ROAD TRANSPORT AND INTERMODAL RESEARCH

Dynamic Interaction between Vehicles and Infrastructure Experiment (DIVINE Project)

Policy Implications

Organisation for Economic Co-operation and Development

FOREWORD

The Road Transport and Intermodal Linkages Research Programme is a co-operative approach among OECD Member countries to address technical, economic and policy issues relevant to safe and efficient road transport. The Programme, through its broader linkages to other modes of transport, reflects a multimodal approach to common transport problems and represents a combined attempt to reduce the negative impact of transport on the environment. The Programme has two main fields of activity:

- International research and policy assessments of road and road transport issues to provide analytical support for decisions by Member governments and international governmental organisations.

- Technology transfer and information exchange through two databases -- the International Road Research Documentation (IRRD) scheme and the International Road Traffic and Accident Database (IRTAD).

Its mission is to:

- Enhance innovative research through international co-operation and networking.

- Undertake joint policy analyses and prepare technology reviews of critical road transport issues.

- Promote the exchange of economic, scientific and technical information in the transport sector and contribute to road technology transfer in OECD Member and non-member countries.

- Promote the development of sound policies to achieve a safe and efficient transport sector that is responsive to the environment.

The activities of the programme concern:

- Sustainable multimodal transport strategies.
- Economic performance, transport infrastructure and management.
- Transport safety and environment.

ABSTRACT

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The Dynamic Interaction between Vehicles and Infrastructure Experiment (DIVINE) Project provided scientific evidence of the dynamic effects of heavy vehicles and their suspension systems on pavements and bridges. These conclusions are detailed in the DIVINE Technical Report [DSTI/DOT/RTR/IR6(98)1/FINAL]. The purpose of the present report is to examine the policy options available to countries with a view to improving the interaction between heavy freight vehicles and pavements and bridges. Regulatory and economic options are considered, as well as changes in the design, construction and maintenance of infrastructure. These policies could allow countries to make significant savings through increased transport productivity and reduced infrastructure costs. The report guides the policy maker through the implications of the technical findings in order to allow national policies to be designed which fit in with national priorities, whether those are to increase weight limits or reduce the wear of existing infrastructure.

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TABLE OF CONTENTS

1. INTRODUCTION

This report examines the policy implications of the findings of The Dynamic Interaction between Vehicle and Infrastructure Experiment (DIVINE) (a technical report is also available OECD, 1998). The present report is intended as a guide for policy makers wishing to improve the interaction of heavy road transport vehicles with pavements and bridges. In fact, a number of findings are worthy of immediate consideration. A participant at the European Conference on DIVINE findings noted that:

> *DIVINE has provided conclusions on which it is possible to take immediate action. We should without hesitation review our inventory of short-span bridges to identify those who may be threatened by frequency matching, and adjust our maintenance guidelines to ensure that the importance of smooth bridge and approach profiles is respected. Also, we should review our road construction standards and if necessary reduce tolerances on the desired uniformity of bearing capacity, layer thickness and surface evenness.* (Christiansen, 1997)

DIVINE was an international collaborative research project instigated by the OECD in 1993 following earlier work by an OECD Scientific Expert Group on the Dynamic Loading of Pavements (OECD, 1992). It involved national road agencies, national road research organisations, and the private sector and included active participation from over 17 OECD Member countries. Details of the project and its management are set out in the technical report of the DIVINE project (OECD, 1998, pp. 16-19).

DIVINE aimed to provide scientific evidence of the effects of the dynamic forces of heavy vehicles on pavements and bridges. The project comprised six research elements:

- Accelerated Pavement Testing.
- Pavement Response Testing.

- Road Simulator Testing and Road-friendliness Assessment.
- Computer Simulation.
- Spatial Repeatability.
- Bridge Dynamic Load Testing.

The project should address key issues of heavy vehicles in road traffic which are significant today and likely to become increasingly prominent in the future. They are:

- *Reducing all types of heavy vehicle impacts in road networks, including deterioration in road condition, safety and environmental effects.*
- *Improving road freight productivity through reforms in vehicle size and weight policy.*
- *Quantifying the potential benefits of "road-friendly" vehicle suspensions in extending pavement life and reducing maintenance costs related to trucks.*
- *Taking greater account of the effects of heavy vehicles in pavement and bridge design methods adapted in the construction of new infrastructure. (Christensen, 1997).*

Possible policy responses by OECD Member countries to the findings of DIVINE and the reasons for their interest in the DIVINE project are varied. The interest of Australia is concentrated on the potential to improve productivity in transport operations at minimum costs to infrastructure. Similarly, New Zealand is concerned with optimising both transport operations and infrastructure to minimise total costs. Europe's greatest concerns are related to minimising the costs associated with an ageing infrastructure and environmental issues. The United States, on the other hand, places much emphasis on safety. Different primary policy objectives may exist in other countries.

A range of possible policy options is considered. They are grouped as follows:

- Regulatory and economic options.

- Changes in the design, construction and maintenance of infrastructure.

The environments in which public policies are made vary considerably among OECD Member countries, as do transport systems and available infrastructure. Consequently, the relative merits of different policy responses to the findings of DIVINE will also vary significantly.

2. BACKGROUND AND FINDINGS OF THE DIVINE PROJECT

In a recent paper, Kulash (1996) reminds us of the tension that has existed for almost 3 000 years between the builders of roads and the operators of the vehicles that use them.

> *Carriers have always had an incentive to carry larger loads and those responsible for building and repairing roads have always had an incentive to protect their facilities by limiting the loads and regulating various features of the traffic using them. Although information from distant ages is sketchy, it appears that the tensions between roads and loads have been in existence from the beginning.*
>
> *In the long run, the demands of the vehicle appear to have determined the strength of the road. However, this dependence has often been ignored in the short run, where attention has often concentrated on regulating vehicles to suit the road. The fact that the two are intertwined in a system and that it is in society's interest to treat them as such appears to have been rediscovered from time to time but it is not until this century that we have had the engineering know-how to do this. Forthcoming studies of highway cost allocation and vehicle size and weight will allow policy makers to address these ancient questions armed with engineering understanding that has been absent through much of the long history of roads and loads.*

Initially, loads were limited by weight, as they were by Diocletian in 301 AD; later in 1718, tyre widths were regulated as well as loads when England required tyres (a wooden wheel with iron rims) to be 2½ inches wide. Sixty years later, 16 inch wide tyres appeared in response to regulation of weight by tyre width. In the last century, France apportioned road maintenance funds based on whether carts were loaded or empty and the size of animals being driven along the road. The number and size of the loads were determined by periodic 24-hour surveys at more than 4 000 locations (Kulash, 1996).

Consequently, the OECD DIVINE project is but the latest in a long line of efforts to determine the best way to use the economic advantage of public roads while minimising their maintenance costs. For the first time, vehicle suspension systems have been comprehensively analysed to determine if some are sufficiently better for the road system to warrant encouraging the use of "road-friendly" suspensions.

The importance of these issues is demonstrated by macroeconomic studies which indicate that worthwhile road investments can generate flow on benefits in economic growth (measured by Gross Domestic Product) and expansion of final consumption expenditure in the order of five times the direct benefits (Brain, 1997). Similar effects can be expected from improving the efficiency of infrastructure investment and maintenance. Other macroeconomic studies indicate that reductions in the costs of freight transport, through productivity improvements such as increases in payload, can result in economic growth of the order of three times the direct productivity benefit to transport operations (National Road Transport Commission, 1997*a*).

DIVINE found that pavements and bridges react to dynamic loads produced by vehicles, and that these dynamic loads are closely related to the roughness of the surface the vehicles operate over, their suspension characteristics and the speed at which they are driven. The reactions of pavements and bridges vary depending on the type of pavement, type of bridge and type of suspension. These interactions are illustrated in Figure 2.1.

Interaction between vehicles and infrastructure varies with a number of vehicle characteristics. DIVINE focused on a single characteristic, the performance of heavy vehicle suspensions. Consequently, the DIVINE project did not deal with road-friendly vehicles but only with road-friendly suspensions. The reason for concentrating on suspension performance was that, unlike other aspects of vehicle/infrastructure interaction, there is a reasonable potential that policy makers can influence the performance of suspensions.

