A PAVEMENT DAMAGE BASED SYSTEM FOR CHARGING HGVS FOR THEIR USE OF ROAD INFRASTRUCTURE

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1 Introduction
Financing the maintenance and renewal of road transport infrastructure requires substantial investment. This task has traditionally been the responsibility of national governments. Generating sufficient funds for financing road maintenance and renewal activities has generally been achieved using a number of mechanisms including user taxes and charges (e.g. fuel tax, vehicle excise duty, tolls). Charges and taxes are calculated using road track cost allocation and charging methods which attempt to allocate and recover road costs (e.g. pavement damage) from users based on a ‘polluter pays’ approach.

Urquhart and Rhodes (1990) for example identify several shortcomings with these charging mechanisms in applying the ‘polluter-pays’ approach. More recently, the European Commission (EC) has promoted the implementation of fairer and more efficient mechanisms for pricing transport infrastructure (European Commission, 1995). According to the EC, new charging mechanisms should align more closely costs generated by individual road users and the charges these users pay. Of particular interest are Heavy Good Vehicles (HGV) because they are responsible for virtually all road pavement damage. For example, a single 8 tonne axle of an HGV causes approximately 65,500 times more damage than the 0.5 tonne axle of a car (Cebon, 1999). Significant variations also exist in the costs generated among and between different HGV classes and the corresponding vehicle charges attributed to them. The EC argues that the introduction of (electronic) charging mechanisms that incorporate key variables responsible for road infrastructure costs will allow HGVs to be charged more fairly and efficiently.

Switzerland, Austria and Germany have been at the forefront recently in terms of practical implementation by developing electronic distance-related charging systems for HGVs (Sundberg and Cunningham, 2002), while a similar system is planned to start in the UK in 2008. However, Dodoo and Thorpe (2004) report that these systems omit several important variables that affect the extent of damage caused by individual HGVs as they travel around the network. These relate to vehicle characteristics (e.g. axle loads, suspension type, and tyre type and configuration) and pavement properties (e.g. type and structure, surface temperature and surface roughness).
This paper describes the development by the authors of a new electronic on-board system for charging HGVs which includes key variables for estimating the amount of pavement damage each HGV causes on the road network.

The paper is organised as follows. Section 2 summarises briefly the main factors affecting pavement damage. Section 3 presents the financial costs of road infrastructure maintenance and construction, reviews current practice for recovering pavement damage costs from HGVs and identifies the need to improve these systems. Section 4 of the paper describes the development and field demonstration of a new pavement damage based HGV charging system which includes key variables for estimating the amount of pavement damage caused by an HGV. Section 5 discusses some potential benefits that can be achieved with the implementation of the charging system. Finally, the paper concludes with a summary of the key points discussed.

2 Road Pavement Damage by HGVs

Road pavements play a vital role in modern economies by providing a means for the movement of people, goods and services. It is of particular importance to the freight industry where road freight carried mainly by HGVs accounts for over 70% of domestic freight movement in most European Union countries (Department for Transport, 2003). Road pavements suffer distress and deteriorate with use and over time as a result of traffic loading from HGVs and also climatic interactions. Studies conducted by AASHO in the 1960s revealed that the amount of pavement damage caused by an HGV was related exponentially to the static axle load of the vehicle (AASHO, 1962). Further studies have revealed that pavement damage is also affected by a number of vehicle characteristics (e.g. axle configuration, suspension type and tyre type) and pavement properties (e.g. type and structure, surface roughness) (see for example Gillespie et al., 1993). The nature and variety of these properties is such that pavement damage caused by HGVs can vary widely both spatially and temporally (European Commission, 1995). Knowledge about the factors responsible for the extent of pavement damage caused by HGVs on road pavements provides a useful basis for providing a more equitable, efficient and transparent way of charging HGVs as championed by the EC.

3 Financing Road Transport Infrastructure Maintenance

The OECD (1994) estimates that member countries each spend between 0.2 – 1.9 percent of their GDP annually on the maintenance of road transport infrastructure.

