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Fuel Consumption Due to Pavement Deflection Under Load

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ABSTRACT

It is well known that the principal effects influencing vehicle fuel consumption are engine and transmission efficiency, air resistance and tyre hysteresis. This paper however considers the influence of pavement stiffness. A 3D finite element analysis is described, modelling the passage of a wheel. Pavement depth up to 10m is modelled explicitly and the effect of pressure waves crossing boundaries is allowed for using visco-elastic boundary elements. The model was validated with reference to Falling Weight Deflectometer test data. It was then used to generate values for energy loss under different wheel loads at different speeds over different types of pavement construction. The interim conclusion is that total energy loss from a heavy goods vehicle due to pavement deflection, although small in comparison with total fuel energy consumption, is significant in comparison with the embedded energy typically associated with pavement construction, providing apparent justification for use of concrete.

INTRODUCTION

Embedded energy and carbon life cycle analysis are acknowledged as being of paramount interest in ensuring that engineering construction is as environmentally friendly as possible. In the case of a highway the bulk usage of materials is considerable, resulting in high costs, high embedded energy – particularly where bitumen or cement is involved – and consequently large carbon footprints. This is well understood and there is pressure from governments across the world to reach increased levels of sustainability in terms of material usage.

Embedded energy is not easy to estimate with confidence over the full life cycle of a highway, including demand for materials during maintenance and rehabilitation and the potential for re-use of existing materials either on site or elsewhere. The requirements of life cycle analysis are well established [BSI, 2006a, 2006b, 2008] but there are few studies of pavement construction that meet them [e.g. Stripple, 2001; Huang et al, 2009; Waymen et al, 2009]. Estimates will be sensitive to assumptions, notably the extent of future maintenance, which is hard to justify for the excellent reason that this is something which varies greatly from site to site. Concrete roads can last for 40 years or more when they are properly constructed, with no need for any replacement materials other than very minor repairs, while asphalt surfaces on major highways typically need replacement every 10-15 years, but the problem is that this level of performance for concrete is far from guaranteed and the consequences of underperformance can be very expensive, both in direct monetary terms and in associated energy and carbon.

However a full life cycle analysis of energy should include use of the road and there is an environmental benefit that is claimed for concrete over asphalt, namely a reduction in vehicle fuel consumption due to reduced pavement deflection under load. Measurements have been made both on actual highways [Taylor, 2002] and under controlled trafficking experiments [Benbow et al, 2007] and these appear to show a distinct advantage for concrete. Admittedly on closer inspection the advantage is sometimes less clear than it first appears due to differences unrelated to the properties of the material itself, most notably texture, but even a small advantage has the potential to dwarf the environmental differences due to embedded energy in the materials and associated carbon consumption. It is therefore important to ascertain whether the claims made for concrete roads are genuine or not and this paper reports on an investigation with that aim.

EMBEDDED ENERGY VERSUS FUEL ENERGY

To illustrate a simplified comparison between material embedded energy and vehicle fuel energy, Table 1 presents material embedded energy estimates for two quite different pavements, based on the values given in Thom [2008] which were derived from Stripple [2001]. They are both heavy duty pavements suited to motorways, one with an asphalt surface, the other with concrete. They are intended to be approximately equivalent in terms of traffic carrying capacity.

Table 1. Estimates of Embedded Energy

	Asphalt	Concrete	Lean Concrete	Crushed rock	Gravel	**Energy per m^2**
Embedded Energy	700MJ/T	900MJ/T	450MJ/T	20MJ/T	10MJ/T	
Pavement 1	300mm	-	-	150mm	300mm	**517MJ**
Pavement 2	-	250mm	150mm	-	300mm	**724MJ**

Multiplied over the width of a traffic lane, 3.65m in the UK, the total embedded energy for these materials in the two pavements is 1887 and 2643MJ/m and in terms of initial construction alone the concrete option is therefore much less ‘sustainable’ in energy terms than the asphalt option.

To extend this simple illustration to maintenance and rehabilitation it might be assumed for example that a further 100mm of asphalt will be required on Pavement 1 over the course of a 40-year life while there is no such demand on Pavement 2, in which case the material embedded energy demand for Pavement 1 has to be increased to 2500MJ/m, only marginally lower than that for Pavement 2. Overall therefore there appears to be little difference in total material embedded energy between the asphalt and concrete options.