Some essential aspects of more road-friendly vehicles were not evaluated in the project. These included:

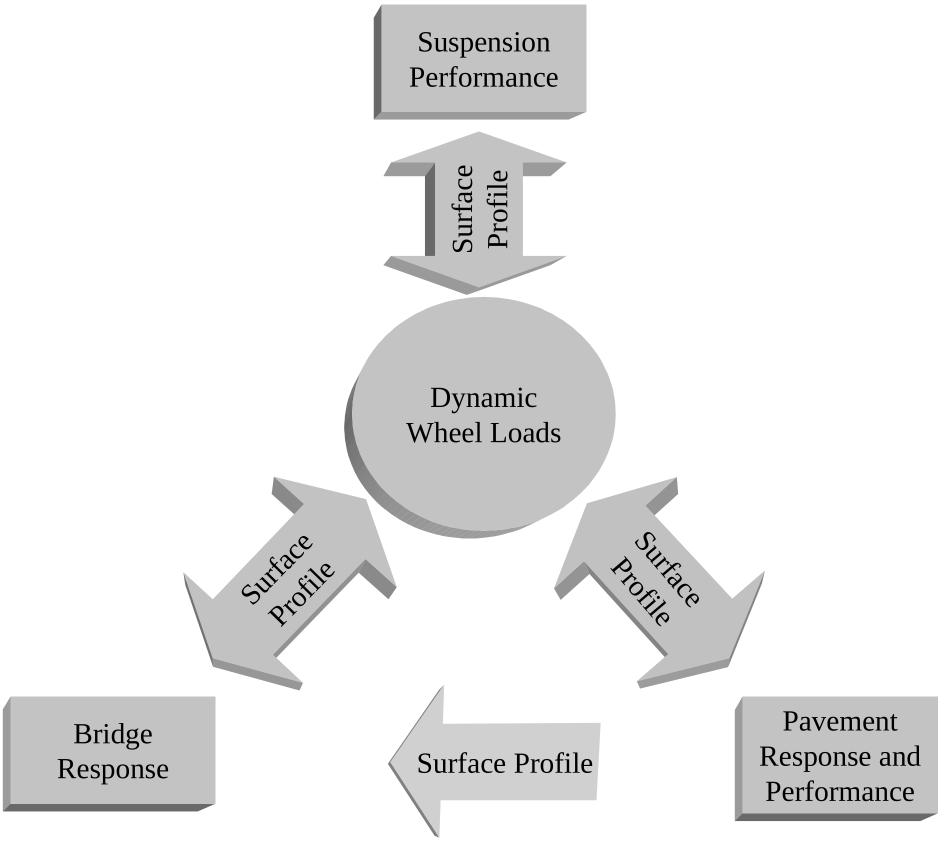
- The maximum legal static load for axles.

- The use of multiple axles versus a single axle.

- The contact pressures of different tyre types.

For example, the increased use of wide single tyres to replace dual wheels on the trailers of articulated vehicles has raised concerns about their effect on rutting of heavily trafficked bituminous pavements.

Figure 2.1: Interaction of Suspensions, Bridges and Pavements under Dynamic Loading



In order to put the findings of DIVINE and its policy implications into perspective, a little should be said about the interaction of heavy vehicles with pavements and bridges. The impact of heavy vehicles on road safety and the environment is also an important consideration in policy development, and therefore is considered here as well.

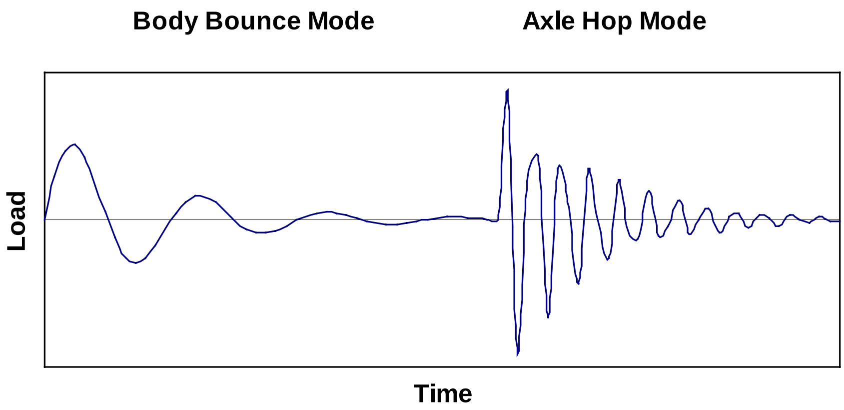
2.1 Suspension Performance

Heavy vehicle suspensions react to vertical variations in the surfaces over which they operate. A suspension is a spring that isolates the body of a vehicle from unevenness in the road surface. The way in which it reacts varies with the performance characteristics of a vehicle's suspension system. Three major characteristics are used to measure performance:

- Frequency (how often a vertical force on the suspension is replicated through the action of the spring).
- The degree of damping (how quickly its responses are diminished).
- The degree to which loads are evenly shared between individual axles in a multi-axle group.

The first two of these elements characterise the suspension's dynamic performance. Figure 2.2 provides an illustration of the dynamic performance of suspensions. Lower frequency responses (1.5 to 4 Hz) occur with body motions of a vehicle, where the vehicle's body (sprung mass) bounces, or pitches and rolls, in relation to the vehicle's tyres (unsprung mass) and the pavement surface. High frequency responses (8 to 15 Hz) correspond to axle hop vibrations, where the vehicle's body remains constant in relation to the pavement surface, but the axle and tyres vibrate between the two.

Figure 2.2: Dynamic Performance of Heavy Vehicle Suspensions



Mechanical heavy vehicle suspensions such as steel leaf suspensions are generally thought to produce higher frequencies and lower damping of dynamic loads than well-designed air suspensions.

Dynamic loads are transmitted to the pavement in response to changes in pavement profile. These loads are influenced by changes in the load on the vehicle, and by variations in the stiffness of the vehicle structure and tyres. Combined dynamic and static loads may be significantly larger than the magnitude of the static loads alone (the weight when the axle or axle group is stationary). The magnitude of dynamic loads generally increases with operating speeds and roughness.

The reaction of suspensions is closely related to the smoothness of operating surfaces. In general, gradual undulations in the surface of a road will set body modes of reaction in place. Sudden or large variations, such as a pothole, are more likely to result in axle hop. Operating speeds also influence the magnitude of dynamic loads simply through increases in the wheel forces applied.

Damping of both types of mode is an important consideration in assessing the effects of a specific suspension. Highly damped systems (up to 20% damping) will have less effect on road infrastructure than systems with lower levels of damping.

The third element of heavy vehicle suspension performance is load sharing. This is a much simpler concept and is described as how evenly the load on a multi-axle group is distributed between the individual axles of the group. Load sharing is highly sensitive to proper installation and regular maintenance of suspensions as well as to correct tyre pressures. Clearly if the loads on a multi-axle group are not evenly shared across the axles, the forces transmitted to a pavement by some of the axles will be larger than those transmitted by others.

2.1.1 Ensuring Road-friendly Suspensions

The important factors in reducing dynamic loads were found to be suspension frequency, damping and road roughness. Given the current advances in suspension design, DIVINE proposed a maximum sprung mass frequency of 1.5 Hz and viscous damping greater than 20% for road-friendly suspensions. The current European bounce test regards suspensions with frequencies of up to 2.0 Hz as road-friendly. However for rough roads, reducing the frequency from 2.0 Hz to 1.5 Hz is believed to reduce dynamic loading by 24% (OECD, 1998, p. 106).

The greatest concern for policy makers is the performance of suspensions while they are being used on the road. Adequate maintenance of suspension performance is required to ensure that suspensions remain road-friendly.

DIVINE also recommended a stringent level of load sharing. Many OECD countries require all heavy vehicle suspensions to meet a minimum standard of load-sharing performance. However, as outlined in Section 2.1, policy makers should note that DIVINE considered the road-friendliness of suspensions in isolation from other aspects of vehicle design which might contribute to the road-friendliness of the vehicle system as a whole. If dynamic wheel load reductions are to be achieved for some vehicles, attention may need to be paid not only to the road-friendliness of suspensions, but also to the dynamics of the whole of the vehicle.

