VEHICLE-GENERATED VIBRATIONS IN ROADS AND THEIR SURROUNDINGS

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ABSTRACT

This paper provides an introduction and background to current research in Cambridge on (i) the forces applied to road surfaces by moving vehicles, (ii) the dynamic response of road structures and theories of road-damage accumulation, and (iii) the transmission of traffic-generated vibration to the surroundings.

1. INTRODUCTION

According to the Department of Transport's statistics for the financial year 1985/86, the annual cost of structural maintenance of roads in the UK was

	£ million
Motorways	109.5
Trunk roads	87.2
Local roads	581.8
	778.5 .

This included the cost of road reconstruction, resurfacing, surface dressing, patching, drainage, footways, bridges, earthworks and fences [1]. There is also statistical evidence that the number of structural defects visible at the road surface is increasing for both trunk and non-trunk roads [2]. It is known that an important factor which leads to road deterioration is the repeated dynamic loading caused by traffic. However at present there is inadequate knowledge about the characteristics of these loads, how they are affected by vehicle design and speed and by road roughness, how dynamic loads cause stress below the surface, and how stress in the road leads to surface deterioration.

In 1980, the Armitage Report [3] considered the implications of introducing heavier road vehicles in the UK. The "4th power law" was used to relate static axle loads to projected road damage. As a result of this report, the maximum UK gross vehicle weight was raised from 32.5 tonnes to 38 tonnes.

The "4th power law" stems from the AASHO road test (carried out in the USA, 1958-60) [4] from which it was deduced that the decrease in pavement serviceability caused by a heavy vehicle axle could be related to the 4th power of its static load. The validity of the 4th power law is questionable [5]. It was derived from a limited number of tests, performed under a particular set of conditions appropriate to the USA in 1958. For UK roads of different construction in different weather conditions it is unlikely to be accurate. The 4th power law does not allow for the effects of different vehicle configurations, suspension types, or for modern tyres. Addis and Whitmarsh [5] re-analysed the AASHO data, assuming typical UK traffic conditions and found that the exponent in the notional damage "law" could range between 2.4 and 6.6.

It is clear that the 4th power law does not adequately characterise the road-damaging potential of heavy goods vehicles. Nor does it account for other damaging effects of axle loads, for example to bridges or underground pipes. Also there is increasing concern about the level of ground vibration transmitted from moving road and rail vehicles. This is particularly so in congested urban areas. Perhaps surprisingly, there is relatively little detailed knowledge about the generation and transmission of ground-borne vibration from roads and railways or about the transmission of these vibrations into buildings.

There is growing pressure within the EEC to harmonise vehicle regulations. For the UK this would mean an increase in the maximum permitted overall vehicle weight. More information about the environmental consequences of heavier road vehicles is therefore needed urgently. The programme of research now being undertaken by the authors' group in Cambridge, with the cooperation of the Transport and Road Research Laboratory (TRRL), has this objective. There are three main goals. The first is to obtain fundamental information on the mechanics of vehicle-road interaction so that the relationships between traffic characteristics and road damage can be modelled more accurately than at present. The second is to find a basis for allocating track costs to vehicles according to their road-damaging potential. The third goal is to learn more about the generation and transmission of ground-borne vibrations and to find ways of minimising their effect.

This paper, which is the first of four papers to this conference by the same group of workers, is intended to give an overview of the research in progress on these topics in Cambridge and its strategic plan. Details of specific aspects of the work will be described in the three following papers.

2. TYRE FORCES GENERATED BY MOVING VEHICLES

A vehicle travelling along a smooth, straight horizontal road at steady speed will theoretically apply constant forces, the static wheel loads, to the road through its tyres. In practice all roads have surface irregularities which excite vibration of the vehicle. As a result, the wheel forces fluctuate about their static levels. These fluctuating loads are known as dynamic tyre forces (or dynamic wheel loads). They may be accompanied by large dynamic stresses in the road surface, which are in turn transmitted by ground-borne vibration to adjacent structures, whether roadside buildings or buried pipes. In order to determine dynamic tyre forces, it is necessary to model vehicle response to road surface irregularities. The influence on tyre forces of vehicle design features, vehicle speed and load distribution, and road roughness characteristics can then all be investigated.

It has been found that road surface roughness can be modelled as a homogeneous Gaussian, random process, providing that occasional large local irregularities, such as potholes, are isolated and treated separately [6]. Considerable data is available on the statistical nature of road topography and it is possible to generate surface roughness artificially by appropriate pseudorandom processes [7]. For three-dimensional vehicle models, it is necessary to know the correlation between the roughness of two or more parallel tracks across the surface. One approach is to assume that the roughness is isotropic, in which case the surface can be described by a two-dimensional spectrum which can be derived from the measured spectrum of a single track. [7].