Figure 1 provides a snapshot of road maintenance investment and their proportion of total road investments in 1999 for a number of European countries. The columns on the left-hand side of the figure represent the total amount spent on road maintenance activities in each country while those on the right represent the road maintenance investment as a percentage of total road investment.

The figure suggests that Norway, Germany, Turkey and France each spent over 1.5 billion Euros on road maintenance in 1999 with Italy and the UK spending over 1 billion Euros. In terms of the percentage of investment spent on road maintenance,
Scandinavian countries spent the most with over 50 percent of their total road budget on road maintenance activities in 1999. In the UK, road maintenance activities account for approximately 40 percent of total annual road investment (Asphalt Industry Alliance, 2003).

**Figure 1** Investment in road maintenance for 1999 (EUROS).

![Investment in road maintenance for 1999 (EUROS)](image)

Source: (adapted from Papí et al., 2004)

Raising the revenue to finance the maintenance of transport infrastructure has generally been achieved in most countries through a variety of taxes and charges. User taxes and charges are calculated using road track cost allocation and charging procedures which attempt to allocate road infrastructure costs based on the ‘polluter pays’ principle. Highway costs (e.g. maintenance, reconstruction) are allocated to different vehicle classes based on their collective responsibility for different components of these costs using a variety of measures which are considered to relate vehicle use to road costs. These measures include vehicle characteristics and use-related data (such as vehicle-km travelled, standard-axle-km and PCU-km).

Even though road track cost allocation and charging mechanisms enjoy use worldwide, they suffer from well known weaknesses which undermine the performance of these models in applying the ‘polluter pays’ principle to the cost allocation and charging process (see for example Harrison 1979; Nash 1980). These weaknesses concern (for example), the reliability and quality of input data used in the models, the use of aggregate data to allocate costs to HGV groups and the continued use of static loads rather than dynamic loads which are generated by HGVs on road pavements (Urquhart and Rhodes, 1990). As a result, road track cost allocation and charging mechanisms produce, at best, only crude averages for HGV costs that relate weakly to the actual costs generated by individual HGVs.

In recent years, there have been significant developments in new systems for charging HGVs as a result of the EU’s policy to introduce fairer and more efficient ways of charging vehicles. The Swiss Heavy Vehicle Fee introduced in 2001 is the first
electronic system for charging HGVs for the use of all roads in the country in Europe (Krebs and Balmer, 2002). On-board GPS units record the distance travelled on the Swiss road network. Charges are then calculated based on the actual distance travelled, the vehicle’s plated weight and its emission class. In 2004, Austria introduced an electronic distance charging system for HGVs for the use of its motorway network. An on-board unit installed in each HGV calculates and accumulates charges based on the number of axles (2, 3 or 4+) and distance travelled on the Austrian motorway network. Germany are currently in the final stages of introducing an electronic distance charging scheme which will charge HGVs (over 12 tonnes unladen weight) on the country’s Autobahn network. The German system calculates charges based on vehicle characteristics (i.e. number of axles, gross vehicle weight and pollution rating), distance travelled and route taken. Similar electronic charging schemes for HGVs are being planned for a number of countries in the near future (e.g. UK, Sweden and The Netherlands). Even though these new systems address some of the issues noted in the EC report, they still omit several key variables that are crucial for estimating pavement damage costs by individual HGVs.

Dodoo and Thorpe (2002) identify the main factors responsible for pavement damage caused by HGVs. The factors include:

- dynamic axle loads;
- number and type of axles (e.g. single, tandem);
- tyre properties (e.g. wide-base, dual); and
- pavement properties (e.g. pavement type, thickness, temperature and roughness).

Of these factors, dynamic axle loads and pavement thickness are the predominant factors responsible for pavement damage by HGVs (Gillespie et al., 1993).

Table 1 indicates which of these key pavement damage parameters are included in current HGV charging systems. Almost all the current systems include factors relating to the number of axles on an HGV and the distance travelled. However, none of the systems include the dynamic axle loads imposed by HGVs on pavements even though dynamic axle loads are one of the principal causes of pavement damage and a main source of variation between the damage caused by individual HGVs. Tyre and pavement properties do not feature in any of the systems.