2.1.2 Performance Requirements and Testing

An important priority for policy implications should be to develop a test procedure, and associated criteria for road-friendliness, and assess the relationship with the existing European bounce test. A Simultaneous Sinusoidal Sweep (SSS) test protocol was proposed by DIVINE to test both body bounce and axle hop modes of suspension response. Associated criteria and test procedures, however, have not been developed.

Once test procedures are available, certification (or type approval) systems should be developed for new suspensions. Most countries already have certification systems for design standards on new vehicles. These systems could be extended to include certification of suspension performance. As only the performance of suspensions, and not that of the vehicle as a whole, has been considered, it may be possible to apply this certification process to suspension manufacturers rather than vehicle manufacturers.

The procedures for in-service tests must have different features to certification tests applied to new suspension designs. They must be able to be completed in a relatively short period and results must be available immediately. The cost of the equipment required for the test must also be kept to a minimum.

The point at which in-service tests are applied will depend on the compliance and enforcement regimes in place in each country. Some regimes rely on periodic inspections by government or approved inspectors, others rely on maintenance programmes instigated by vehicle operators. It will be difficult to develop a suitable test for regimes that rely on roadside testing. In this case the test must be easy to administer and completely portable.

2.1.3 Keeping Suspensions Road-friendly

One of the concerns that arises from moves to encourage the use of road-friendly suspensions is whether the suspension stays road-friendly over time. Greatest concern lies in the performance of shock absorbers (dampers). For example, at each of the conferences on the findings of DIVINE, it was noted that "*Damping of both the suspension and the vehicle are fundamental to controlling the dynamics in short-span bridges. Air suspensions with inadequate damping are potentially very damaging to short-span bridges.*" (Heywood, 1997). Nevertheless, before large amounts of resources are devoted to establishing complex test procedures and enforcement regimes, the size of any problem must be ascertained.

Suspension use and maintenance is more likely to affect damping than the frequency. DIVINE found, however, that road-friendliness is not highly sensitive to small reductions in damping, when damping is above 20%. Safety (in relation to vehicle handling) and tyre wear are also likely to be sensitive to damper wear, and existing mechanical inspections may be sufficient to control this issue.

Stability, handling and tyre wear all deteriorate significantly with poor damping on road-friendly suspensions. Deteriorating tyre wear, in particular, presents a significant financial incentive to operators to maintain the performance of shock absorbers or dampers. Whether increases in tyre wear and handling problems are triggered immediately the performance falls below acceptable levels for road-friendliness, however, is not known. A survey of in-service suspension performance, concentrating on damping, is required to ascertain this.

From a policy-making perspective, whether or not suspensions remain road-friendly throughout their service lives is a crucial issue. "Concessions" for vehicles with road-friendly suspensions, such as increased mass limits, and regulations requiring a specified level of performance may be inappropriate unless policy makers can have confidence in the in-service performance of suspensions. Greater certainty in the performance of suspensions over time could be achieved by surveys, such as an in-field survey (at the roadside or at vehicle depots), or through testing shock absorbers removed from vehicles where the periods and condition of service are known.

2.1.4 DIVINE's Findings for Suspensions

Key findings in relation to suspensions were:

1. Suspension design type (air or mechanical) can have a marked effect on dynamic loads, depending on frequencies and damping. Dynamic loads are generally lower for well-designed air suspensions than for mechanical suspensions.
2. Both low and high frequency responses of suspensions are important for pavements and bridges, and both should be controlled.
3. The European bounce test, with some variations, provides a reasonable measure for low frequency response, but a lower criterion of a maximum 1.5 Hz in frequency should be required, along with minimum damping of 20%.
4. Not all air suspensions will meet these criteria. Consequently suspensions should not be deemed "road-friendly" simply by virtue of their design.
5. The load-sharing performance of suspensions should also be controlled.

Other vehicle design features (*i.e.* tyres, wheel assemblies and internal axle group spacing) that affect the road-friendliness of the integrated vehicle system were not assessed.

2.2 Pavement Deterioration

There are three major types of pavements, depending on the design, construction and materials used:

1. Flexible pavements are constructed with layers of either unbound materials (such as crushed rock) or materials bound with bitumen and a bituminous concrete surface or very thin chip seal surface.
2. Rigid pavements are constructed using either a reinforced or jointed cement concrete surface over layers of bound or unbound materials.
3. Semi-rigid or composite pavements comprise bituminous concrete surfacing laid on materials that have been bound together with a cement binder.

Deterioration of pavement structures and surfaces occurs as a result of many factors including the loads applied by heavy vehicles: the effect of cars is negligible. The deterioration of pavement structure reduces the functional performance of the pavement by increasing:

- Roughness (the longitudinal profile), as permanent deformation is not uniform along the road.

- Rutting in the wheel paths induced by permanent deformation.

- Fatigue cracking. which reduces the stiffness of the pavement and allows ingress of water into the pavement, thus increasing permanent deformation and roughness.

Permanent deformation and rutting can also occur in the upper layers of a pavement, even on a well-designed pavement structure. The deterioration processes of the pavement structure, which occur in the lower layers (fatigue of the bound layers) or in the soil (permanent deformation), are related to the applied loads. On the other hand, the deterioration processes which occur in the upper layers (such as the permanent deformation of the asphalt wearing course, or the permanent deformation of an unbound layer under a thin asphalt layer) are not as directly related to wheel loads. Other factors such as tyre contact pressures may have a significant influence.

DIVINE's Findings for Pavements

Key findings in relation to pavements were:

1. The interaction of pavement variability and truck dynamics accelerates local pavement distresses, roughness and failure. Road-friendly suspension systems, properly maintained, lessen the effects on pavements.
2. Importantly, poor-quality pavement construction (variations in layer thickness and foundation characteristics), as well as heavy vehicle static and dynamic loads, contribute to reduced pavement life.
3. These findings are sensitive to pavement roughness. It was found that there was little difference between road-friendly and non-road-friendly suspensions on smooth heavily trafficked roads. However, on secondary roads with rough surfaces the difference is significant.

4. The responses of thick bituminous pavements are closely related to dynamic loads. The responses of thin bituminous pavements are also related to dynamic loads, but not as closely.
5. For the accelerated pavement performance test, maximum rut depth was found to be greater with steel suspensions. However, the average rut depth was much the same for the air and steel suspensions (slightly greater with the air suspension).
6. Some locations along a pavement have a higher than average incidence of wheel loads greater than the static loads. That is, there is spatial repeatability in wheel loads along the length of a road.

The scientific work undertaken for DIVINE did not assess the impacts of dynamic loads on other pavement types. In particular, it is inappropriate to extrapolate the results to rigid, semi-rigid or composite pavements, granular chip-seal pavements and unsealed roads.

2.3 Bridge Design and Performance

Bridges are designed to carry loads imposed by heavy vehicles, referred to as the live load. The majority of the strength of a bridge structure, however, is required to hold up the weight of the bridge itself (the dead load). Variations in the costs of bridge construction are, therefore, more closely related to the length and number of spans required, the height of the bridge, the materials used and the need to provide safe approaches and sufficient deck area to allow free-flow of traffic across the bridge.

Bridges are typically designed to withstand a specified static load. Allowances are made for the likelihood of more than one heavy vehicle being on the bridge at the same time, for dynamic load effects and for safety factors to take account of uncertainties in the design procedure and to minimise risks of catastrophic failures.

Bridges react differently under heavy loads depending on a range of factors in their design, including:

- The length of individual spans within the bridge.
- The construction materials used (for example, timber, steel, pre-stressed concrete, reinforced concrete).

- The design type (for example, steel beam, steel truss, timber truss, timber arch, box girder, reinforced concrete slab).

- Whether or not the bridge is continuously supported along its total length.

- The loads which the bridge was originally designed to carry.

These factors influence the natural frequency and damping which is inherent in the bridge structure. When the natural frequencies of the bridge and the vehicles using it are the same, there is a danger that they will resonate together, amplifying the stresses in the bridge.

