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IMPROVING THE INTERACTION BETWEEN HEAVY TRUCKS, ROADS & BRIDGES

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ABSTRACT

A major co-operative international research program known as DIVINE (Dynamic Interaction between Vehicles and Infrastructure Experiment) has been completed by the Organisation for Economic Co-operation and Development. DIVINE involved seventeen OECD member countries, and included specialists in vehicles, pavements, bridges, road management and transport policy. Inter-linked research projects were carried out in nine countries and the project took almost four years to complete. DIVINE set out to investigate the benefits of “road-friendly” suspensions for reducing pavement wear and to develop better means of assessing vehicle suspensions for road-friendliness.

This paper summarises the most important results of DIVINE and presents means of assessing and simulating the road-friendliness of truck suspensions. Dynamic loading depends on the vehicle suspension, and the use of air suspension generally reduces dynamic loading. Current air suspensions could be improved in certain respects and the effectiveness of their dampers influences dynamic loading. Current designs of air suspension also have advantages for vehicle stability and safety performance, ride quality, driver comfort and quieter operation. The results of the DIVINE Project have shown that, under controlled experimental conditions, the dynamic loading associated with conventional mechanical suspension causes a significant increase in pavement roughness (or unevenness) in certain aspects of cracking and rutting. Assessment of vehicles for road-friendliness was extensively researched in the DIVINE Project and it was found that dynamic suspension tests utilising a road simulator provide the most effective means of vehicle assessment.

The implications of the DIVINE results for pavements, bridges and vehicles are summarised and the differing means of implementation of the results in Asia-Pacific, North America and Europe are indicated.

Introduction Content

INTRODUCTION

A world-wide reduction in the availability of funds for infrastructure construction and maintenance, along with rapidly-expanding demands for freight transport, requires scientific and engineering responses to the issues of reducing pavement and bridge maintenance costs related to truck use and to better, more-integrated, design of vehicles, pavements and bridges.

Upkeep of roads generally represents between 40% and 80% of total road costs and could typically represent 0.4% of GNP, or an annual unit cost of million US$15 per 1,000 kilometres of road length. A certain portion of pavement construction and maintenance costs is attributed to the effects of heavy vehicle traffic, which in turn is related to axle load. The method of attribution usually involves a "power law" relationship which means that costs increase at a faster rate than the axle loads.

The proportion of road costs directly attributed to heavy vehicles varies between countries, but is always significant (for example, up to 50% of pavement rehabilitation costs). These cost pressures will continue to exist even if the use of other transport modes, especially rail, and possibilities for intermodal transport, are exploited to the full. However, it is not always understood that total freight vehicle operating costs, which are distributed over many private companies, are many times larger than road maintenance costs. These costs are strongly influenced by road and traffic conditions and, in an indirect way, by regulations imposed by road agencies.

Road freight vehicles are operated in a highly-competitive and strongly-regulated environment and are essential elements in increasingly-global freight transport systems providing integrated logistics services. The increasingly stringent operating parameters for heavy vehicles have brought about rapid technological improvements in vehicle design and operation.

The DIVINE Project (1) described important aspects of the interaction between heavy vehicles and the infrastructure in an objective manner and suggested ways in which those responsible for the main parts of this interaction - pavements, bridges, vehicles and transport regulations - could act to reduce the negative consequences of road freight transport and reduce costs.

In order to provide new options for advanced road management techniques, the DIVINE Project set out to quantify - *for the first time* - the influence of heavy vehicle suspension design and of pavement longitudinal profile and pavement structural variability, on pavement wear. DIVINE involved road agencies and road and bridge research organisations, as well as the private sector, with active participation from 17 member countries. The project commenced in 1992 and was completed in 1997. Six inter-related experiments, involving various aspects of pavements, bridges and vehicles and their interaction, were carried out under the scientific control of OECD Expert Group IR6.