Table 1 Pavement damage parameters in HGV charging systems

<table>
<thead>
<tr>
<th>Country</th>
<th>Dynamic Axle Weight</th>
<th>Number of Axles</th>
<th>Type of Axle</th>
<th>Tyre Properties</th>
<th>Pavement Properties</th>
<th>Distance Travelled</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Zealand</td>
<td>X</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>Eurovignette</td>
<td>X</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>HELP (US)</td>
<td>(✓ ¹)</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>Switzerland</td>
<td>X</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>Austria</td>
<td>X</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>Germany</td>
<td>X</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
</tbody>
</table>

¹ Weigh-In-Motion used for enforcement of axle and gross weight limits only.
An ideal system would incorporate all the variables that affect the extent of pavement damage by each individual vehicle. As Newbery stated in 1988, ‘if every link on the road network had a tollgate, then vehicles could be charged at a vehicle and road specific rate (per ESAL km, at different rates depending on the characteristics of the road, or the road type, measured by strength, traffic flow, maintenance strategy)…..In practice, of course such fine tuning of the system of road user charges is impractical with current technology…..’ (1988, pp 298). We argue here that advances in technology over the last two decades have now made the implementation of such a system a real possibility.

4 HGV Pavement Damage Road User Charging System

4.1 Concept of the System
The concept behind the road user charging system for HGVs being developed by the Transport Operations Research Group at Newcastle University (TORG) evolves from the way HGVs cause road pavement damage as they travel around the road network. Figure 2 presents an overview of the Newcastle system.

Figure 2 Overview of pavement damage road user charging system

As mentioned earlier, the extent of relative pavement damage that an HGV causes is affected by a number of vehicle and pavement variables. In the Newcastle system, dynamic wheel forces generated by a moving HGV on the road pavement are recorded frequently (in this case, every 10 seconds). Since the extent of pavement damage on different pavement types in the network differs, there is also the need to identify these different pavement types (and their characteristics) that the vehicle has traversed. To achieve this, the vehicle’s position is also recorded regularly (i.e. again every 10 seconds). Other data which are necessary, include the vehicle’s speed, direction of travel, date and time. Together with the specific properties and
characteristics of each individual vehicle (e.g. axle and tyre type and configuration) all the data being gathered is stored on a data storage device on-board the vehicle and communicated to a Central Computer System for processing. The Central Computer System holds the data recorded on-board each vehicle, digital road maps and a road pavement database. A map-matching algorithm is used to identify the pavement properties of the road links used by the HGV during its journey. Then using a pavement damage estimation model, the vehicle and road pavement data are used to estimate the relative pavement damage that a particular vehicle has caused during a given period.

4.2 Description of the System

The charging system comprises on-board equipment and a central computer system. The on-board equipment shown in Figure 3 comprises:

- an on-board unit with an integrated GPS receiver, GSM unit and data storage memory; and
- an axle weighing system, consisting of sensors installed on each axle of the HGV.

Figure 3 On-board equipment

The central computer system holds:

- Ordnance Survey Centre Alignment of Road (OSCAR) digital road maps;
- the UK Highway Agency Pavement Management System (HAPMS) database; and
- a pavement damage model.

During a journey, the on-board system records at regular (10 second) intervals vehicle coordinates obtained from the GPS receiver, the dynamic axle loads measured by the axle weight sensors and vehicle speed. These data are stored on the on-board unit which can provide approximately 33 hours of data storage. The central computer system uploads the data from the on-board unit daily via GSM for processing.
Data processing involves the following steps;

**STEP 1: Identifying Vehicle Routes**
Vehicle position coordinates are plotted on the OSCAR digital road maps using ESRI ArcGIS software (see Figure 4). A map-matching tool uses the vehicle positions plotted on the digital road map to identify automatically the road links an HGV has used during its journey.

