

ROAD USER CHARGING FOR HEAVY GOODS VEHICLES

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ABSTRACT

The aim of this project is to develop, field-trial and evaluate a dynamic road user charging system for Heavy Goods Vehicles (HGVs). The need for fairer and more efficient means of pricing road use through the "polluter pays" principle has prompted many governments throughout Europe and other parts of the world to investigate alternative pricing strategies for urban and inter-urban road networks. Of particular concern is the road freight sector, as HGVs cause a disproportionately high level of road pavement wear per vehicle-kilometre compared to other vehicle classes, and fixed annual taxation payment systems are highly inefficient at capturing the external costs of pavement wear which can vary by pavement type, dynamic axle load, HGV class and axle configuration. In order to align better the actual costs of pavement wear and charges for road use more accurately, various distance and weight-based charging approaches have been implemented recently. For example, in Europe and the USA, Weigh-In-Motion (WIM) systems have been installed on certain roads and bridges to assist infrastructure cost recovery (for example the HELP Programme in the USA). In Sweden and Norway, HGVs pay a distance and HGV-class based charge, Australia and New Zealand operate an axle-weight-based distance charge, and in Switzerland, the recently introduced Heavy Vehicle Fee charges HGVs on the basis of actual distance travelled and gross permissible axle weights.

However, the main drawbacks with extending these systems into a pan-European system for charging for actual pavement wear at the point-of-use include the likely roadside infrastructure costs and serious concerns about using measured static axle loads (as opposed to dynamic axle loads) to estimate actual pavement wear. In addition, it is argued here that these systems are not able to satisfactorily align pavement wear costs to road user charges. Therefore this paper concludes with a functional specification of an on-board charging system which seeks to overcome these drawbacks by extending state-of-the-art technologies for variable road-user charging, automatic vehicle locationing and dynamic axle-load measurement to enable HGVs to be charged a price which includes the dynamic effect of loading on structural pavement wear. It is envisaged that the evaluation of the prototype system will lead to recommendations for new approaches to allocating road track costs more efficiently and fairly between individual road-users.

INTRODUCTION

Roads and road transport have undoubtedly played and continue to play a tremendous role in the continued development of human civilisation. The importance of road infrastructure in the economy can be seen from the fact that road freight, which is carried mainly by HGVs (> 3.5 tonnes unladen weight), accounts for about 81% of all freight transport in the UK and other European Union countries (FTA, 1999).

The cost of maintaining and improving this vital infrastructure, which amounts to about 0.2 to 2 percent of a country's Gross Domestic Product, (OECD, 1998), has generally been met through various forms of road and vehicle charges and taxes (e.g. fuel taxes and vehicle excise duty). Throughout the world, various approaches are in use to facilitate the collection and administration of these taxes and charges. However, the underlying philosophy behind them is that 'each road user should pay the highway costs that is creates or occasions' (HCAS, 1997). This approach, known as the Cost Occasioned approach, is used widely all over the world and is in recognition of the fact that various vehicle classes differ in the extent of road wear they cause. However, until the 1960s, there was no way of incorporating this in either pavement design or in cost allocation procedures.

One of the most significant results of the extensive full-scale road tests conducted by the American Association of State Highway and Transport Officials (AASHTO) between 1958 and 1960 was the establishment of a quantitative relationship explaining the extent to which different vehicles cause road wear. It established that 'the decrease in pavement serviceability caused by heavy vehicles could be related to the fourth power of its static load' and is known as the Fourth Power Law (Cebon 1993, p. 9). This 'Holy Grail' has been used by engineers since then to assess the damaging potential of vehicles on pavements and also for allocating road user charges between HGVs.

Over the years, continued research (see for example AASHO Road Test, 1958-1960; OECD, 1992, 1998) has been carried out to investigate and provide scientific evidence of pavement-vehicle interactions and how the characteristics of vehicles and road pavements affect road wear (OECD, 1998). These studies have shown that the major factors which affect pavement wear include the characteristics of the vehicle (in terms of its axle and tyre configuration, suspension system and vehicle speed), the dynamic wheel forces generated by the vehicle and pavement characteristics (type, surface roughness and temperature).