Pavements and bridges are designed for relatively long lives. This is especially the case for bridges that are often designed for a life of 50 to 100 years. As with pavements, the relationship between the reaction or response of a bridge to a load and the deterioration of the bridge is not well understood. Nevertheless, it is believed that larger responses (such as larger deflections) may result in bridge failure or an unacceptable increase in risk of failure. Typically, there are two modes of bridge failure:

- Catastrophic failure, where the stresses the bridge is subject to exceed the stresses it is able to withstand and the bridge collapses.

- Fatigue failure, where the materials from which the bridge is constructed wear out through repetitions of loads and fatigue damage occurs.

Bridge failure of either type is a serious concern to infrastructure providers as it may not only have significant consequences for infrastructure costs but may also pose a severe risk to public safety.

Stresses on a bridge may exceed design stresses for a number of reasons. Commonly, the bridges which were designed earlier this century and are still in use were designed for much lower static load limits than those that now apply. Dynamic loads may not have been a significant consideration in early designs. In some countries, particularly where there are long lengths of road in sparsely populated areas, design stresses may also be exceeded as the result of significant levels of overloading of heavy vehicles, where very large payloads are sometimes carried illegally.

DIVINE's Findings for Bridges

Key findings in relation to bridges were:

1. Road-friendly suspensions are generally benign for bridges unless the natural frequency of the bridge and suspensions match. Consequently, road-friendly suspensions are not always "bridge-friendly".
2. Rough pavements on bridge approaches and rough bridge decks interact with vehicle suspensions, particularly air suspensions, to set up truck dynamics that can stimulate harmful bridge vibrations in short-span bridges at critical speeds.

2.4 Safety and the Environment

While DIVINE did not directly examine safety and environmental issues, the issues with which it dealt may have significant safety and environmental implications. These are important factors in policy development. Suspension type may have a direct impact on:

- Vehicle stability.
- Braking.
- Noise.

The effects of greater use of road-friendly suspensions, and other policy options, are discussed in detail in Chapter 4.

3. POLICY OPTIONS

Policy options that respond to the findings outlined in Chapter 2 fall into two broad groups:

- Regulatory and economic options.
- Changes in the design, construction and maintenance of infrastructure.

Within the first group are changes in design and weight limit of vehicles and preferential pricing. The second group includes pavement design and construction procedures, maintenance practice, and bridge deck construction and maintenance. These policy options are not exhaustive, but they represent the range of actions which may be considered.

3.1 Regulatory and Economic Options

A range of regulatory and economic measures is possible in response to the findings of DIVINE. These options are concentrated on the vehicle and/or its operation. All are designed to encourage greater use of road-friendly suspensions.

3.1.1 Mandating Suspension Performance Standards

The most direct policy option would be to reduce dynamic loads on road infrastructure by introducing a regulatory requirement for road-friendly heavy vehicle suspensions. This implies a mandated performance standard for suspensions. A DIVINE finding indicates that not all suspensions of a general design type, such as air suspensions, will meet the performance characteristics necessary to reduce dynamic loads.

Performance standards can be applied to vehicles and components when they are new or when they are used on roads (in-service). In most countries it is only possible to introduce new or more stringent requirements on new vehicles or components. Retrospective standards that require changes to existing vehicles are a much harsher regulatory intervention, often accompanied by significant net costs to vehicle operators. This would clearly be the case if road-friendly suspensions were to be mandated on all existing vehicles. On the other hand, improving the performance of new vehicles, while the existing fleet does not change, will not rapidly improve the overall performance of the heavy vehicle fleet.

Evidence in Australia, for example, suggests that it would take in excess of 20 years for the entire heavy vehicle fleet to be replaced and, therefore, for all vehicles to be updated to meet a new standard (National Road Transport Commission, 1994). As newer vehicles tend to travel further than older vehicles, this problem is not as bad as it might seem, but the total dynamic loads produced by heavy vehicles will only be gradually reduced.

3.1.2 Pricing

One of the aims of DIVINE was to provide an improved understanding of vehicle/infrastructure interaction to assist in assigning cost responsibilities to road users. The project was only partially successful in this. It found that there is greater interaction of vehicles with rough pavements than with smooth pavements, and that the interaction of vehicles and pavements increases as the pavement becomes rougher and weaker. DIVINE suggested that the pavement damaging effects of heavy vehicles might be over-estimated in some cases, and noted that the influences of vehicles and climate cannot be separated.

Pricing mechanisms can be used to encourage greater use of road-friendly suspensions where these suspensions will be effective in reducing pavement damage. Prices for use of road infrastructure can be set at lower levels for vehicles with road-friendly suspensions compared to other vehicles. There are two approaches to setting relative prices:

1. Road use charges can be set to reflect the relative infrastructure costs associated with the use of road-friendly and non-road-friendly vehicles. This requires knowledge of the effects on the costs of supplying and maintaining pavements and bridges that will result from greater use of road-friendly suspensions.
2. Vehicle prices can be influenced by setting tax differentials on road-friendly and non-road-friendly vehicles resulting in a desired level of use of road-friendly suspensions. To do this, price elasticities of demand must be known; that is, the change in

quantity of road-friendly vehicles associated with a small change in price must be known. The differences in costs to vehicle operators of using road-friendly suspensions must also be taken into consideration.

From the perspective of a government, or public infrastructure provider, a range of pricing mechanisms can be used to put in place price differentials of the kind described above. The most common approach would be to use registration or access charges on heavy vehicles. Other options include special permit fees and rebates on other government taxes and charges. The choice of mechanism will depend largely on the associated administrative costs and on government policy.

3.1.3 Relaxation of Other Regulations

Where an increase in mass limits is accompanied by measures that reduce the impact of heavy vehicles on infrastructure, increases in costs to infrastructure providers can be avoided. DIVINE indicates that savings in pavement wear may be possible through encouraging greater use of road-friendly suspensions. Consequently, if mass limit increases are restricted to axles with road-friendly suspensions, and the increases are set so that any additional costs to pavements from increasing mass limits are offset by savings due to increased road-friendliness, a net increase in pavement costs can be avoided.

Increasing mass limits has the direct result of increasing productivity in road transport, thereby reducing transport costs. A reduction in transport costs will benefit the whole community, provided the road transport industry is relatively competitive. These benefits can be large, but difficult to achieve where infrastructure providers are operating under a budget constraint that cannot accommodate increases in pavement costs.

An increase in mass limits may also result in costs to bridges, if they have not been built to withstand the higher static loads. DIVINE has shown that dynamic loads can be significant for bridges under some circumstances, particularly for short-span bridges with rough approaches (see Section 2.6). Consequently, in the case of bridges -- in contrast to road pavements -- increased road-friendliness may not offset the effects of increases in mass limits.

Relaxation of mass limits for vehicles with road-friendly suspensions provides a strong financial incentive for operators to use road-friendly suspensions. Operators unable to take advantage of an increase in mass limits, for example, would be at a significant competitive disadvantage. Consequently, relaxation of such regulations can be a powerful means of encouraging greater use of road-friendly suspensions.

On the other hand, many vehicles do not operate at maximum static mass limits, either because they are not rated to carry these loads or for operational reasons. These vehicles still produce significant pavement loadings, albeit smaller loads per vehicle than vehicles operating at maximum mass. A trade-off between mass limits and increased road-friendliness will not encourage these vehicle operators to use road-friendly suspensions.

Directive 96/53 of the Council of the European Union allows an increase in loads on the drive axle when it is fitted with an air suspension or equivalent under the European bounce test procedure. Similar approaches are being developed in Australia and Mexico.

3.2 Infrastructure Policies

The results of DIVINE also suggest that changes in approaches to designing, constructing and maintaining infrastructure should be considered. These new methods may be used in conjunction with regulatory and economic measures to minimise the total cost to the community of transport infrastructure and transport operations.

3.2.1 Pavement Design, Construction and Maintenance

DIVINE found that the effects and size of dynamic loading vary with pavement characteristics, in particular strength and roughness. Consequently, the benefits of changes in approaches to design, construction and maintenance of a pavement will vary according to its intended purpose.

Design Methods

The DIVINE results tell us that, even though static loads may be constant over the life of a pavement, in practice the loads increase due to the effect of increasing pavement roughness on vehicle dynamics. Pavement design methods need to take account of this.