By way of comparison, consider the fuel energy expended in a heavily trafficked lane of a busy highway. The traffic flow may be around 30,000 vehicles per day. If the average fuel consumption is 7km per litre (assuming a high commercial vehicle percentage) this equates to a fuel demand of around 4 litres per metre per day, or approximately 140MJ of energy per metre per day. Over an assumed lifetime of 40 years, this gives 2000GJ per metre, nearly one thousand times the estimate of material embedded energy in a heavy duty pavement. Clearly if a change in pavement construction could make a small improvement in fuel consumption it would be worth investing a considerable amount of embedded energy to achieve this – considered from a holistic standpoint.

PRINCIPLES OF ANALYSIS

Given the difficulties involved in carrying out direct measurements of fuel consumption in a fair manner when comparing two different pavement constructions, it was decided to adopt a computational approach to the problem. This allows individual variables such as vehicle speed, wheel load and pavement construction details to be controlled. The 3-D finite element package ABAQUS was used to simulate the passage of a load (constant pressure over a defined rectangular area) along a 10m section of a 40m long pavement utilising small time steps. Fig. 1 shows the model used in outline. Full details will be presented in Lu et al [2010].

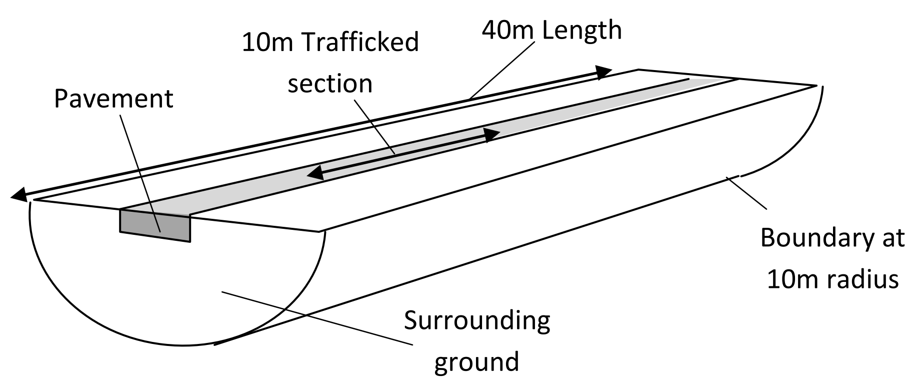

Fig. 1. Outline of Simulated Pavement

The start condition for each simulation is that of a static load applied to the start point of the 10m trafficked section. Then, as the loaded area is time-stepped forwards it generates pressure waves that propagate along, across and down into the pavement. The boundary conditions have been selected (by use of multiple spring-dashpot elements) in order to absorb these pressure waves, simulating the actual situation in which the waves would propagate outwards in uninterrupted fashion. The general reliability of the model has been checked by using it to simulate tests from a Falling Weight Deflectometer, a device that applies a pulse of load to a pavement through a circular contact patch. Both the magnitude of deflection and its retardation relative to the applied load pulse have been successfully modelled (within reasonable error margins). Whilst this type of loading is significantly different from that applied by a moving wheel, it nevertheless forms a check on the ability of the model to deal with inertial effects, the primary reason for the retardation of the deflection.

A similar retardation of deflection is found to occur under a moving wheel. As the wheel approaches a certain point on the surface of the pavement it begins to deflect, reaching a deflection δ_1 as the leading edge of the zone of applied pressure arrives. During the time that the pressure is present the deflection increases and then begins to decrease again after the centre of the area of pressure passes. However when the trailing edge of the pressure zone passes it will only have recovered to a deflection δ_2, which is slightly greater than δ_1 due to retardation caused by inertia. Thus, in stress-deflection space the result is as shown in Fig. 2.

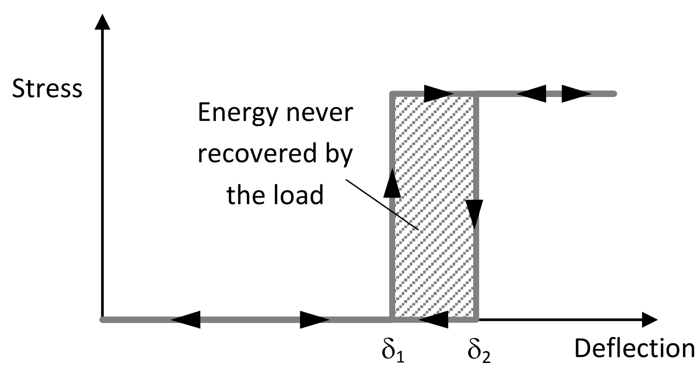

Fig. 2. Stress-Deflection Plot under a Moving Wheel Load

The shaded rectangle in Fig. 2 represents energy imparted by the load but not recovered. When multiplied by the width of the wheel pressure area it represents the energy lost per metre of wheel travel. This is the primary output of the model presented in this paper.