A review of road and highway cost allocation procedures and other charging systems implemented throughout the world reveals that these systems are not able to adequately satisfy the requirements of the cost occasion approach - to charge a user the highway cost he creates - as is being sought. This is evident in the considerable efforts being made by various governments striving to constantly improve existing methodologies (for example the Federal Highway Cost Allocation Studies in the USA) and the introduction of new charging systems by others (for example the Heavy Vehicle Fee in Switzerland). This is because the fundamental factors causing pavement wear are not satisfactorily and adequately employed in the cost allocation and charging methodologies. In addition, temporal and spatial variations in pavement wear associated with vehicle use are not sufficiently catered for. As a result, these systems lack fairness and efficiency in the resulting vehicle class-based charges. These issues were part of the subject matter in the European Commission's Green Paper published in 1995, 'Towards Fairness and Efficient Pricing in Transport', which noted that, because of the apparent lack of fairness and efficiency in transport pricing, it recommended, as a matter of urgency, the introduction of Electronic Kilometre charges based on infrastructure damage and possibly other parameters (European Commission, 1995).

With a view to the introduction of such a scheme, some time in the future, this research project aims to develop, test and evaluate a dynamic road user charging system for HGVs based on pavement wear. To achieve this aim, the following objectives have been set (Thorpe, 1998):

- § to undertake a critical review of current procedures for allocating road track costs between different HGV groups;
- § to design and develop an in-vehicle automatic debiting system for charging HGVs in relation to expected structural pavement wear and other external costs of road-use by HGVs;
- § to test the automatic debiting system through off-road and on-road experiments with suitably-equipped HGVs;
- § to evaluate the system's ability to accommodate varying road-use charges, both spatially and temporally and by HGV type; and
- § to assess the likely impacts of a 'pay-as-you-go' system for charging HGVs on the freight distribution sector.

The purpose of this paper is to describe the design of the functional specification for a dynamic road user charging system for HGVs. Conclusions arrived at from this initial work show that this new dynamic charging system for HGVs will indeed be capable of addressing many of the more critical issues of concern associated with current charging systems by charging HGVs for pavement wear as and when it is caused. The various functional components and technologies necessary for developing the system have also been identified and a functional model of the charging system is presented.

The next section of this paper presents a review of the interaction of HGVs with road pavements and points out the major parameters which determine the extent of pavement wear. This is followed in the subsequent section by describing methods currently employed to recover pavement wear costs from HGVs and identifying the need for new improvements with these methods. The final section then describes preliminary work on the design of a system for charging HGVs based on pavement wear.

VEHICLE - PAVEMENT INTERACTION: A REVIEW

Modern road pavements can be classified as being flexible of bituminous construction, rigid from Portland cement concrete or composite consisting of both flexible and rigid components. In most countries world-wide flexible pavement construction generally dominates. During its service life, road pavements are subjected to a variety of external conditions (e.g. traffic loading and environmental conditions), which leads to a decrease in pavement performance. These external conditions cause the pavement to suffer a variety of distress types, which can be classified as functional or structural and load or non-load associated. Whereas functional pavement wear is primarily non-load associated and is concerned with the 'ride quality' of the pavement from the viewpoint of the road user, structural pavement wear is mainly load associated and describes both visible and / or non-visible defects on the road pavement such as fatigue cracking or pumping (Huang, 1993). A significant development from the Fourth Power Law was the concept of the Equivalent Standard Axle Load (ESAL) which provides a way of comparing the relative damaging potential of different vehicle classes on the road network (Cebon, 1993). Using this concept, it can be estimated that one pass of a single 11.5 tonne axle of a heavy goods vehicle is equivalent to about 276,000 passes of a 0.5 tonne axle of a car. Thus, in comparison to HGVs, cars cause relatively insignificant load associated road wear and as a result, all load associated road wear is usually attributed to HGVs.

Even though the Fourth Power Law has been used extensively in both pavement design and cost allocation methodologies, it has received much criticism (see for example Addis and Whitmarsh, 1981) regarding its validity

in light of differences in tyre sizes and pressures, pavement construction materials and methods, traffic volumes and wheel loads and axle load group configurations which are all significantly different now from the time of the AASHO road tests (Cebon, 1993). Research shows that the exponent in the Fourth Power Law varies widely, with different exponents for the different pavement types. For flexible pavements, values ranging from 1.3 - 6 have been cited while for composite and rigid pavements, it may be as high as 8 - 12 (Cebon, 1993). This variation is important as the value of the exponent in the Fourth Power Law has implications for the allocation of road track costs. A lower exponent (say 1 or 2) would mean that the current practice of attributing all load-associated damage to HGVs is questionable. Alternatively, a higher exponent implies more damage by HGVs. However, the lack of any widely accepted alternative means that the Fourth Power Law is still used by engineers and researchers in studies of pavement design and damage and also to allocate road track costs between different vehicles.