Existing mechanistic pavement design methods use static wheel loads, which are assumed to be constant over the life of the pavement. Dynamic wheel loads are considered only implicitly; their effect is introduced in the calibration (or shift) factors applied to the computed stresses or strains. These factors allow for all the simplifications and approximations that cannot be avoided in the theoretical mechanistic pavement design methods.

Construction Methods

Pavement variability may result from at least four problem areas in pavement construction:

- Variable soil bearing capacity.
- Non-uniform paving materials.
- Uneven pavement layer thickness.
- Surface roughness.

These problems result initially from the construction of the pavement. The combined effects of traffic loads and environmental conditions, especially with increasing dynamic loads, eventually amplify them.

Of the four, the first three result in variable pavement strength, and this adds to the fourth (surface roughness) as the weaker portions of the pavement fail first, resulting in the vehicle-pavement interaction process of pavement deterioration observed by DIVINE. Consequently, good control of the construction of all pavement components (uniform strength in the subgrade, well-mixed paving materials, constant pavement layer depth, and smooth wearing surfaces) to provide uniform pavement strength and surface evenness will help to avoid early pavement deterioration.

Construction techniques that can reduce pavement variability are:

- Placing thick capping layers on the subgrade made from soils treated with hydraulic binders.
- Careful levelling of the subgrade and laying of paving materials with guided pavers.
- Checking pavement thickness with modern non-destructive real time methods.
- Development and use of construction techniques or equipment to ensure that the pavement surface is as smooth as possible.

Traditionally, much effort is devoted to controlling the variability of pavement materials and their compaction, particularly in Europe. Policies to extend this effort to the other factors mentioned above may result in significant increases in pavement lives, based on the findings of the DIVINE project.

To be effective, both pavement construction practitioners and contractual arrangements for pavement construction should take account of these issues. For example, contractual arrangements might place greater emphasis on quality assurance systems to minimise variability in pavement strength and minimise surface roughness. DIVINE suggests greater reliance on the use of measures of local pavement strength at the time of construction and recommends the use of recognised deflection measurements as a non-destructive means of monitoring local strength (OECD, 1998, pp. 111-114). Requirements for this type of measurement and specifications for maximum variations in strength could be included in project specifications and in contractual arrangements for pavement construction. Clearly this may result in an increase in the costs of pavement construction, however significant savings may result in later years through extended pavement life.

Maintenance Strategies

The structural deterioration of pavements results in an increase in their roughness. DIVINE has confirmed that, when a sufficiently high level of roughness is reached, this induces a significant increase in the dynamic wheel load under spatial repeatability conditions. In those locations where the highest dynamic wheel loads are applied, pavement deterioration is induced, particularly permanent deformation, which in turn increases road roughness and dynamic wheel loads. This interaction of pavements and dynamic wheel loads accelerates pavement deterioration.

To avoid this phenomenon, preventive maintenance strategies should be adopted to ensure that a pavement never reaches a roughness level where the dynamic wheel loads increase appreciably. This assumes that maintenance strategies incorporate changes in traffic volumes and other characteristics to achieve overall economic efficiency in the management of the road network. Under preventive maintenance strategies, a high level of road evenness is maintained by more frequent thin or very thin asphalt overlays or reseals. In contrast, curative maintenance strategies allow the pavement to deteriorate until a thick strengthening overlay or reconstruction is necessary.

This is particularly applicable to flexible pavements, because their roughness increases progressively during the life of the pavement. For pavements with a cement treated base, the rate of change of roughness may be different. Pavement evenness stays at a high level for most of the life of the pavement before decreasing suddenly close to the end of its life.

At the time of pavement construction, efforts are made to minimise the roughness of the pavement surface. This practice is equally valid for periodic maintenance such as thin reseals and overlays. Use of equipment and techniques for reseals and overlays that result in as low a level of roughness as is achieved at initial construction may result in even greater extensions of pavement lives.

3.2.2 Bridges

The response of bridges to heavy vehicles is generally expressed as a function of static loads plus an allowance for dynamic effects. Dynamic effects have traditionally been a function of the span length of the bridge (or the fundamental frequency in more modern bridge codes), but are not related to the road profile on bridge approaches or the bridge deck. The DIVINE project has shown that:

> *The dynamic response of bridges can only be understood when considered as part of a system which incorporates the bridge, the road profile and the vehicle mass, configuration and speed as well as the vehicle suspension. The need to understand this complex system is becoming increasingly important in an era when ageing and deteriorating bridge infrastructure must carry ever-increasing loads in response to industry and government efforts to improve transport efficiency*. (OECD, 1998, p. 117).

The major implications of DIVINE for bridge design and construction are that:

- Potentially large dynamic effects should be considered in the design of bridges with natural frequencies that might resonate in sequence (match) the body bounce and axle hop frequencies of the suspensions to be used on them.

- Dynamic effects should take account of both the natural frequency of the bridge and of road profiles.

- Greater emphasis should be placed on maintaining a smooth road profile on approaches to bridges and over bridges, especially short- and medium-span bridges.

Short-span concrete bridges may be particularly vulnerable, depending on the design. This implies that greater co-ordination between pavement and bridge engineers is required to monitor and maintain bridge profiles. Further greater emphasis should be placed on monitoring fatigue relating to dynamic effects of loads on short bridge spans.

4. ASSESSING POLICY EFFECTIVENESS

Assessing the impacts of any policy proposal is difficult. It is even more difficult in the case of complex proposals affecting all aspects of vehicle/infrastructure interaction. Nevertheless, it is important for the impacts of different options to be considered, as the results of DIVINE suggest that they will differ across regions and countries. The need for detailed assessments was noted at each of the conferences on the outcomes of the DIVINE project (Christiansen, 1997).

4.1 Pavements

The effects of encouraging the use of road-friendly suspensions on pavements have been shown by DIVINE to be complex. In general terms, the effects of increased use of road-friendly suspensions can be expected to be greater on thick bituminous pavements with high levels of roughness along the pavement surface and large degrees of variability in pavement strength. They can also be expected to be greater at higher operating speeds.

To decide whether measures by regulatory authorities to influence the performance of heavy vehicle suspensions are justified by reduced pavement maintenance costs, a study should be performed on the road network of a given country, using available information on pavement performance (such as pavement management systems). For this to be done, data on the factors noted above would be needed. In addition, the reduction in dynamic wheel loads that can be expected to arise from the use of road-friendly suspensions, taking account of the effects of spatial repeatability, is required. The relationship between a reduction in dynamic wheel loads and pavement roughness is needed, along with pavement deterioration models that take account of dynamic wheel loads. Using these relationships, maintenance requirements can be estimated in situations where all suspensions are road-friendly and where no suspensions are road-friendly.

Of course, other effects of introducing road-friendly suspensions should also be taken into account in the decision (road safety, vehicle costs, driver comfort, effect on the goods transported).

The effects of spatial repeatability on pavement life are significant. One commentator estimates that:

> *This phenomenon [spatial repeatability] may significantly increase pavement wear (by 35 to 50%) with respect to the predicted lifetime under static loading, even on a good evenness. This becomes more critical for rough pavements (+ 80 to 200% of wear). The design rules of pavements should take that into account and the generalisation of road-friendly suspensions could reduce costs of road construction and maintenance.* (Jacob 1997.)

The benefits of road-friendly suspensions when spatial repeatability occurs are not as large (a few per cent) for smooth pavements; however for rough pavements, they may be as large as 15%. For thick asphalt pavements (where the fourth power law is considered an appropriate measure of load equivalence), a move from all suspensions being non-road-friendly to all road-friendly suspensions may result in an even larger increase in the remaining life of rough pavements.

The DIVINE report suggests that increased road-friendliness would equate to increases in static loads of 4 to 12%, using a fourth power law (OECD, 1998, p. 123). Clearly, this will vary depending on local circumstances such as the characteristics of the road system and the existing level of mass limits. Estimates of the relative impact of increased use of road-friendly suspensions and increased mass limits prepared for Australia suggest that increases in axle mass limits of up to 15% may be outweighed by the effects of greater use of road-friendly suspensions (National Road Transport Commission, 1997*b*).