At this stage it should be acknowledged that the pressure distribution beneath a pneumatic tyre is not actually uniform, tending to be highest at the edges of the loaded area due to tyre wall effects [e.g. De Beer, 1996]. However it is reasonable to suggest that the error in predicted energy loss due to non-uniform pressure is a relatively small percentage of the total and is unlikely to affect the conclusions here.

SIMULATION RESULTS

Effect of Vehicle Parameters

Two variables were considered under this heading, namely wheel load and vehicle speed. Fig. 3 shows predicted energy loss (per wheel) calculated over a heavy duty asphalt pavement with a cement bound base layer. In all cases the tyre pressure was kept constant at 552kPa.

A key finding here is that vehicle speed has only a secondary effect on energy loss due to pavement inertia – although of course it has a much greater effect on losses due to air resistance. However there is a slight tendency for increased losses at higher speeds. The calculated effect of wheel load is reasonably logical although the difference between 20kN and 40kN is less than might have been expected and indicates that the influence of wheel load is non-linear.

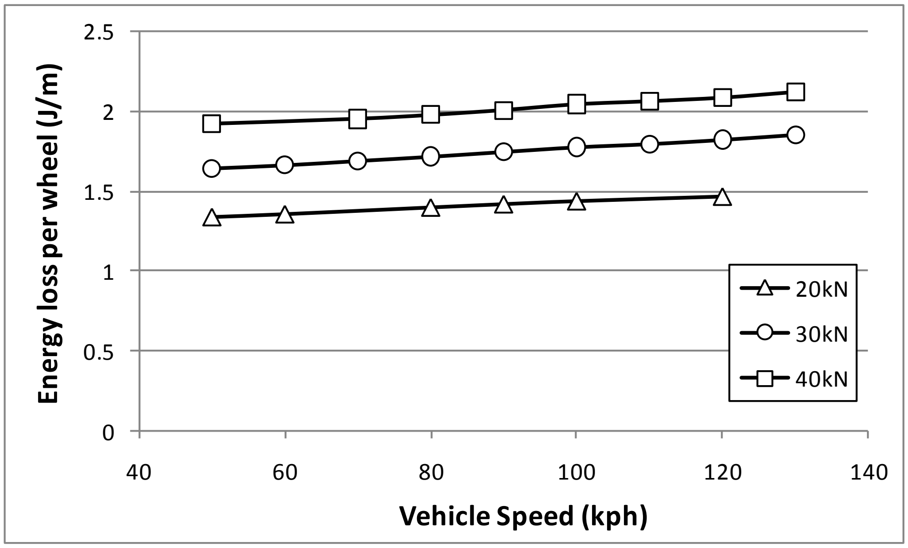

Fig. 3. Influence of Wheel Load and Vehicle Speed

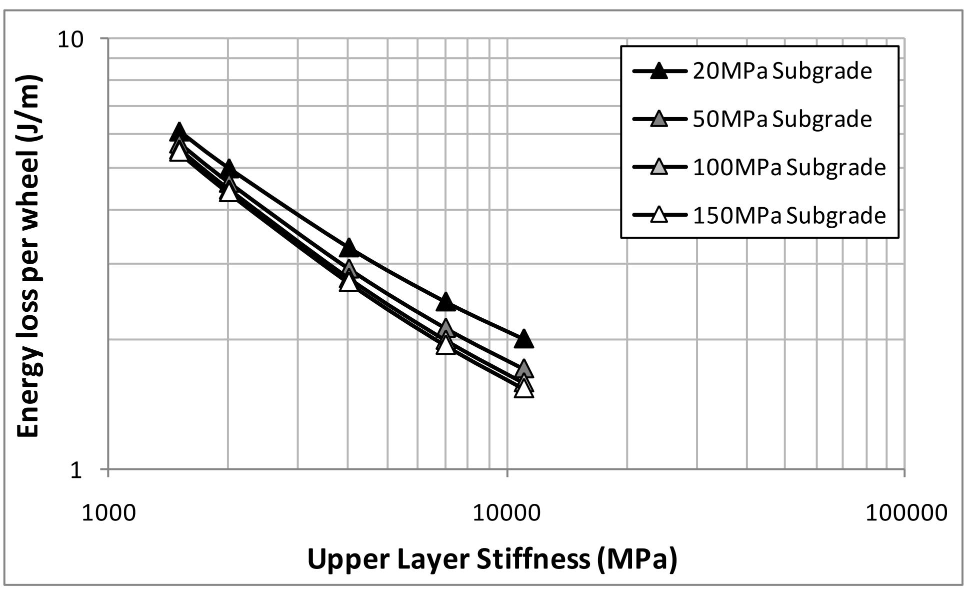

Fig. 4. Influence of Upper Layer and Subgrade Stiffness

Effect of Pavement Parameters

The pavement structure simulated here is one with four layers, of thickness 140mm, 200mm, 300mm and infinite. The stiffness moduli of Layers 2 and 3 have been kept constant at 7000MPa and 2400MPa, representing strong and weak cement bound layers respectively. These were initially selected to simulate a real pavement for which Falling Weight Deflectometer data was available. The upper layer, representing asphalt, has been varied between 1500MPa (poor material and/or high temperature) and 11000MPa (good quality material and/or low temperature). Layer 4, representing the subgrade, has been varied between 20MPa (very soft soil) and 150MPa (firm ground). The predictions for a 40kN wheel travelling at 90kph are shown in Fig. 4.

The first point to note from Fig. 4 is that the subgrade effect is secondary, with very little difference between predictions for 50MPa and 150MPa. The effect of the upper layer however is very significant. A high quality asphalt may have a stiffness modulus of around 2000MPa on a warm day, giving an energy loss of about 4.5J/m per 40kN wheel; on a cold day the modulus might be 10000MPa and the energy loss would reduce to about 1.7J/m. However, extrapolating to a concrete stiffness of 40000MPa the energy loss is likely to be no more than about 1.0J/m.

DISCUSSION

