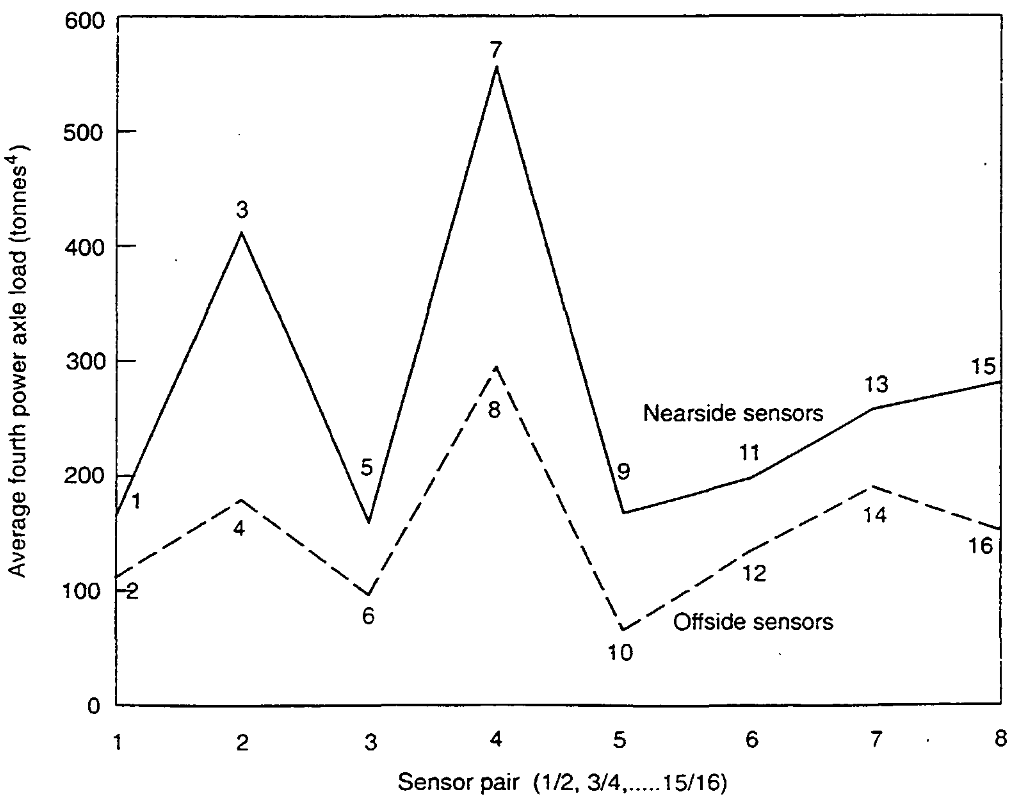


Figure 1 **Localised damage at points of high dynamic loads on a test pavement in the CAPTIF pavement test facility with different suspensions running in the two test tracks.**



a. Offside relative impact factors over time



b. Average fourth power axle loads at each sensor location

Figure 2 Dynamic loading on 4721 axles measured on the A34 at Abingdon
(source: I Barbour, 1993)