The estimates of savings in Australian pavement costs associated with increased use of road-friendly suspensions shown in Table 4.1 provide an illustration of the possible impacts on pavements of a trade-off between road-friendly suspensions and increased mass limits (National Road Transport Commission, 1997*b*).

The estimates comprise changes in pavement rehabilitation costs resulting from possible increases in mass limits for vehicles with road-friendly suspensions in Australia. The effects partly arise from reductions in the distances travelled by freight vehicles to perform the current Australian freight task. Both savings and costs in pavement rehabilitation were estimated to be small, as only the heaviest rigid and articulated trucks were assumed to be affected by the proposals and because their fully laden activity is small in comparison to all truck activity.

Table 4.1: Changes in Pavement Rehabilitation Costs with Greater Use of Road-friendly Suspensions and Increases in Mass Limits in Australia
(percentages)

Change in Costs	Proportion of Road-Friendly Suspensions			
	40%	**60%**	**80%**	**100%**
Option 1				
Increased Road-friendliness	-0.61	-1.10	-1.61	-2.10
Increased Mass	0.65	0.97	1.31	1.62
Total Change	0.04	-0.13	-0.30	-0.48
Option 2				
Increased Road-friendliness	-1.71	-3.27	-4.82	-6.35
Increased Mass	1.34	2.01	2.68	3.35
Total Change	-0.37	-1.26	-2.14	-3.00
Option 3				
Increased Road-friendliness	-1.78	-3.34	-4.91	-6.47
Increased Mass	1.52	2.29	3.05	3.81
Total Change	-0.26	-1.05	-1.86	-2.66
Option 4				
Increased Road-friendliness	-2.01	-3.69	-5.34	-7.06
Increased Mass	2.48	3.74	4.97	6.22
Total Change	0.47	0.05	-0.37	-0.84

Notes:

It was assumed that 20% of heavy vehicles currently use road-friendly suspensions.
Option 1 = a 10% mass increase on triaxles (or a 5% increase overall).
Option 2 = a 3% increase on tandem axles plus a 10% increase on triaxles (or a 6% increase overall).
Option 3 = a 3% increase on tandem axles plus an 11% increase on triaxles (or a 7% increase overall).
Option 4 = a 3% increase on tandem axles plus a 15% increase on triaxles (or a 9% increase overall).

4.2 Bridges

As with pavements, the effects of the various policy options on bridge infrastructure will be varied. They will depend on the characteristics of the local bridge infrastructure such as those that influence the natural frequency of the bridge (*e.g.* span length, and type of construction):

- The smoothness of the approaches to the bridges and the profile of bridge decks.

- Design loads.

Long-span bridges are unlikely to be affected (either positively or negatively) by encouraging the use of road-friendly suspensions unless they have particularly poor surface profiles. Medium- and short-span bridges may be more affected, especially short-span bridges with natural frequencies that harmonise with axle hop modes of heavy vehicle suspensions.

Increasing road-friendliness can be expected to benefit medium- and short-span bridges that do not have natural frequencies that coincide with the body bounce and axle hop frequencies of suspensions. Where natural frequencies of bridges coincide with suspension responses, road-friendly suspensions may have adverse effects on bridge responses, and thereby on bridge costs. These responses can be exacerbated in some circumstances, such as where axle hop is initiated at a critical speed by a poor surface profile on the approach or deck of a bridge. The likelihood of these circumstances coinciding is low, but the consequences may be severe.

The effects of encouraging greater use of road-friendly suspensions are therefore likely to be greater in regions which have greater numbers of medium- and short-span bridges with rough surface profiles. For example, in Australia, researchers have found that some short-span concrete bridges are adversely affected by road-friendly suspensions, while short-span timber bridges generally benefit. As there are large numbers of short-span bridges in Australia and some bridges have been found to have rough profiles the consequences of these effects can be large, as shown in Table 4.2 (National Road Transport Commission, 1997*b*). In this case, although costs increase on some bridges, increased road-friendliness reduces total bridge costs because of the large number of timber bridges involved that will benefit from increased road-friendliness. The example shown should be considered against a backdrop where a large number of bridges were estimated to be deficient at existing mass limits.

4.3 Industry

Transport operations will be affected in several ways by greater use of road-friendly suspension. These impacts should be assessed as part of the policy-making process.

There is a range of private incentives for truck and bus operators to use vehicles fitted with road-friendly suspensions. The primary incentive is improved ride resulting in:

- Greater driver comfort and consequently less fatigue.

- Greater protection for freight and improved passenger comfort.

- Improved vehicle handling.

Table 4.2: Change in Costs of Bridge Replacement for Increased Mass Limits and Increased Road-friendliness on Arterial Roads in Australia
(percentages)

Bridge Replacement Costs	**Proportion of Road-Friendly Suspensions**				
	20%	**40%**	**60%**	**80%**	**100%**
Mass Increase for Road-friendly Suspensions					
Additional Up-front Costs	..	13.4	17.0	22.3	33.0
Increased Ongoing Replacement Costs	..	11.0	15.3	18.4	19.6
Mass Increase for All Vehicles					
Additional Up-front Costs	114.8	76.6	56.8	33.0	33.0
Increased Ongoing Replacement Costs	6.1	17.7	19.6	26.3	19.6

Notes: Based on costs for Option 3 (see Table 4.1). A large number of bridges were estimated to be deficient under current loads. Higher costs result when mass limit increases are not restricted to vehicles with road-friendly suspensions (in part because of greater take up of the mass limit increases). If more vehicles use road-friendly suspensions, however, the total additional bridge replacement costs decrease.

Road-friendly suspensions are generally more expensive to install than mechanical suspensions, particularly on trailers. Consequently, a move to increased use of road-friendly suspensions will result in increased capital costs for heavy vehicle operators.

There is conflicting evidence on whether road-friendly suspensions result in reduced ongoing maintenance costs for vehicle operators. There is some evidence that road-friendly suspensions may not be well suited to all heavy vehicle operations (such as transport involving mining, quarrying, other primary production or transport in remote areas). Any moves to encourage the use of road-friendly suspensions may put these industries at a relative disadvantage. These impacts must also be considered in assessing the effects of various policy options (Duncan and Wright, 1996).

Relaxation of other regulations, such as mass limits, will also have a significant effect on transport operations. The productivity improvements associated with an increase in mass limits may be very large. Mass limit increases in Australia have been estimated to have the potential to reduce the distance travelled by vehicles in performing the existing freight task by around

2% across total road freight activity. This is estimated to result in savings of around 3% in the total costs of operating freight vehicles (Bayley, 1996). This is a large improvement considering that most freight vehicles are small rigid trucks which carry light freight (and, therefore, do not benefit from increases in mass limits). These direct savings in transport costs are believed to result in economic growth, and may therefore increase future demand for freight transport. Macroeconomic analyses suggest that the total benefits to the community through increased economic activity may be as much as three times the direct savings in transport costs (Zeitsch, 1996).

Of course, savings in road freight costs may have adverse effects on other modes of transport, particularly short-haul rail freight. Where the prices paid for different transport services do not reflect the full costs to the community (including infrastructure costs, environmental costs and road safety costs), savings in one mode may have inappropriate impacts on other modes. Where the prices paid reflect the full community costs, it is a purely a matter of government policy whether reductions in other transport modes due to a productivity improvement in road freight transport are considered inadvisable.

4.4 Safety and the Environment

The stability of vehicles will improve with a move to more road-friendly suspensions fitted with auxiliary roll stiffness. Vehicle stability is related to a complex mix of vehicle characteristics including a range of dimensions, mass, centre of gravity, configuration and method of coupling. Suspensions also influence stability. This is borne out by analyses of the relative stability of a range of typical vehicles with different suspensions (Sweatman, 1996; National Road Transport Commission, 1996).

Other aspects of vehicle dynamics may also be affected by suspension type. For example, the degree of off-tracking and rearward amplification of combination vehicles are also significant for road safety. This is because ingress into the road space used by other vehicles may have severe road safety consequences. They may also influence stability.

Braking will improve under road-friendly suspensions such as air suspensions, which are generally non-reactive on multi-axle groups. This reduces the tendency to skid when braking.