This study predicts that there is a large proportional difference in the energy loss due to pavement deflection between surfaces with stiffness chosen to represent asphalt and concrete. The issue however is whether this difference is significant in a wider context and for this it is necessary to take an example traffic flow. If it is assumed that a lane of a major road carries traffic of 3000 commercial vehicles per day, still significantly lower than the maximum flow which is probably around 10000, and it is further assumed that they have an average of eight 40kN wheels each, then the calculated energy losses should be multiplied by 24000 to arrive at a daily total. If the life of the road is taken to be 40 years then the whole-life multiplier is about 3.5 10^8. Thus the energy lost from a concrete pavement becomes 350MJ/m while that from an asphalt pavement at moderate temperature (stiffness modulus 4500MPa say) is about 900MJ/m. The potential saving by switching to concrete in this case is 550MJ/m.

While these numbers are very small in comparison to the total fuel energy consumption – estimated above at 2000GJ/m – a more meaningful comparison is with the embedded energy in the pavement materials. Taking the example pavements introduced previously in Table 1, the respective values for concrete and asphalt pavements were 2643 and 2500MJ/m, including an allowance for maintenance to the asphalt option. The straightforward conclusion therefore is that fuel energy lost through pavement deflection tips the balance in favour of concrete due to its much higher stiffness. Clearly this conclusion is traffic dependent; the difference would only be significant where the traffic volume exceeds about 2000 commercial vehicles per day. However it becomes very significant indeed on the most heavily trafficked lanes, approaching 10000 commercial vehicles per day.

This conclusion must also only be considered interim in nature. The problem is that only one term in the overall equation has been evaluated, namely the influence of pavement deflection, and it is considered likely that another pavement-related term, the influence of tyre distortion in the contact zone, may be at least of equal significance. To a large extent tyre distortion depends on tyre pressure, which is unrelated to the pavement surface, but the distortion of individual tread blocks will also be a function of the texture of the pavement. This effect should therefore be studied in some detail before any overall conclusions regarding pavement surface material can be made.

CONCLUSION

A model has been developed and substantially validated that calculates the energy dissipated within a pavement due to surface deflection under the passage of a moving wheel. Results from this model indicate only minor effect on energy loss from both vehicle speed and subgrade stiffness. The effect of load level was more significant, as expected. However the effect of upper pavement layer stiffness was of most significance, with a factor of 1.7 to 4.5 between pavements with stiffnesses representing asphalt and concrete surfaces, the range of factors reflecting the range of possible asphalt temperatures and therefore stiffnesses.

In the context of embedded energy in pavement construction this difference is significant and suggests that a concrete surface generates a lower energy demand over a full pavement life cycle for heavily trafficked roads. However the point is made that it is necessary to carry out a similar study of the energy loss induced in the tyre tread as a function of pavement surface texture before any final conclusion can be made.

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