Pavement wear is affected by a variety of static vehicle load characteristics. Research by Gillespie *et al.* (1992) shows that whereas static wheel forces are the main cause of fatigue damage to pavements, gross vehicle weight is the dominant factor in rutting damage. Axle configuration also affects pavement wear with tandem and triaxle groups carrying more weight than the same number of widely spaced single axles for equal pavement wear to flexible and rigid pavements (Peattie, 1984; Cebon 1993). The effect of tyre pressures and configuration on pavement wear has also been studied. For example, Christison *et al.* (1978) report that, in theory at least, single tyres cause about seven to ten times more damage than a dual tyre pair while a report by the OECD (1992) recommends that wide-base single tyres should be considered to be 2.1 times more damaging and conventional single tyres to be 2.9 times more damaging compared to dual tyres. Cebon (1993) reports similar results that have been reported by Treybig (1983), Huhtala (1988) and Gillespie *et al.* (1992).

The magnitude of static wheel forces has been thought to be the main cause of pavement wear and the use of the Fourth Power Law was considered appropriate for cost allocation. However, because of the surface nature of road pavements, construction methods, materials and vehicle dynamics, forces which are applied to the road pavement are not uniform or of a constant value but fluctuate above and below a constant static force. These fluctuations are referred to as *dynamic forces* or *loads*. These forces are generated by two distinct components of vehicles – the sprung mass of the vehicle, which generates low frequency dynamic wheel forces (1.5 - 4Hz), and the unsprung mass, which generates dynamic wheel forces in a higher frequency range (8 - 15 Hz). The forces are generated in the low frequency range from the body bounce or pitch motions of the vehicle while the high frequency forces are associated with wheel hop vibrations. For most vehicles, dynamic wheel forces are generated from the sprung mass motion in the low frequency range (i.e. 1.5 - 4Hz). However, vehicles with poorly damped suspensions also generate large amounts of unsprung mass vibration (Cebon, 1999).

Dynamic wheel forces are thought to cause considerably more pavement wear than static wheel forces and, in recent years, research has focused on understanding the full effects of these forces on pavement wear (OECD, 1992). The effects of dynamic wheel forces during vehicle and pavement interactions have been studied by instrumenting either the vehicles themselves or the road pavement (see for example Mitchell and Gyenes, 1987; Cole and Cebon, 1989), or through computer simulations (Captain *et al.*, 1979; Hu, 1988; Cole and Cebon, 1992) to measure or simulate stresses and strains which develop within the pavement structure. These stresses and strains are the primary pavement responses when road pavements are loaded with vehicle wheel forces. The magnitude of dynamic wheel forces is influenced by a number of vehicle and pavement characteristics, the most important of these being the roughness of the road surface, the speed of the vehicle, the axle and tyre configuration, vehicle geometry and mass distribution and the properties of the vehicle suspension. It can be represented by a parameter known as the *Dynamic Load Coefficient* which is defined as the ratio of the root mean square dynamic wheel force to the mean wheel force where the root mean square dynamic wheel force is essentially the standard deviation of the probability distribution. In general the magnitude of dynamic wheel forces increases with vehicle speed and pavement surface roughness with typical root mean square amplitudes of approximately 10 - 30% of static wheel loads.

Research has shown that differences in pavement types and characteristics lead to differences in how pavements respond to the effects of dynamic loading. The OECD DIVINE Project (1998, p.66) concluded that, for thicker bituminous pavement structures (i.e. >150mm), 'there was a direct and proportional relationship between primary pavement responses and the instantaneously applied load' implying that strain levels which lead to pavement wear reflect the degree of dynamic loading. For thinner pavements however, the relationship was less clear. Dynamic wheel loads also cause a relative increase in pavement wear due to fatigue damage while on the other hand, there was a decrease in pavement wear due to rutting damage.