OVERVIEW OF OECD DIVINE RESEARCH

Element 1: Accelerated Dynamic Pavement Test

Element 1 comprised an accelerated test designed to cause distress and eventually failure of a road pavement under two different patterns of dynamic loading. In the test, which was carried out by Transit New Zealand and conducted at the University of Canterbury at

Christchurch (CAPTIF), loading patterns were applied to a single road pavement by a steel and an air suspension. Pavement distress, the structural response of the pavement, and the profile and structural condition of the pavement were closely monitored throughout the test.

Element 2: Pavement Primary Response Testing

The aim of this Element, which was conducted by the US FHWA, McLean, VA and the Technical Research Centre (VTT), Espoo, Finland, was to measure the structural responses of several instrumented pavements to known combinations of static and dynamic loads applied at the surface by instrumented heavy vehicles, and hence to establish how the ratio of primary pavement response to applied dynamic load changes as the frequency of the dynamic load varies.

Element 3: Road Simulator Testing

Element 3 was conducted by the National Research Council (NRC), Ottawa, Canada, in two stages. In the first stage, measurements were made of the dynamic wheel loads generated by several vehicles on several roads with different roughness profiles. These profiles were then replicated on a laboratory road simulator to check whether such tests reproduced the dynamic motion and dynamic wheel loads measured in over-the-road tests. In the second stage, the validated road simulator was used to explore ways of using such equipment to rate the road friendliness of a vehicle suspension, including the EC drop test (2) and alternative means of exciting the vehicle suspension.

Element 4: Computer Simulation of Heavy Vehicle Dynamics

Element 4, which was conducted by the TNO Road-Vehicles Research Institute in Delft, The Netherlands, and compared the predictions of a number of simulation models of dynamic wheel loading with measured data from Element 3 of the project.

Element 5: Spatial Repeatability of Dynamic Loads

The objective of Element 5, which was conducted by the Laboratoire Central des Ponts et ChaussÈes (LCPC), France, and by the Transport Research Laboratory, UK, was to establish to what extent dynamic loads concentrate spatially on real roads under mixed traffic. Weigh-in-Motion (WIM) sensors installed in two highly-trafficked highways were used to measure the concentration of dynamic loads under mixed traffic for known road profile characteristics.

Element 6: Bridge Dynamic Loads

Element 6 investigated the extent to which dynamic wheel forces couple with the natural frequencies of bridges, resulting in undesirable bridge vibrations. The aim of Element 6, which was carried out by EMPA, Switzerland, and Queensland University of Technology, Australia, was to investigate whether pavement-friendly vehicle suspensions are also bridge-friendly.

Medium-span bridges were investigated with respect to frequency-matching effects associated with the lower body bounce frequencies of modern soft suspensions, whilst short-span bridges were investigated with regard to effects in the axle hop frequency range. The dynamic wheel forces and the primary responses (in terms of deflection) of the bridges were measured simultaneously and the road and bridge profiles were determined.

CONTROLLING DYNAMIC LOADING

The measurement of dynamic wheel loads, which involve rolling contact between the tyre and road surface, is a specialised task and has usually been accomplished using on-board instrumentation. An earlier OECD report (3) summarised the research in this area. As a result of a variety of static and dynamic processes, heavy vehicles apply wheel loads to roads and bridges that are higher than might be expected based on nominal axle loads. The static component depends on the total weight of the vehicle and its axle configuration and is very significantly influenced by the legal axle and gross vehicle weight limits adopted in various countries. The dynamic component depends on the vertical dynamics of the vehicle, and includes such factors as the mass and stiffness distribution of the vehicle's structure, payload mass distribution, suspension and tyres, and on the road surface's longitudinal profile and the speed of the vehicle.

Most heavy commercial vehicles generate their dynamic wheel in either in the 1.5...4 Hz frequency range associated with body bounce or pitch motions, and/or in the 8...15 Hz frequency range associated with axle-hop vibrations. Axle-hop vibrations are more significant if the pavement is rough and the vehicle speed is higher than approximately 40 km/h.