The use of heavy vehicles also has environmental impacts. Two aspects are relevant to the policy implications of DIVINE:

- Vehicle emissions (noise and pollutants).

- The extent to which materials used in the construction of vehicles and their components can be recycled.

The type of suspension may have a direct impact on the noise emitted by a heavy vehicle. Road-friendly suspensions are generally quieter than mechanical suspensions, especially when the vehicle is empty. The noise associated with suspensions, however, is not significant in comparison to the noise associated with heavy vehicle engines, brakes and tyres. Consequently, no reduction in the perceived noise of heavy vehicles is likely to occur with greater use of road-friendly suspensions, except when the vehicle is empty.

Vehicle suspensions have no significant direct impact on heavy vehicle emissions of pollutants such as greenhouse gases, particulates and noxious gases. These emissions will be affected, however, by proposals that influence the amount of vehicle travel. Little difference is also likely in the degree to which materials used in the construction of suspensions can be recycled, although air suspensions may use slightly more non-recyclable synthetic materials.

The impact of suspension type on tyre wear is difficult to assess. Generally, road-friendly suspensions are held to improve tyre wear, but it is also claimed that tyre wear patterns associated with axle hop are worse on these suspensions. Little overall effect is therefore expected from greater use of road-friendly suspensions.

A policy trade-off between increased road-friendliness and increased mass also has implications for road safety. In a two-vehicle crash, the relative mass of the vehicles and the speeds at which they travel have obvious implications for road safety. As the difference in mass between vehicles increases, and as their speeds increase, the outcome of any collision will be more severe. Therefore, heavier vehicle masses may pose an additional safety risk, although for the heaviest vehicles (where mass increases are a most relevant consideration) the mass of the vehicle is already sufficiently large that the consequences of a collision are likely to be severe (generally fatal at highway speeds). Consequently, any increases in mass are unlikely to influence the outcome. However, increased vehicle weight generally degrades the dynamic performance (stability and tracking behaviour) of vehicles and will have a deleterious effect on braking performance.

Vehicle exposure is also a relevant consideration in road safety: the more a vehicle is used, the greater the risk of being involved in a crash. While crash risks may not be directly proportional to the distance driven, they are clearly related. This is an important consideration for development of any policy. Increased mass limits may reduce emissions and exposure to crash risks if there is a reduction in the distances driven in performing the road transport task. Given that there is a specific amount of freight to be moved at any one time, this should be the case. Hence, any increase in gross vehicle mass for vehicles fitted with road-friendly suspensions should have positive impacts for the environment and for road safety through a reduction in the number of vehicles required to perform the road transport freight task (tonne-kms).

4.5 Potential Effectiveness across Policy Settings

As has been emphasised in the discussions above, the relative effectiveness of any policy responses will depend on local circumstances. In addition, effectiveness must always be judged against governments' objectives, and these vary. Lastly, trade-offs between infrastructure costs and shipper/carrier productivity depend in part on regulatory, taxation and other policies adopted by public agencies. The following sections discuss local situations.

4.5.1 Regulatory Measures

In the United States, gross weight limits and axle load limits are the primary mechanisms at both the federal and state levels for limiting pavement wear by different vehicles, although a number of states also regulate tyre contact pressure. Federal gross weight and axle load limits apply on the Interstate System. Many states in the United States allow higher gross or axle weights off the Interstate System than are allowed on Interstate highways under US Federal law. As a result, heavier vehicles operate on roads that often have lower structural and geometric designs than the Interstate highways.

Similar situations apply in other nations. In Australia, the weight of vehicles is controlled through limits on axle masses, gross mass and manufacturers' ratings. Mass limits vary with axle configuration; the more axles in an axle group, the higher the load that may be carried on the group. Limits are set to take account of the relative road wear of single, tandem and triaxles with different tyre configurations (single, dual or super single). These limits are set under state and territory law, not at the federal level. Uniformity or consistency of requirements is being developed through the National Road Transport Commission, which is responsible for implementing a national approach to road transport regulation and setting national heavy vehicle charges to recover the costs of providing and maintaining roads for these vehicles.

In Europe, a Directive of the Council for the European Union (Directive 85/3, December 84, revised by Directive 96/53, July 1996) harmonises gross weight and axle load limits among EU member states, as well as the dimensions of vehicles used for goods transport. The purpose of the Directive is to prevent differences in regulations of member states from adversely affecting competition and forming a barrier to trade among member states. These limits balance advantages for vehicle operation against the resulting needs of road maintenance, the effects on road safety and protection of the environment. Nevertheless, individual national regulations concerning gross weight and axle load limits are not affected by the Directive for vehicles transporting goods within each member State. For example, France, Belgium and Spain have maintained their axle weight limit of 130 kN (single drive axle), a level nuch higher than the European limit of 115 kN.

The European Union allows additional loads (Directive 96/53) for trucks that are equipped with suspension systems that meet a specified performance standard, often referred to as the "drop test". For the European Union, a regulation that would make the use of road-friendly suspensions mandatory would have a negligible effect on the maintenance needs of most heavily trafficked roads which can be considered smooth. In addition, more than 50% of articulated heavy vehicles in the European Union already have air suspensions. However, the gain from such a regulation may be significant on secondary roads where the roughness level is higher. The gain would also be greater for the pavement maintenance required in central and eastern European countries because the roughness level of roads in these countries is higher.

Mexico is in the process of drafting regulations that will allow additional loads for trucks equipped with road-friendly suspensions. Australia is considering a similar proposal. These countries are providing their motor carriers with strong incentives to put in service trucks that use road-friendly suspensions and therefore reduce their road maintenance costs.

In the United States, there are no regulations at either the federal or state levels on types of suspensions or types of tyres that may be used, and no financial or other incentives are used to encourage the use of specific types of suspensions or tyres. Trucking companies have adopted air suspensions in large numbers in the United States, Canada and Japan without the need for special incentives, not because of benefits to pavements but because they are more comfortable for drivers and reduce cargo damage compared to mechanical steel suspensions. Because the adoption of air suspensions in the United States and Canada has been widespread for other reasons, financial incentives or additional weight allowances for adoption of air suspensions to reduce pavement wear may not be needed or desirable.

4.5.2 *Economic Measures*

The current federal user fee structure in the United States and user fees in most of its States provide little incentive to limit gross weights, axle loads, or otherwise to reduce pavement or bridge wear. The only federal user fee related explicitly to vehicle weight is the Heavy Vehicle Use Tax (HVUT); a relatively low annual fee on vehicles registered over 55 000 pounds. The HVUT increases with vehicle weight, although the increases are not proportional to increases in infrastructure costs for heavier vehicles. Although the tyre tax and fuel tax also vary with vehicle weight, none of these taxes provide an incentive to operate vehicles with more axles, and in fact, the tyre tax has the perverse effect of providing an incentive to limit the number of tyres and thus axles.

In the United States, individual states generally place greater reliance on registration fees and other taxes that more explicitly capture differences in highway costs attributable to vehicle weight. On the other hand, few have incentives to add axles and few have taxes related to vehicle weight that are graduated steeply enough to provide meaningful incentives to register and operate at lower gross weights. Changes to bring highway user fees more closely in line with highway cost responsibility would provide incentives for shippers and carriers to select equipment that balances payload requirements with infrastructure costs.

Australia and New Zealand, on the other hand, set charges for heavy vehicles to recover the costs of providing and maintaining roads for these vehicles. In Australia, charges are varied according to mass (for rigid trucks), number of axles and configuration. They are levied through a combination of fuel taxes and fixed annual registration charges. New Zealand has a more sophisticated pricing mechanism which varies with both the distance travelled and the mass carried. It relies on distance-measuring devices (hubodometers) to measure the distance travelled.

A range of user fees (charges) is levied in European countries. They rely on a number of different charging mechanisms. Efforts to harmonise fees, particularly for cross-border travel, are under way.

Public agencies must often balance the precision of user fees in reflecting the cost responsibility of different vehicles against administrative, enforcement, and compliance costs associated with various user fees. This is particularly true for the weight-distance taxes used in a handful of US states. While many believe that weight-distance taxes are among the best mechanisms to more closely link cost responsibility with vehicle cost responsibility, they are increasingly being challenged because of administrative, enforcement, and compliance cost burdens. Nevertheless, a similar system has been operating successfully in New Zealand for some time. Widespread use of on-board computers and other equipment may reduce those costs in the future.