![Figure 4 Vehicle positions plotted on the digital road map](image_url)

**STEP 2: Establishing Road Link Properties from Pavement Database**
The next step involves determining the pavement properties of the selected road links from a road pavement database. In the UK, the Highways Agency is responsible for the country’s trunk road network and maintains a national database, updated annually, of the current condition of road surfaces and pavements. The HAPMS database contains the following pavement information for 10 and 100 metre sections of each carriageway:

- carriageway texture;
- rut depth across carriageway;
- ride quality (surface unevenness);
- carriageway cracking; and
- construction details (layer thickness and material).

Road pavement data for sections of a number of trunk roads in the northeast of England were obtained with kind permission from the Highways Agency for the development and testing of the charging system. The pavement properties used from the HAPMS are the pavement type, thickness and roughness. These properties are retrieved for the road links identified in Step 1 (see Table 2).
Table 2: Pavement properties of map-matched links

<table>
<thead>
<tr>
<th>Link ID</th>
<th>Road Number</th>
<th>Chainage on Link</th>
<th>Roughness Category</th>
<th>Pavement Type</th>
<th>Layer Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>74239</td>
<td>-</td>
<td>321.7</td>
<td>Medium</td>
<td>Flexible</td>
<td>Thin</td>
</tr>
<tr>
<td>74565</td>
<td>B1326</td>
<td>118.1</td>
<td>Medium</td>
<td>Rigid</td>
<td>Thin</td>
</tr>
<tr>
<td>73179</td>
<td>A19</td>
<td>63.2</td>
<td>Smooth</td>
<td>Flexible</td>
<td>Thick</td>
</tr>
<tr>
<td>73179</td>
<td>A19</td>
<td>275.0</td>
<td>Smooth</td>
<td>Flexible</td>
<td>Thick</td>
</tr>
<tr>
<td>94432</td>
<td>A1058</td>
<td>175.6</td>
<td>Smooth</td>
<td>Rigid</td>
<td>Thick</td>
</tr>
</tbody>
</table>

STEP 3: Pavement Damage Estimation Model

Predicting the performance of road pavements subjected to vehicle loads and climatic conditions remains an area with numerous difficulties and uncertainties because of the complex interactions between vehicles, roads and the environment (Cebon, 1999). Notwithstanding, there has been considerable effort to understand and predict the performance of road pavements from vehicle - pavement interactions. These include the development of models which attempt to simulate the response of road pavements to a combination of vehicle loads, their characteristics (e.g. speed, axle and tyre configuration) and climatic conditions (e.g. temperature and seasonal effects). Cebon (1999) reviews two distinct approaches, the ‘single-vehicle pass’ calculation and the ‘whole – life model’, which have been used widely in recent studies (Cebon, 1999). Dodoo and Thorpe (2002) provide a further review of these two approaches for estimating pavement damage. With the latter method not fully validated at present, the approach adopted for this work is based on the ‘single-vehicle pass’ method as it provides a relatively simple yet effective way of comparing the damaging potential of different vehicle types operating under different conditions such as vehicle speed, axle loads and pavement properties. (Dodoo and Thorpe, 2002).

In this method, a vehicle simulation model is used to generate dynamic tyre forces by a vehicle with known axle loads travelling at a specified speed on a road with a specified road roughness. The generated tyre forces then serve as an input to a pavement model to calculate the pavement’s response to these tyre forces, in terms of stresses and strains, at regularly spaced points along the road. A road damage model combines the stresses and strains with the properties of the pavement material to calculate and accumulate the theoretical damage at each point on the road and for the whole road section. With this approach, it is possible to investigate and compare the theoretical damage caused by various combinations of vehicle types and loading, pavement type and design, speed and roughness levels.

To use this method in this research would involve setting up a matrix of input parameters comprising vehicle operations data (such as speed and axle loads) and pavement characteristics. Then, using the ‘single pass’ calculation model, damage caused by a vehicle travelling under a range of different operating conditions (representing the input parameters) is obtained for all combinations of parameters making up the matrix. This is then used to define a ‘damage tariff’ table to determine damage caused by a vehicle from a record of data collected during a number of journeys.