The magnitude of dynamic loads and their frequency content are both of significance to pavement and bridge interactions. The DIVINE Project adopted the Dynamic Load Coefficient (DLC) as the prime measure of dynamic loading, and considered both low-frequency (1.5...4 Hz) and high-frequency (8...15 Hz) loading. The DLC is defined (2) as the ratio of the RMS dynamic wheel force to the mean wheel force.

Typical magnitudes of dynamic wheel loads, when expressed in terms of the DLC, range between 0.05 - 0.10 for well-damped air suspensions and soft, well-damped, steel leaf suspensions, and 0.20 - 0.40 for less road-friendly suspensions. The magnitude of the dynamic wheel load generally increases with both speed and road unevenness.

The DIVINE Project did not attempt to repeat these on-board measurements, but extended knowledge of dynamic loading through large-scale road-based measurements, analysis of the mode shapes of tractor-semi-trailers and the development of means of measuring dynamic loading in the laboratory and of simulating dynamic loading.

WIM sensor measurements of dynamic loading generated by a large number of heavy vehicles in the traffic stream (4) showed that the use of air suspension on semi-trailers reduced dynamic loading by 10 - 12 % when compared with steel suspension. There was little difference in the dynamic loading generated by air and steel single-drive-axle suspensions on tractors; this could reflect efforts in Europe to develop single-drive-axle steel suspensions which are equivalent to air suspension under EC axle weight Directives. The WIM sensor measurements also highlighted the relatively large contribution of tyre/wheel non-uniformity to dynamic loading on smooth road surfaces.

DIVINE found that air suspension damping has an important effect on dynamic loading. This was evidenced in several different situations. One scenario involved testing air suspensions both with and without dampers (5, 6). Table 1 shows the relative dynamic wheel force magnitude under resonant conditions, for air and steel tandem suspensions (5).

Table 1. Dynamic wheel force magnitude for tandem suspension under resonant conditions (laboratory test with 1 mm frequency sweep excitation) (5)

Suspension Type	Dynamic Wheel Force Magnitude (steel suspension = 100)	
	Low-Frequency	High-Frequency
Air (with dampers)	11	750
Air (dampers removed)	28	2480
Steel	100	100

When the dampers were removed from one axle of an air-suspended tridem group (6), the amplitude of dynamic loading on that axle increased by 110 %. This test involved travel over a bridge with smooth profile at approximately 60 km/h and the high-frequency (axle hop) mode was most affected.

In another scenario, a 2-axle straight truck simulation model which was validated by the DIVINE Project was used to determine the effect of air suspension damping on dynamic loading expressed in terms of the DLC (5). It was found that the DLC does not increase significantly until the damping falls below 10 %, and the total removal of dampers therefore represents an extreme case.

The DIVINE results confirmed that the use of air suspension often greatly reduces low-frequency dynamic loading, but not in all cases. This does not seem to apply to European single-drive-axle suspensions, and is negated when the damping of the air suspension is allowed to fall below 10 %. The DIVINE results have also shown that high-frequency dynamic loading is a significant issue for current air suspensions, more so than for steel suspensions.

Well-maintained air suspensions are basically road-friendly in the low-frequency modes; further research into the high-frequency modes of air suspensions is needed and DIVINE has indicated that current air suspensions could be improved in this area.

SUSPENSION ASSESSMENT

The essential properties of road-friendly suspensions have been confirmed as low spring stiffness, very low Coulomb friction and an appropriate level of viscous damping (5). Such properties are generally to be found in well-designed and well-maintained air suspensions and it is unlikely that steel spring suspensions could achieve the desired level of performance in low-frequency dynamic loading.

The current EC requirement of 2 Hz maximum frequency and 20% minimum damping (2) generally succeeds in differentiating between air and steel suspensions but is less appropriate to its original purpose of specifying performance equivalent to air suspension.