The net effect of dynamic wheel forces on road pavements compared to static wheel loads is a further reduction in the pavement life due to increased levels of stresses and strains. Cebon (1993, p.66) states that 'depending on the method of analysis, assumptions, and mode of failure, dynamic wheel loads increase *average* theoretical road damage by 10 - 40%, and *peak* theoretical damage by a factor of 2 to 4 (over damage due to static loads) for typical vehicles and operating conditions.' However, the presence of spatial repeatability (which is the phenomenon where by under mixed traffic conditions, dynamic loads typically tend to concentrate at points along a road at intervals of 8 - 10 metres) means that peak pavement damage rather than average pavement damage is the critical consideration for pavement wear. In this case (i.e. with spatial repeatability), the relative increase in peak

damage by dynamic wheel forces can range from 2 - 14 times more depending on the suspension type of the vehicle.

Dynamic wheel forces, and in particular the presence of spatial repeatability on road pavements, lead to a relative increase in road pavement damage. Road pavements also wear at different rates depending on factors such as the type and thickness of the pavement, the nature of the surface roughness and the characteristics and speed of passing vehicles.

Clearly therefore, there are a number of truck, pavement and environmental factors which contribute to pavement damage. The nature and extent of these various contributions was investigated by Gillespie *et al.* (1993). Their findings suggest that the different factors affect pavement damage in different ways and to different extents. Interaction between some of the factors also impact on their relative contribution to pavement damage. For example, whereas static axle loads are the primary cause of fatigue damage, gross vehicle weight has a direct influence on rutting with individual axle loads being less significant. The relative importance of these various parameters can be appreciated by looking at the extent of variability in the range of damage ratios of the different parameters in Gillespie's research. Based on this criterion, the most important of these factors are listed below (in no particular order):

- § axle loads;
- § gross vehicle weight;
- § tyre type;
- § pavement roughness;
- § slab / wear course thickness;
- § surface temperature (flexible) / temperature gradient (rigid); and
- § wheel path location.

This knowledge of how vehicles and pavements interact can help improve not only the design and maintenance of road pavements and vehicles but also form the basis of providing a more equitable, efficient and transparent way of charging vehicles for their use of road space.

ROAD TRACK COST ALLOCATION AND HGV CHARGING SYSTEMS

Road Track Cost Allocation Models

The recovery of 'sunk' road transport infrastructure cost has traditionally been informed by Highway Cost Allocation (HCA) models. HCA is the assignment of highway-related costs to various classes of highway users (and sometimes non-users), usually to estimate the share of highway costs that various users pay and to evaluate the equity of highway user fees (USDOT, 1997). A number of approaches to highway cost allocation exist and are summarised below (see US Highway Cost Allocation Study 1997 for details). These are:

- § the *Benefit Based Approach*, which allocates costs according to the relative benefits realised by different vehicle classes from highway investments. The greater the benefits, the greater the share of user fees a vehicle class should pay, regardless of its contribution to highway costs;
- § the *Cost Occasioned Approach* where the physical and operational characteristics of each vehicle class are related to expenditures for pavement, bridge, and other infrastructure improvements; and
- § the *Marginal Cost Approach* which charges vehicles according to environmental, congestion, pavement, and other marginal costs associated with their highway use. Unlike other approaches, the objective of the marginal cost approach is not to assign all highway agency expenditures to different vehicle classes, but rather to estimate user fees that cover the marginal costs of highway use by different vehicle classes.

Of these three approaches to highway cost allocation, the Cost Occasioned Approach has been the most widely used (see for example the UK Road Track Cost Allocation Model). The underlying philosophy of this approach is that each user should pay the highway costs that it creates or "occasions". Traditionally, these costs have been limited to the obligations and expenditures of the various highway agencies responsible for the improvement and maintenance of the road infrastructure. The focus has thus been on the highway cost paid from highway user charges and how close these user charges reflect the true cost of each vehicle's use of the highway. Different user charge mechanisms and structures are then evaluated to ensure equity in the user charge structure.

An example of a road track cost allocation model is the UK Road Track Cost Allocation Model (RTCAM) which was, until recently, used to estimate and allocate costs to different classes of road users based on the cost occasioned approach (UK Department of Transport, 1994). Other models used in different countries, such as the Highway Cost Allocation (HCA) Model used in the USA (HCAS, 1997) and the 'PAYGO' system in Australia (National Road Transport Commission, 1998), are also based on the cost occasioned approach with a similar methodology to the UK RTCAM. However, unlike the UK model, the US HCA model allocates costs separately for new and/or added lanes and for maintenance. For new pavement construction, costs for a hypothetical 'base facility' that would serve the purposes of all vehicle classes are shared evenly after which costs for additional requirements such as thicker pavement structures relating to HGVs are allocated to the vehicle class responsible for such costs.