Generation of the equations of motion of linear or nonlinear vehicle models with many degrees-of-freedom can be complex. A method for simplifying this task has been devised [8,9]. In this method, each suspension sub-assembly is represented by general dynamic characteristics which are independent of the geometry of the vehicle. The resulting vehicle model can be used for both linear and nonlinear simulations. Road surface roughness is "filtered" by pneumatic tyres. A linear theory has been developed to describe the ability of the tyre contact patch to absorb (or envelop) short wavelength irregularities [10]. Leaf springs are the most common suspension elements in heavy goods vehicles. A method for simulating their behaviour under realistic operating conditions has been developed and validated in Cambridge using a purpose-built dynamic testing machine [11]. This rig has also been used for measuring the characteristics of leaf springs, to provide parameters for vehicle simulations [9].

The response of a theoretical vehicle model to road roughness can be calculated by linearising the equations of motion and using random vibration theory to obtain frequency domain solutions [8,12]. However, accurate prediction of peak wheel/road forces requires more realistic representations of the nonlinear suspension elements, and it is necessary to solve the equations of motion in the time domain by numerical integration [8,9,13(part 1)].

Numerical simulations of vehicle behaviour have been validated by a programme of measurements conducted on MIRA's pavé test track with an instrumented, three-axle, rigid vehicle. Predicted wheel/road forces were found to correlate well with the measurements [9]. Further model validation work is in progress. A programme of measurements was performed on an instrumented four-axle articulated vehicle on the TRRL test track during the summer of 1987. These tests and the corresponding theoretical predictions are presented in one of the accompanying papers [14].

3. ROAD RESPONSE AND MECHANISMS OF ROAD DAMAGE

In recent years, considerable research effort has been concentrated on the measurement and prediction of dynamic wheel loads, and on static analysis of road structures and their failure mechanisms, see literature review in [13(part 2)]. Very few investigators have examined the relationships between dynamic tyre forces of heavy vehicles and road surface deterioration.

Some experimental studies have been performed [15-17], in which instrumented vehicles have been driven over instrumented pavement sections with buried strain gauges. These studies provided considerable experimental data concerning the instantaneous strains in roads at specific measuring points due to the passage of known wheel forces. In particular, measurements at TRRL [15] and the University of Hanover [17] have shown that for a given road profile, peak dynamic strains occur repeatedly near the same locations for similar vehicles operating at similar speeds.

The major problems associated with these studies were:
(i) The high sensitivity of pavement response to the lateral position of the tyres during their passage over the measuring points.
(ii) The high sensitivity of pavement response to environmental conditions, particularly temperature.
(iii) The difficulty of providing sufficient measuring points in the road to determine the statistics of road response to the fluctuating wheel forces.
(iv) The difficulty for other researchers to duplicate the test conditions particularly the structural properties of the test road and the environmental factors.

In 1984, a pilot study into the theoretical road damage caused by heavy vehicles was performed in Cambridge [8,13,18]. The objectives were:
(i) to assess the importance of dynamic wheel forces in road damage
(ii) to ascertain the most important factors influencing road damage, and
(iii) to indicate the direction for future research.

The approach of the study was to examine the theoretical damage accumulated at specific points along the road due to the passage of realistic theoretical vehicle models. Road damage was modelled by four different damage criteria which were developed from published results on road design and failure. Two of the criteria required a method for calculating the transient response of road surfaces to moving random forces. The theory that was developed for this task is presented with sample calculations in [8,13(part 1)].

A typical result of the pilot study is shown in fig. 1, which is reproduced from [13(part 2)]. This shows the variation of theoretical fatigue damage as a function of speed due to the passage of a tandem-axle vehicle model (representative of a typical UK semi-trailer) over three different road profiles. The data has been normalised with respect to the fatigue damage caused by a "non-dynamic" vehicle travelling at the same speed.

The main conclusions of the pilot study were:
(i) Theoretical road damage done by common commercial vehicles increases with speed. There are certain "critical" speeds at which the damage increases suddenly due to pitch coupling between the axles and increased excitation of the modal responses.
(ii) On roads with relatively smooth surface profiles, at high speeds, the increase in dynamic wheel loads with speed may be outweighed by the decrease in road surface dynamic response due to its visco-elastic properties.
(iii) The damage done to approximately five per cent of the road surface area during passage of a theoretical model vehicle at typical highway speeds may be as much as four to eight times the "non-dynamic" damage.
(iv) Dynamic coupling between axles increases theoretical road damage. It appears that this contribution can be reduced by use of improved suspensions which incorporate additional damping of particular modes of the whole vehicle and of the static axle load equalising system.