Table 3 shows an example of the pavement damage matrix. The shaded portions of the table show a vehicle with an axle weight of say 5 tonnes, travelling at an average...
speed of 70 km/h on an A road with a thick flexible pavement which has a medium surface roughness. This combination of parameters is used to determine the ‘damage tariff’ (of say 0.5 units per unit distance travelled) from a predefined ‘damage tariff’ table generated using the ‘single pass’ model. The value of the ‘damage tariff’ remains the same as long as there are no changes in the categories for the vehicle or pavement parameters. However, if there is any change in one of these parameters which results in a change in category for the parameter (e.g. the pavement changes from a flexible to rigid pavement type), then a new value of ‘damage tariff’ results. Pavement damage is calculated by multiplying the ‘damage tariff’ which represents the pavement damage caused by the HGV per unit distance travelled with the total distance travelled at that tariff value.

Table 3 Example of parameter matrix for pavement damage estimation

<table>
<thead>
<tr>
<th>Axle Load (tonnes)</th>
<th>Vehicle Speed (km/h)</th>
<th>Road Class</th>
<th>Pavement Type</th>
<th>Pavement Thickness</th>
<th>Surface Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2</td>
<td>0 - 20</td>
<td>Motorway</td>
<td>Flexible</td>
<td>Thin</td>
<td>Smooth</td>
</tr>
<tr>
<td>2 – 4</td>
<td>20 - 60</td>
<td>A road</td>
<td>Flexible</td>
<td>Thick</td>
<td>Medium</td>
</tr>
<tr>
<td>6 – 8</td>
<td>60 - 100</td>
<td>B road</td>
<td>Rigid</td>
<td>Thick</td>
<td>Rough</td>
</tr>
<tr>
<td>8 – 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Since the summer of 2004, a 2-axled HGV has been equipped with the prototype charging system for demonstration purposes. The HGV is based in Newcastle but operates between Huddersfield (200 km south of Newcastle) and Greenock in Scotland (290 km north of Newcastle). The system has performed without malfunctioning and has been recording data related to the vehicle’s activities. Figure 5 presents a sample of axle loads recorded for the front axle of the HGV for part of a particular journey. The figure shows the HGV initially at rest with a constant front axle weight. During motion at relatively constant speed, the axle load varies as expected about the mean axle load. High axle loads are generated especially during vehicle accelerations and decelerations. These high axle loads are generated due to a combination of an increase in axle forces and torsional forces which develop in the axle as the vehicle accelerated and decelerates. These high axle loads can result in increased pavement damage. Further studies are being undertaken to factor out from the dynamic axle load measurement the torsional effects which develop in the axle.
Figure 5 Sample of axle loads recorded for the front axle of the HGV

5 Potential Impacts and Benefits of Scheme Implementation

The potential benefits of the widespread implementation of a pavement damage-based HGV charging system as described in this paper include:

- an improved system for the recovery of pavement damage costs from individual HGVs which encompasses more fully the EU’s policy of fair and efficient pricing;
- improved information on where and how much pavement damage is occurring around the network to inform maintenance activities and targeting of resources;
- improving loading practices such as reduced axle and vehicle over-loading; and
- a more pavement-friendly fleet of HGVs (e.g. more widespread use of air suspensions, an increase in the number of axles per vehicle).

6 Conclusions

The maintenance of road infrastructure for the transport of goods and services requires substantial investment that is generally generated from user charges and taxes. This paper has presented arguments that current systems for charging HGVs for road damage costs need to be improved further to link more closely individual HGVs pavement costs and their respective charges. The paper has proposed a new pavement damage road user charging system that is able to charge HGVs more fairly and efficiently by linking individual HGV pavement damage cost to charges. Potential benefits of the implementation of such a scheme have also been discussed. It is hoped that current efforts by various countries to improve their HGV charging system will
serve as a stepping-stone towards the realisation of more fair and efficient charging systems in the future.

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8 References