The dynamic loading generated by suspensions is sensitive to both the frequency and damping of the suspension, as measured in the EC bounce test. It was also found that the frequency and damping of air and steel suspensions are not independent parameters. For practical reasons, it is difficult to design an air suspension or steel suspension with good damping and a frequency above 2 Hz.

The sensitivity of dynamic loading to suspension damping is such that there is very little increase in dynamic loading as the damping reduces from 20% to 15%, a slightly greater increase as damping is further reduced to 10% and then a strong increase as damping is reduced below 10%. This is particularly true if the suspension frequency is limited to 1.5 Hz.

It was also found (5) that there is limited value for reducing dynamic pavement loading in reducing suspension frequency below 1.5 Hz or in increasing damping beyond 20%. However, damping greater than 20% could have benefits for heavy vehicle safety performance and for reducing axle hop vibrations under severe conditions of road roughness.

DIVINE has recommended (1) that “road-friendly” suspension should be defined by the following criteria, as determined in the EC bounce test:

- frequency of 1.5 Hz or less,
- damping of 20% or more.

The DIVINE Project has also suggested an alternative test method, using a 1mm sinusoidal excitation sweeping through a wide frequency range, that may be more accurate and consistent than the EC bounce test.

In the case of axle group suspensions (for example, in tandem and tridem axle arrangements), it is also necessary to control suspension equalisation performance.

DYNAMIC LOADING & PAVEMENTS

For relatively thick pavements (160 mm of bituminous material) horizontal strains measured at the bottom of the asphaltic layer were found to be almost directly proportional to the dynamic wheel force (7,8). A 10% increase in dynamic wheel load, for example, produced a 7-12% increase in strain; given the accepted relationship(s) between strain and pavement material damage, this implies significantly increased pavement wear under traffic which consistently applies such loads. This effect was independent of wheel load frequency content: low-frequency loading and high-frequency loading alike affected strains in thick pavements.

In the case of thin pavements, horizontal strains are less sensitive to dynamic wheel force and appear to be influenced by surface contact conditions between the tyre and pavement (8).

Under mixed traffic, dynamic loads tend to concentrate at points along a road at intervals of typically 8 - 10 metres (4). On a smooth road, the cumulative sum of axle loads at a point of concentration is about 10%. On a rough road, this effect is at least twice as large. The concentration of dynamic loads for air suspension has only about half the magnitude of that for steel suspensions.

This phenomenon is heavily dependent on the road profile, the mix of suspensions in use on the vehicles in the traffic stream, the wheelbases of those vehicles, and the range of their speeds. In circumstances where the composition of the truck traffic flow tends to be confined to a few particular types, the risk of pavement wear from spatial repeatability will thus be higher. Such circumstances are increasingly frequent, particularly as the nature of heavy goods vehicles tends to be function-specific.

The DIVINE accelerated dynamic pavement test (9) showed that pavement profile deteriorates more rapidly under a steel suspension than under an air suspension carrying the same load. Some aspects of cracking and the maximum rut depth were also greater under the steel suspension. Pavement wear under the steel suspension was at least 15% faster than under the air suspension.

Power Spectral Density (PSD) comparisons showed investigated the wavelengths where most of the changes in longitudinal profile occurred for both wheelpaths. These analyses showed that:

- there was some concentration of profile changes under the steel suspension around a wavelength of 5.8 metres, which corresponded to the steel suspension frequency; and
- a small concentration of profile changes was evident under the air suspension around a wavelength of 8 metres, which corresponded to the air suspension frequency.

In the accelerated test (9), long-term pavement profile changes under the steel suspension were correlated with both dynamic wheel load and local structural strength of the pavement and it is difficult to separate these two effects: the development of pavement roughness is truly an interactive process involving dynamic wheel loading and variability in pavement structural strength, as measured in dynamic deflection tests. On the other hand, very little long-term profile change occurred under the air suspension.