A number of important issues of concern regarding HGVs regarding these systems are the continued use of static loading as against dynamic loading in cost allocation procedures, the inability of these systems to distinguish and align costs to temporal and spatial variations and ensuring equity in user charges to all vehicle classes. These limitations, some of which are inherent in the adopted methodologies, arise because of the lack of resources required to obtain all the necessary data and ensure a minimum level of data quality (Urquart and Rhodes, 1990). The result is that there is generally a mismatch between pavement costs and the prices paid, which varies both within and across different vehicle classes.

Heavy Goods Vehicles Charging Systems

The need for fairer and more efficient ways of charging (especially HGVs) for road use has led to the introduction of charging systems aimed at addressing the issue of aligning pavement costs with prices paid in a more equitable and efficient way. For example, the New Zealand Heavy Vehicle Fee (HVF) introduced in 1977 and still in use today, attempts this by allocating heavy vehicle charges based on the number and spacing of axles, the number of tyres per axle and the actual distance travelled as monitored by a Hubodometer - the rationale being that these additional vehicle parameters are known to affect the extent of pavement wear caused by HGVs and therefore offer more differentiation in vehicle charges (Galenson, 1990).

The Heavy Vehicle Electronic License Plate (HELP) Programme introduced in the early 1990s in the USA is a multi-state heavy vehicle monitoring and charging system using Automatic Vehicle Identification (AVI), Automatic Vehicle Classification (AVC) and Weigh-in-Motion (WIM) technologies. Vehicles equipped with transponders pass key data (such as distance travelled and registration details) to roadside infrastructure, while vehicle loads are measured at normal driving speeds by fixed WIM stations on the highway. Charges are then calculated based on a range of vehicle characteristics, distances travelled and measured vehicle loads. Although a welcome step in the right direction, such a system is unable to evaluate key pavement wear factors such as dynamic wheel forces and differences in pavement types and roughness and could involve considerable capital investments if implemented on (say) a European scale.

The Swiss Heavy Vehicle Fee introduced in 2001 is an electronic charging system for charging HGVs on the country's road network (Liechti *et al.*, 2000). The system consists of On-Board Units (OBUs) and roadside infrastructure for charging and enforcement purposes. The OBU consists of a distance recording device which is complemented with a satellite positioning system (GPS), a tachograph, a movement sensor, a chip card interface and a microwave communications link interface - Dedicated Short Range Communication (DSRC). The roadside infrastructure consists of radio beacons installed along the carriageways at national borders, roadside video/license plate recognition cameras and scanners. Charging is performed by the OBU based on fixed parameters (emission values of vehicles and the maximum laden weight of the tractor and trailer) and on a variable parameter (kilometres driven). Clearly, with this system, an unloaded vehicle is charged the same as a fully laden vehicle per unit distance although in reality, the extent of pavement wear caused is different not only because of differences in weight but also in pavement type and surface characteristics.

A similar electronic charging scheme has been announced for implementation in Germany (Williamson, 2000), while other EU countries also have plans to introduce electronic schemes. Clearly, a considerable amount of effort is being made to improve cost allocation procedures and HGVs charging mechanisms by constantly improving on the data used and introducing more parameters. However, the fundamental issues of concern regarding pavement wear such as dynamic wheel forces and pavement surface roughness remain unresolved.

FUNCTIONAL DESIGN OF A NEW DYNAMIC CHARGING SYSTEM

System Objective

The design of the new road user charging system for HGVs based on actual pavement wear proposed here is based on the principle that such a system should be able to charge individual vehicles for the actual costs of pavement wear caused. In order to do this there is the need to identify, measure and record the necessary factors that contribute to pavement wear. The major factors are;

- § pavement type and thickness;
- § pavement surface roughness;
- § dynamic wheel forces;
- § axle and tyre configuration;
- § vehicle speed; and
- § environmental factors (temperature)

In the UK, flexible pavements make up 85% of all road pavements, with 10% being rigid and 5% of composite construction (DETR, 2000). Depending on ground conditions and other environmental factors, pavement thickness varies between 300mm for 'thin' pavements to 1200mm for 'thick' pavements. Pavement surface roughness also varies depending on the traffic and environmental conditions. These pavement and environmental factors, coupled with vehicle factors such as the axle and tyre configuration, vehicle speed and suspension type, cause differences in the dynamic wheel forces generated as the vehicle travels along the carriageway.