States in the United States generally require special permits to operate above legal limits, and permit fees would be an ideal mechanism for reflecting additional infrastructure costs of overweight operations. However, few states have progressive permit fee structures intended to fully capture added infrastructure costs of overweight operations.

5. CONCLUSIONS

The OECD's DIVINE project has highlighted the need for the interactive effects of vehicles, bridges and pavements to be taken into account in all aspects of providing, maintaining and managing road infrastructure. These interactions are complex, however, and vary across routes, regions and countries depending on the characteristics of local vehicles and infrastructure.

Consequently, each region or country will need to make an individual assessment of the range of policy options that might be adopted in response to the findings of DIVINE. On the basis of existing information in different regions (supplemented by the results of DIVINE), such assessments can be made, despite the difficulties involved. Depending on the results of these assessments, and the region or country's objectives, different options are likely to be appropriate in different circumstances.

All countries can benefit from improved design and maintenance of infrastructure. A wider range of options has also opened up in relation to other possible policy responses, whether through regulation, pricing or relaxing other limits. For example,

> *The DIVINE results provide greater understanding of the nature of certain vehicle characteristics and their effect on road response. The project has developed new means of identifying and assessing the road-friendliness of vehicles, and a first basis for the quantification of road and bridge life obtainable through road-friendly suspensions. From a European viewpoint, the use of this knowledge may be viewed under the following categories:*
>
> *First, it provides policy makers with a scientifically sound basis for assessment or prediction of the impact of certain vehicle configurations on external (infrastructure) costs. Second, it provides those who initiate and develop legislation with specific knowledge which arms them when dealing with regulatory activities relating to road-friendliness of heavy vehicles. Third, it provides vehicle equipment manufacturers*

with a basis for developing better concepts (such as suspension systems) which lead to a reduced negative impact on road deterioration. And finally, it provides pavement designers with a basis for optimisation of road design and maintenance methods in line with expected road traffic composition and demand. (Bastiaans, 1997, p. 23)

5.1 Research Directions

DIVINE has provided a significant amount of information which will provide guidance on many policy issues, but it has also raised a number of issues worthy of further research. These include:

- The interaction between the environment (temperature, rainfall), suspension type and long-term performance of different pavements.

- The impact of dynamic loading on bridge fatigue.

- The need to develop comprehensive and consistent test procedures, including their relationship with the existing European bounce test to evaluate a "road-friendly" suspension, from which certification systems for new suspension systems may be developed.

- Development of effective in-service test procedures for road-friendly suspensions to ensure that their road-friendliness is maintained throughout their operating life.

- Improving the interaction between a vehicle's road-friendly suspension system and other aspects of vehicle design to increase the overall road-friendliness of vehicles.

Co-operative efforts involving vehicle, bridge and pavement engineers across countries, through organisations such as the OECD, may allow these issues, and others raised by DIVINE, to be addressed in order to improve the efficiency with which road infrastructure is used and administered.

5.2 Policy Directions

The DIVINE results have generated key policy implications for the management of the considerable investment by OECD Member countries in road infrastructure. As indicated in Chapter 4, the DIVINE results suggest that increases in static loads of between 4 and 12% (using the fourth power law) could be achieved through the use of road-friendly suspensions. In addition, recent Australian research indicates that the potential road damage effects arising from increases in gross vehicle mass limits of up to 15% may be outweighed by the effects of greater use of road-friendly suspensions.

In Chapter 2, it is shown that the flow-on effects to the broader economy from reductions in the costs of freight transport through payload increases could be of the order of three times the direct productivity benefits to transport operations. These results raise significant challenges for improving the productivity of road freight transport through a more strategic and efficient management of the road network. In addition, any reduction in the number of vehicles required to perform a given road freight task will provide benefits to road safety and the environment.

In order to realise the potential benefits of the DIVINE results, policy makers need to give consideration to:

- The merits of mandatory requirements for heavy vehicle suspension systems to become more road-friendly:

    – There is a clear need to distinguish between mandatory requirements for new vehicles and retrospective fitting of in-service vehicles, particularly given the cost implications of the latter, especially for vehicles travelling short distances.

- Price incentives to encourage the uptake of road-friendly suspensions by transport operators, such as:

    – Introduction of differential road use charges to favour vehicles fitted with road-friendly suspensions.

    – Reduction in the taxes applied to road-friendly suspension systems at the point of sale.

- Operational incentives, such as increases in gross vehicle mass limits for vehicles fitted with road-friendly suspensions.

- Current standards and practices for pavement construction and maintenance.

- Current standards and practices for bridge construction and maintenance, including the smoothness of pavements on approaches to bridges.

- Network impacts, both in terms of road infrastructure and the overall efficiency of freight transport, given the important link that road transport forms in the transport system.

The relevance and application of the policy implications arising from the DIVINE results rest with individual OECD Member countries.

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ANNEX A

LIST OF PARTICIPANTS

Policy Report

Australia	Ms. F. Calvert
Denmark	Mr. J. Christensen
France	Mr. J. Bonnot
United Kingdom	Mr. R. Addis
United States	Mr. P. Blow
OECD	Mr. C. Levins Dr. A. Ockwell

Executive Committee
Chairman: Mr. Jørgen Christensen (Denmark)

Denmark	Mr. J. Christensen
France	Mr. J.- F. Coste
Netherlands	Dr. C. van Theylingen Mr. P. Mazure
United Kingdom	Mr. G. Bowskill
United States	Mr. R. Betsold

Scientific Expert Group
Chairman: Dr. Peter Sweatman (Australia)

Australia	Dr. R. J. Heywood Mr. K. Sharp Dr. P. Sweatman
Austria	Mr. G. Fichtl Dr. J. Litzka Mr. H. Tieffenbacher
Belgium	Mr. A. De Henau
Canada	Mr. J. Woodrooffe
Denmark	Mr. E. Larsen
Finland	Mr. M. Huhtala
France	Mr. B. Jacob
Germany	Dr.- Ing. W. D. Hahn Mr. M. Stanzel
Hungary	Mr. C. Koren Mr. L. Palkovics Dipl.- Ing. S. Tombor
Japan	Mr. T. Ikeda Dr. T. Maruyama
Netherlands	Mr. R. J. Henny Mr. B. Hoogvelt
New Zealand	Dr. J. de Pont Dr. B. D. Pidwerbesky
Sweden	Mr. J. Aurell Mr. G. Magnusson

Switzerland	Dr. R. Cantieni Mr. A.- G. Dumont Dr. W. Krebs
United Kingdom	Mr. R. Addis (Project Manager) Dr. C. Mitchell
United States	Mr. W. J. Kenis Dr. W. Wang
OECD	Mr. B. Ficheroulle Ms. M-D. Gorrigan Mr. P. Hasson Mr. B. Horn Mr. C. Levins

Additional Researchers

Australia	Dr. P. S. Baburamani Mr. G. Jameson Mr. J. R. Johnson-Clarke Mr. S. McFarlane Mr. M. Moffatt Mr. D. Swenson Mr. N. J. Vertessy Mr. R. Yeo
Canada	Mr. E. Feser Mr. P. Leblanc Mr. S. McLoud Dr. N. Mrad Mr. Y. Séguin Mr. R. Senn
Czech Republic	Mr. V. Bily

Finland	Mr. R. Alkio Mr. P. Halonen Mr. V. Miettinen Mr. J. Pihlajamaki
France	Mr. O. Brunet Mr. V. Dolcemascolo Mr. P. Faucheur Mr. T. O’Connor
Netherlands	Mr. P. Ruijs
New Zealand	Mr. J. Devine Mr. A. Fussell Mr. B. Steven
Switzerland	Ms. S. Barella Dr. A. J. Felber
United Kingdom	Mr. I. Barbour Mr. L. Gyenes Mr. J. Hanley Mr. D. Jacklin Mrs. P. Lewis
United States	Mr. D. George Mr. J. Hammouda Ms. P. Minkle