It was found that a relationship of the form

$$VSD = c * FWD^{P1} * WF^{P2} \qquad (1)$$

provided the most effective representation of the test data and that the highest correlation coefficients, for the range of relationships investigated, were obtained for the following relationships for each wheelpath:

$VSD = c * FWD^{1.1}$ (air suspension wheel path) $r = 0.53$ (2)

$VSD = c * FWD^{3.2} * WF^{1.8}$ (steel suspension wheel path) $r = 0.76$ (3)

where VSD = vertical surface deformation of pavement (between 20,000 cycles and 1.7 million cycles),

FWD = maximum Falling Weight Deflectometer deflection at 20,000 cycles, and

WF = average of dynamic wheel forces at 20,000 cycles and at 1.7 million cycles.

Whilst these relationships require further investigation, they suggest that:

- the local structural strength of the pavement had a significant influence on vertical pavement deformation for both suspension types;
- dynamic wheel force had a significant influence on vertical pavement deformation for the steel suspension only; and
- vertical pavement deflection under the steel suspension could be related, via a power law, to the product of: (i) pavement structural compliance (as measured by the FWD), and (ii) the dynamic wheel force.

DYNAMIC LOADING & BRIDGES

The DIVINE bridge testing (6) found that the surface profile of a bridge and its approaches are fundamental to the response of the truck suspension and in turn the dynamic response of the bridge. For a smooth profile, the influence of the truck suspension is insignificant; the importance of the suspension increases as the unevenness of the profile increases.

For medium-span to long-span bridges (20 - 70 metres) with smooth profiles, dynamic responses are relatively small for both air-suspended and steel-suspended vehicles; within this range of responses, increased responses occur for air-suspended vehicles on 1.6 Hz (70 metre) bridges and for steel-suspended vehicles on 3.0 Hz (40 metre) bridges. For short-span bridges (10 metres) with poor profiles, large dynamic responses occur for both air-suspended and steel-suspended vehicles. The highest measured responses were for short-span bridges with poor damping traversed by air-suspended vehicles with large axle hop vibrations.

Dynamic responses of medium-span to long-span bridges (20 - 70 metres) with smooth profiles fall within current dynamic load allowances in bridge design codes. Dynamic responses of short-span bridges with poor profiles are well above current dynamic load allowances in a significant number of cases. There is a strong case for further investigation of the high-frequency behaviour of air suspensions and for improved design to reduce high-frequency dynamic loading of current air suspensions used in tandem and tridem axle groups.

IMPLICATIONS OF DIVINE RESEARCH

Road Condition Measures

The DIVINE Project has highlighted the importance to vehicle-pavement interaction of two pavement condition measures in particular. These are pavement profile evenness, and local structural strength (or compliance) of the pavement.

The pavement surface profile has a determining influence on dynamic loading and is believed to also influence the degree of spatial repeatability of dynamic loading; it is also the prime indicator of pavement functional condition and a key manifestation of pavement wear. While the IRI roughness index provides a reasonable indication for some of these purposes, the DIVINE Project found that PSD-based profile indices are to be preferred. Further development of profile indices to better represent (i) dynamic loading, (ii) spatial repeatability and (iii) functional condition and wear is recommended.

The local structural strength of the pavement, as measured by the FWD, was found to provide an excellent indication and prediction of pavement wear, pavement damage and local failure. It is recommended that the FWD is used at closely-spaced intervals to determine the structural variability at construction and at other appropriate intervals throughout the life of the pavement.

Greater prominence of (i) current and improved profile indices and (ii) structural variability in pavement management techniques would bring about a significant enhancement of both truck and pavement performance.

Pavement Technologies

The DIVINE Project has highlighted the need to enhance technologies for the design and function of pavements. Specific areas which the DIVINE results have identified as requiring further research are:

- greater consideration of structural variability, dynamic loading and spatial repeatability in mechanistic pavement design;
- calibration of accelerated pavement tests against field tests, especially with regard to functional performance;
- the development of improved, lower-cost pavement response instrumentation with better reliability and accuracy, in order that higher quality data may be obtained for developing and validating pavement models.