Ideally, during each individual journey, vehicle speeds and dynamic wheel forces are monitored continuously and recorded, and the different pavement types and surface characteristics of these roads travelled on noted. These data, together with details of axle and tyre configuration, are used to determine the appropriate road use charge based on an estimate of actual pavement wear caused.

One argument against such an approach has been that it might discourage road authorities from maintaining the road network to a satisfactory standard. Although possible, this is considered unlikely because of the political and socio-economic importance of roads in modern societies. Highway maintenance is also formulated within the framework of legislation (including the important issues of health and safety) and national specifications, Codes of Practice, European Standards, Road Notes and Quality Assurance Schemes. In the UK for example, legislation is embodied in the Local Authority Association's Highway Maintenance Code of Good Practice (LGACP).

Functional System Components

The following functional components are identified for a possible dynamic road user charging system for HGVs:

1. an Automatic Vehicle Positioning (AVP) system to provide vehicle route information;
2. a digital road map database, which combines with the positioning system to provide vehicle location on the road network as well as characteristics of the pavements travelled on;
3. a Dynamic Wheel Force (DWF) measuring device capable of measuring continuously dynamic wheel forces as the vehicle moves;
4. a distance measuring device;
5. a road use charging model to estimate pavement wear;
6. an on-board computer for processing and storing data;
7. a data retrieval system;
8. a man-machine interface device to provide system information to the driver; and
9. a device for communicating with the roadside for enforcement and transmission purposes.

Modelling Pavement Damage

One of the key components of the charging system is the charging model. This is responsible for converting a range of vehicle characteristics (e.g. axle/tyre configuration and loads, vehicle speed and position) and pavement properties (e.g. pavement type, surface roughness) recorded on the vehicle during its journey for estimating pavement wear. Extensive research into the mechanisms of pavement wear has led to a considerable understanding in this area. Of particular interest are road damage models, which relate road damage at specific points along the road surface by aggregating the dynamic tyre forces applied by the vehicle. Two methods based on this approach to estimating pavement damage are the 'single-vehicle pass' calculations and 'whole-life models'. A summary of these two approaches is provided below. A more detailed review is provided by Cebon (1999).

The Single Vehicle Pass Calculation determines the incremental road damage due to the passage of a vehicle over a particular road. It is very useful for comparing the effects of vehicle features on road damage. The procedure for the single vehicle pass calculation involves measuring the dynamic tyre forces generated by a vehicle travelling over a specific road profile. The forces generated are used as inputs to a pavement model (flexible or rigid) where primary pavement responses (stresses, strains and displacements) are calculated at points along the road. Equations for estimating material damage (fatigue and permanent deformation) are then used with damage accumulation calculations to determine the theoretical road damage at each location.

Whole-Life Models are similar in methodology to the single vehicle pass calculation model but also attempt to predict the deterioration of a pavement's structural integrity and surface profile over time. The calculation attempts to include the effects of environmental/seasonal factors on the strength of the road and variations in the structure and properties of the road. However, these models require an empirical relationship between wheel forces and the degradation of the road surface profile. According to Cebon (1999), this is still an area of much uncertainty and at present no such relationship exist. He points out however that whole-life models could offer the best prospects for understanding the complex interactions that occur in the vehicle-road-environment system.

The single-vehicle pass calculation provides a relatively simple and effective way of comparing the damaging potential of different vehicle types operating under different conditions such as vehicle speed, axle loads and pavement properties. Implicit in this system however is the assumption that pavement characteristics remain constant and hence, under the same operating conditions, pavement wear caused by vehicles in the same category remains unchanged. In reality, this is not so as the degradation of the pavement surface would generally lead to increased pavement wear by subsequent vehicles. In this respect, the whole-life model provides a more realistic approach to pavement damage modelling because of the presence of a feedback loop which updates the condition of the pavement after each vehicle pass. However, as has been mentioned, the whole-life model has yet to be fully validated. Consideration is therefore being given to the choice of model to be adopted since this has implications for the development of the charging system being proposed.