VEHICLE-GENERATED VIBRATIONS

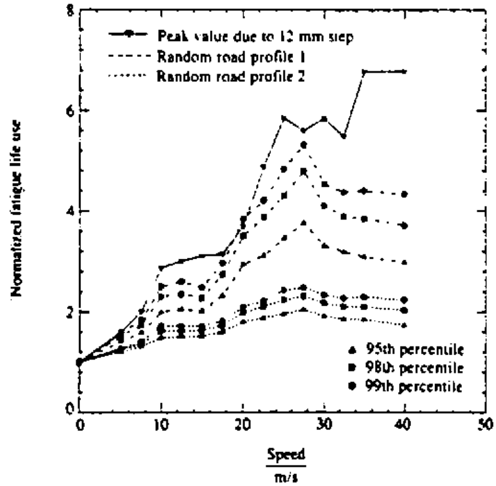

Fig. 1 Normalised fatigue damage as a function of vehicle speed for a tandem-axle vehicle.

In addition, the pilot study showed that considerably more research was needed to:

(i) Develop and validate the road-response calculation referred to above.

(ii) Collect enough dynamic wheel force data from typical commercial vehicles to study the loading pattern on UK roads.

(iii) Investigate the mechanisms of road surface deterioriation caused by dynamic wheel loads.

Items (i) and (ii) are being pursued actively at present. It is intended that (iii) will become a major area for future work.

During the summer of 1987 a programme of measurements was performed on an instrumented section of the TRRL test track in order to validate the road response theory in [8,13(part 1)]. The results are provided in an accompanying paper [19]. This calculation method will be used in future to simulate the response of long (statistically significant) sections of a "standard" road for a variety of vehicles. The theoretical road response will be used to assess the road damaging effects of measured and simulated wheel forces. Most of the problems associated with the previous experimental studies of dynamic road response (described above) will be eliminated by this novel approach.

In order to measure the wheel forces generated by many different uninstrumented vehicles, a load-measuring mat has been developed with closely-spaced force-sensitive transducers. This will be secured to the road surface and is sufficiently flexible to conform to the road profile at wavelengths that cause significant wheel/road interaction. It is intended that data collected with the mat will ultimately be used to develop a vehicle performance standard (and possibly a type-approval test) based on the road-damaging potential of vehicles.

Vehicle modelling work will continue in parallel with this experimental programme. The objective will be to determine the limits by which suspension systems may be improved to minimise road surface damage. A parallel design project will be performed in consultation with vehicle manufacturers and will use the results obtained from the modelling study to put forward a number of preferred suspension systems. This work will include investigations of semi-active and active suspension elements.

4. GROUND-BORNE VIBRATION TRANSMISSION

The problem of vibration transmission from roads is increasingly important in crowded urban areas. There is also a similar problem involving the transmission of ground-borne vibration from underground trains to adjacent buildings. Work has been taking place in Cambridge to model the transmission of ground-borne vibration using visco-elastic ground models. The calculations so far have been concerned with estimating the vibration spectrum at some distance from a busy motorway. They have been made on the assumption of a random distribution of vehicles along the road with average suspension characteristics. Although these calculations are complex, numerical computation has enabled typical vibration fields to be predicted for a representative ground model. The details of this calculation are provided in an accompanying paper [20]. The measured results show satisfactory agreement with theoretical predictions.

Structural vibrations have been measured within a new reinforced concrete building near Moorgate station in London. The main source of excitation is from a nearby underground railway line. Some typical results are shown in fig. 2. Preliminary calculations have also been made and the calculated response spectra are qualitatively similar to the measured data. These results will be published shortly.

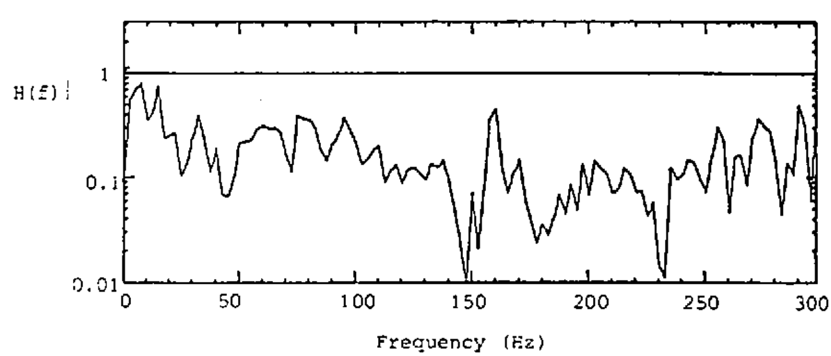

Fig. 2 Magnitude of the transfer function between measuring positions two storeys apart in a modern reinforced-concrete building.

There is at present considerable interest in the vibration attenuation that may be achieved by using a resilient interface to separate the main structure of a building from its foundation. Further calculations and a more comprehensive programme of measurements are being considered.

5. CONCLUSION

The environmental effects of heavy vehicle wheel forces are becoming increasingly important. The integrated research programme described in this paper is intended to improve current understanding of the interaction between vehicles and their surroundings and to make positive suggestions as to how commercial vehicles may be improved to minimise their detrimental effects. One of the main aims of the research is to provide sufficient information to enable the formulation of a vehicle standard and a type approval test, with the objective of minimising the damage to roads, bridges and underground services and the vibrations transmitted to buildings.

6. REFERENCES

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