Heavy Vehicle Regulations

Policy-related information concerning the likely effects of increments in heavy vehicle regulations, and of substituting more road-friendly vehicles for steel-suspension vehicles in our national fleets, is highly-relevant in the Asia-Pacific, European and North American regions. Examples of such issues are:

- How much more road maintenance and costs are associated with a certain increase in axle weights?
- How much more weight can be allowed when a further axle is added to a vehicle (for example, substituting a tridem for a tandem axle group)?
- How much more weight can be allowed when road-friendly suspension is substituted for non-road-friendly suspension?

The results of DIVINE show that such issues need to embrace a full range of pavement construction, pavement condition and vehicle configuration variables in order to arrive at realistic and credible answers.

To support the implementation of improved regulatory policies, it is necessary to have access to credible and practical tools for assessing pavements and vehicles. DIVINE made a strong contribution in the following areas:

Measurement of pavement structural condition and its variability - DIVINE found the FWD is a powerful tool for this purpose.

- Measurement of pavement functional condition - although profilometer technologies are well developed, DIVINE found that current profile indices require further development to better reflect dynamic loading and spatial repeatability.
- Means of assessing the road-friendliness of suspensions - DIVINE has provided several methods for doing this.

Validated modelling of pavement functional condition in response to the dynamic interaction of vehicles and pavements - DIVINE has provided guidance on effective vehicle models and further work is now needed to develop, evaluate and validate vehicle-pavement dynamic models of functional condition.

Road Cost Responsibility of Trucks

The DIVINE results indicate that current pavement design and evaluation techniques tend to over-estimate the direct contribution of heavy vehicle loads to the shortening of pavement life. The DIVINE results also show that it is difficult, and probably inappropriate, to partition the influences of the vehicle and the pavement. These elements need to be considered in an interactive way.

The real role of heavy vehicles and their wheel loads - static or dynamic - in creating pavement wear and pavement distress is a major issue deserving of further research, given the significance of this question with regard to cost allocation. Important research questions are raised, and it is recommended that the DIVINE results are used to design an appropriate research programme.

Further Research

The DIVINE Project pioneered a new approach to the interaction of heavy vehicles and the infrastructure and has provided at least partial answers to some of the key issues surrounding the management of trucks and roads. Much remains to be done, however.

In particular, it is recommended that an experimental approach to the effects of vehicle weights, axle configurations, suspensions and tyres on pavement functional condition is developed using the findings of the DIVINE Project to aid experimental design. It is anticipated that this would involve a judicious combination of accelerated pavement testing, full scale pavement-vehicle functional condition testing and pavement-vehicle response testing, and would result in a validated dynamic vehicle-pavement functional condition model.

From the point of view of bridge research, further work is needed on those areas not covered by DIVINE. In particular, consideration needs to be given to the effects of dynamic loading on medium-to-long-span bridges under rough pavement profiles, loaded by air suspension, and to the effects on short-span bridges, with smooth profiles, for both air and steel suspensions.

Because field studies of these effects are costly, it is anticipated that much of this work could be achieved through the use of the analytical tools now available.

SCIENTIFIC FINDINGS

1. Primary responses of pavements reflect the total dynamic loading applied by heavy vehicles for dynamic wheel loading frequencies up to at least 15 Hz.

2. Primary responses are directly proportional to total load, including dynamics, for thick pavements (approximately 150 mm thick) and are proportional, with a lower sensitivity, for thin pavements (approximately 80 mm thick).

3. An accelerated dynamic test has shown that pavement profile deteriorates more rapidy under a steel suspension than under an air suspension carrying the same load. Some aspects of cracking and the maximum rut depth were also greater under the steel suspension. Pavement wear under the steel suspension was at least 15% faster than under the air suspension.