System Architecture

Two candidate system architectures have been identified for the proposed dynamic heavy goods vehicle charging system. The first separates the charging system into two main subsystems; an on-board processing sub-system and an post-processing subsystem (Figure 1). Within this system architecture, the on-board system acts as a data collector - recording dynamic wheel forces and position data and vehicle speeds as the vehicle undertakes its journey. The data collected is then communicated to the post-processing subsystem where it is processed to determine information such as the roads travelled on and the properties of the road pavement (e.g. pavement type and surface roughness). These data are then used in the charging model to enable the appropriate road use charge to be calculated. Bills could then be issued to vehicle operators on a monthly or annual basis.

An alternative system architecture involves combining the two subsystems described above into one on-board, real-time processing system (Figure 2). With this system architecture, each equipped vehicle has all the necessary functional components to estimate autonomously road use charges in real-time. The choice of which system architecture to adopt depends on an evaluation of both systems based on the overall system objectives. The interactions and data flow between the various components of the charging system architecture is shown in Figure 3. Charges may then be collected in real-time, possibly via a smartcard payment system.

Technologies for Functional Components of Charging System

Various technologies exist for each of the functional system components identified in the real-time system architecture depending on factors such as accuracy, cost and the requirements of the dynamic charging system (Drane *et al.*, 1998; Zhao, 1997). For example, the need for the vehicle to be located on the road network in real time requires a sufficiently reliable and accurate positioning system (say less than 10m positional accuracy). It also requires an on-board database for mapping purposes. The dynamic wheel forces of all the axles should also be measured and recorded continuously throughout the vehicle journey. In addition, the amount of data to be stored requires a robust and sufficient capacity data storage device.

For the purposes of this research project the following technologies are proposed to satisfy the functional requirements of the charging system;

- § a GPS unit to provide positioning information as well as vehicle speed, distance travelled and direction data;
- § a dead-reckoning sensor to provide backup to the GPS unit;
- § a strain gauged wheel force sensor for dynamic wheel force measurements;
- § an on-board computer to provide data processing and storage requirements;
- § a GSM interface for external communications; and
- § a man-machine interface for visual and audible signs.

The main focus of the work completed to date has been a review of the various aspects of HGV charging systems and an outline proposal for a new approach to align better road track costs and the charges incurred by vehicle-operators. Currently, alternative methodological approaches for estimating pavement wear by HGVs are under investigation. It is hoped that a decision as to the most appropriate approach can be made soon. This will enable the development of software and hardware systems to commence with a view to pilot installation and field-testing of the prototype system in early 2003.

CONCLUSIONS

In this paper, a brief review of vehicle - pavement has been carried out, summarising some of the important factors and characteristics affecting road pavement wear. An investigation of current road track allocation systems and models and HGVs charging systems reveal that in as much as the ultimate aims of these systems are to provide a fair, equitable and efficient means of charging for road use, it is argued that this has not been achieved to date. This is because the fundamental issues and factors of concern, which relates road use and pavement wear, are not addressed satisfactorily.

This paper has thus described the functional specification for a dynamic road user charging system for HGVs, which will be able to charge road users for the pavement wear. The next steps in the project involve the formulation of the charging model for estimating pavement wear caused by individual vehicles after which the software and hardware development of the charging system will commence. It is hoped that the development of this prototype system will make a considerable progress towards to a fairer, efficient and transparent means of cost allocation and road user charging.