4. Road simulators (shakers) replicate dynamic wheel loads measured on the road provided that all axles of the vehicle are excited. The accuracy of replication of dynamic loads is typically 3% or better, as measured with the Dynamic Load Coefficient.

5. The essential properties of road-friendly suspensions have been confirmed as low spring stiffness, very low Coulomb friction and an appropriate level of viscous damping. Such properties are to be found in well-designed and well-maintained air suspensions and it is unlikely that steel spring suspensions could achieve the desired level of performance. A method of measuring these parameters is suggested that may be more accurate and consistent than the drop and step tests currently used.

6. The use of air suspensions on the drive and trailing axles of heavy vehicles (perhaps with the exception of the steering axle) would reduce road wear and should be encouraged.

7. Some computer simulations of dynamic wheel loads are capable of calculating these loads to an accuracy of approximately 5%, as measured with the Dynamic Load Coefficient. It is essential for these models to accurately represent the non-linear characteristics of the suspension, particularly the Coulomb friction in steel leaf springs.

8. Under mixed traffic, dynamic loads tend to concentrate at points along a road at intervals of typically 8 - 10 metres. On a smooth road, the cumulative sum of axle loads at a point of concentration is about 10%. On a rough road, this effect is at least twice as large. The concentration of dynamic loads for air suspension has only about half the magnitude of that for steel suspensions.

9. The surface profile of a bridge and its approaches are fundamental to the response of the truck suspension and in turn the dynamic response of the bridge. For a smooth profile, the influence of the truck suspension is insignificant; the importance of the suspension increases as the unevenness of the profile increases.

10. For medium-span to long-span bridges (20 - 70 metres) with smooth profiles, dynamic responses are relatively small for both air-suspended and steel-suspended vehicles; within this range of responses, increased responses occur for air-suspended vehicles on 1.6 Hz (70 metre) bridges and for steel-suspended vehicles on 3.0 Hz (40 metre) bridges. For short-span bridges (10 metres) with poor profiles, large dynamic responses occur for both air-suspended and steel-suspended vehicles. The highest measured responses were for short-span bridges with poor damping traversed by air-suspended vehicles with specifically-excited axle hop vibrations.

11. Dynamic responses of medium-span to long-span bridges (20 - 70 metres) with smooth profiles fall within current dynamic load allowances in bridge design codes. Dynamic responses of short-span bridges with poor profiles are well above current dynamic load allowances in a significant number of cases.

CONCLUSIONS

The policy actions and initiatives arising from the DIVINE research will include regulatory changes, design and construction improvements, maintenance improvements and charging initiatives. Regulatory changes could reflect a greater awareness of the benefits of road-friendly trucks for reducing the wear of pavements and permit axle weight or charging concessions for road-friendly vehicles.

Solid evidence of the benefits of road-friendly vehicles should lead to efforts by vehicle manufacturers to meet the road-friendly criteria identified by the DIVINE Project and to further improve suspension systems.

Pavement and bridge design standards should be made more efficient through more explicit recognition of the important role of profile evenness; pavement construction could become more structurally resistant to the effects of heavy vehicles through improved uniformity and greater allowance for dynamic load concentration.

Infrastructure maintenance costs should be controlled by increasing the use of road-friendly vehicles relative to non-road-friendly vehicles and maintaining profile evenness. Road user charges should focus on more realistic assessment of the road wear attributable to heavy vehicles. Charging regimes should give encouragement to the development of vehicle technologies which further improve pavement friendliness and bridge friendliness.

The implementation of the DIVINE results will ultimately depend on changing current perceptions of the interaction between trucks and roads. We used to simply believe that trucks "damage" roads: the DIVINE Project has shown that it is difficult to isolate the truck effect: even though the truck imposes the "load" on the infrastructure, the DIVINE Project has shown that uneven roads contribute to road wear and to the structural distress caused by non-road-friendly vehicles. It is hoped that the DIVINE Project will lead to an improved partnership between road providers and road users.

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