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TABLES & FIGURES

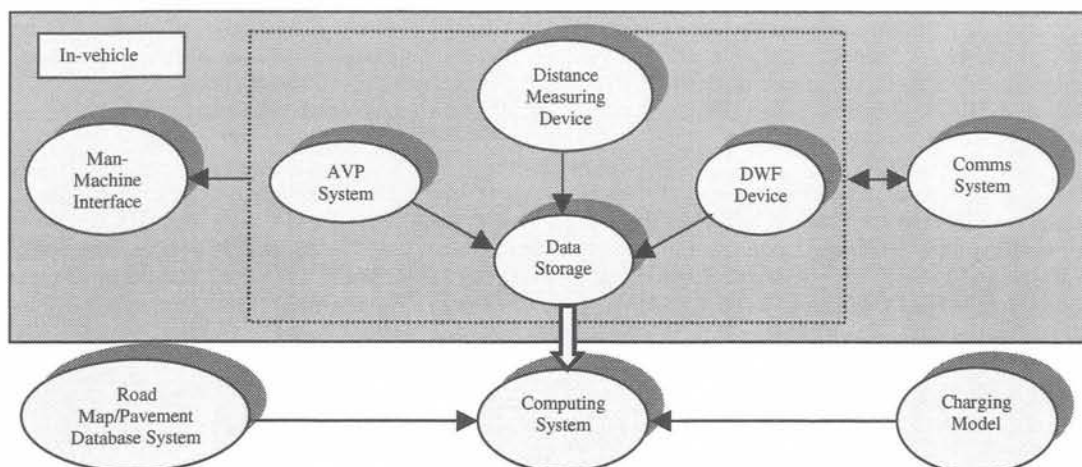


Figure 1 – Distributed Post -Processing System Architecture

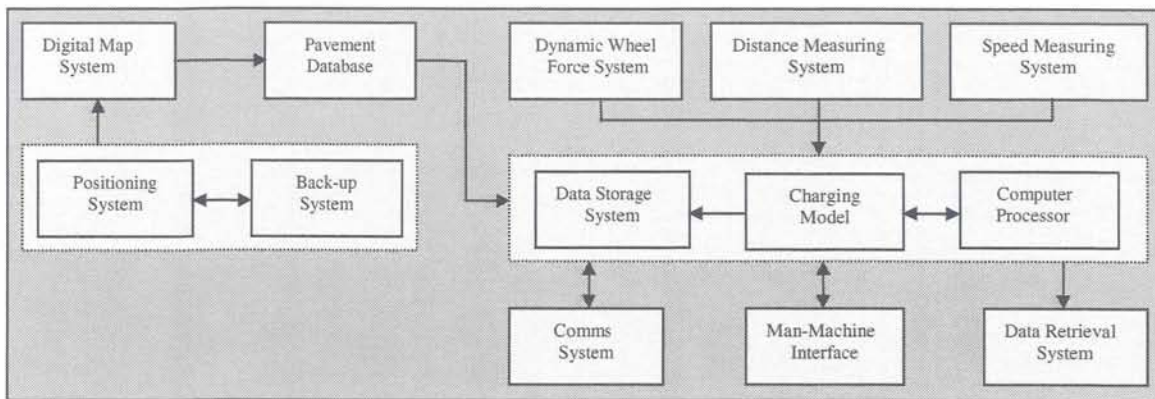


Figure 2 - Real-time System Architecture

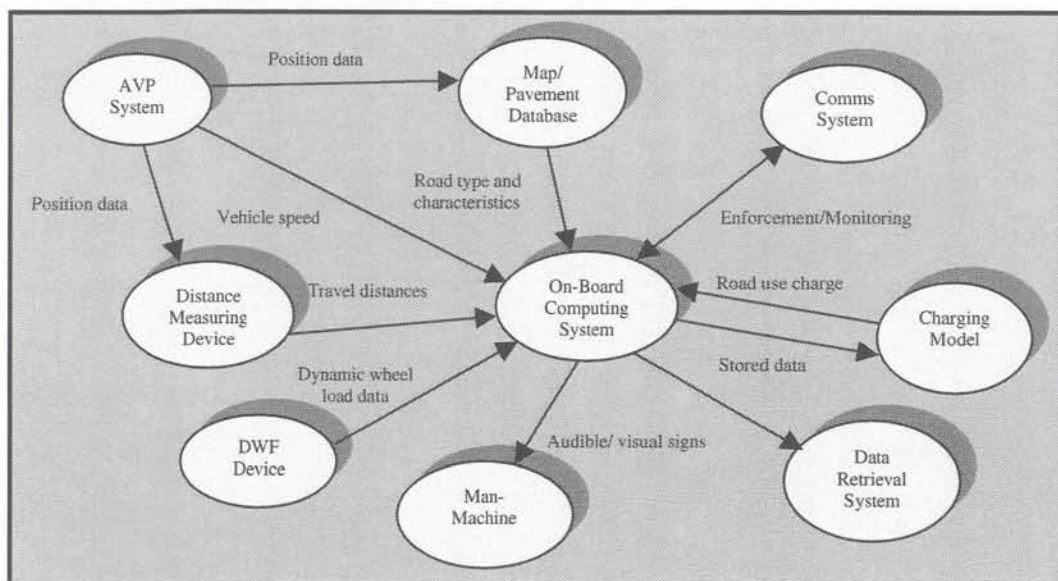


Figure 3 - Data Flow Diagram for Heavy Goods Vehicle Charging System Architecture

