TECHNOLOGIES TO MEASURE INDICATORS FOR VARIABLE ROAD USER CHARGING

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Abstract

A technically and economically feasible road user charging scheme should be based on quantities that are readily and accurately measurable, as well as being directly variable with the amount of road use and its impact on the environment and society. A key requirement for a pricing scheme is that the charging regime used should be easy for motorists to understand, but at the same time flexible enough for the operator to implement a wide range of policies to meet different aims. A set of Variable Road User Charging Indicators (VRUCI) are identified in this paper by considering both the associated costs of a trip and the operational requirements for a feasible road pricing scheme. These are: *geographic area, road class, distance, time, pollutant emissions, driving behaviour, vehicle occupancy* and *traffic density*. Each of these indicators is variable, measurable, and needs to be derived in-motion from actual driving conditions. The selection of technologies and techniques to measure these variables largely depends on the accuracies required by the charge model. However, the ability to locate and track a vehicle in space and time is fundamental to charging for true road use. The focus of this paper is to identify a set of currently feasible technologies to measure these VRUCI in real-time with high accuracies. We focus on the need to accurately track vehicle movements and link these movements to geographical areas and road types. We also focus on the key pollutants CO, CO_2, HC, NO_x and PM, all of which have different potential effects that are in some cases dependent on location and time of emission. Other issues, such as congestion measurement are also discussed.

Keywords: Road user charging, congestion charging, external costs, pollution and emissions, technology

1. Introduction

The relentless growth of motor vehicles imposes a serious challenge to the government, the people, and the environment. This is in part due to the limited capacity of existing roads. In the UK, there were 25.2 million motor vehicles in 1994, increasing to 28.9 million in 2000, and 32.3 million by 2004 (DfT, 2005). The UK is the fourth largest economy in the world and with a booming economy the government has predicted a 29% increase of GDP by 2010 compared to 2000, and a 45% increase by 2025 (DfT, 2005). Historic patterns suggest that as the economy grows the demand for personal, business, recreation, and shopping travel all increase. Therefore, a continuing growth in traffic over the next few decades is expected, and the vehicle fleet expected to increase to 40 million in 2025 (DfT, 2005).

The increase in road traffic deteriorated the quality of public life in many ways. This includes higher time cost due to traffic congestion, poor local air quality, carbon emissions that contribute to climate change, more crashes and their consequent medical costs, and greater wear and tear to the infrastructure. The government is constrained in its ability to tackle these problems. For instance, one frequently used policy to mitigate traffic congestion is to improve the overall flow of vehicles within the network by increasing the capacity of existing roads or by building new roads. However, as traffic flow improves and relative travel times decrease, additional demand is induced off-setting or eliminating any congestion reductions (Noland, 2001). Therefore, the increased capacity may reduce traffic congestion for a relatively short period but at the expense of a larger problem in the long term. Moreover, the building of new roads can damage the environment, landscapes, towns, and cities and hence the quality of life.

Varying road user charges to match the external costs associated with travel would be the most economically efficient means of mitigating the external costs associated with road transport (Ison, 2004, Glaister and Graham, 2004, Blythe, 2005, Bonsall and Kelly, 2005). There are three primary aspects of road user charging: (1) economic, (2) technological, and (3) political. Economic studies consider how efficiently a charge can be derived (see Ison, 2004, Prud'homme and Bocarejo, 2005; Graham and Glaister, 2004 for details), while technological studies examine how effectively, accurately, and reliably the charge can be collected (see Blythe, 2005). Political considerations address the user acceptance of the charging concept for a given set of economic and technological features (see Ison, 2004). Ison (2004) found that the user acceptance of road user charging depends on the technological solution deployed. As a result, these three aspects of road user charging are closely interrelated and a viable charging scheme must take into account all three dimensions of the problem.

The most commonly discussed solution is “congestion charging”, where road users are charged for the use of congested roads or areas. Congestion charging schemes are increasingly being introduced all over the world. In 2003 London became the second large city after Singapore to make drivers pay to enter the city centre. Stockholm has recently followed suit. Other schemes may target specific vehicle types, for example Switzerland, Austria, and Germany began to charge heavy duty trucks in 2001, 2004, and 2005 respectively. Many cities in the United States are implementing High-Occupancy Toll lanes, whereby users are charged to use specific lanes on a motorway, frequently with a time varying component to the charge. The main purposes of these existing charging schemes are to raise revenue, reduce congestion and provide road users with additional choices. There are no schemes that directly relate to the amount of road use, taking into account all factors[1] that one might use to determine the full economic cost of road use. This may be due in part to a shortage of cost-effective technologies and methods to measure these factors accurately and reliably, as well as with the difficulties associated with calculating the correct external cost.

Existing charging technologies include Dedicated Short Range Communication, DSRC, (e.g., ERP in Singapore), Automatic Number Plate Recognition, ANPR, (e.g., London Congestion Charging Scheme), vehicle odometer and GPS (e.g., Swiss Lorry Charging Scheme), GPS and a digital road map (e.g., German HGV Road Segment Charging), and simple transponder systems when passing an entry point (SR-91 and I-5 in California). Each of these can enable road user charging, however, technological limitations may constrain the type of charging policy that may be implemented. Consequently, the choice of a suitable technology should be made as a function of the policy objectives of the scheme. Important considerations include the accuracy and reliability of the monitoring system, methods to include occasional users in the scheme (required by European law), enforcement of the charge and other legal considerations (e.g. privacy and data protection). However, to allow the assessment of potential technologies, the road use factors that form the basis of a variable road user charge must be clearly identified.

The main objectives of this paper are to systematically derive the indicators that are relevant to a VRUC concept, to identify and evaluate some existing technologies for the measurement of these indicators and to consider a roadmap for the implementation of a VRUC system. Field data is used to support the assessment of candidate technologies. This allows a realistic consideration of the extent to which accuracy and reliability requirements may be satisfied, as these capabilities have a strong impact on the charging regime that may be implemented. The paper is organised into sections describing the

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[1] The factors may include the amount of distance travelled, the time of day, the duration of the trip, the amount of exhaust emissions from the vehicle, the type of geographical area (e.g., urban, sub-urban, rural), and the type of road (e.g., motorway or trunk roads).

development of the VRUC indicators, an assessment of potential technologies to measure these indicators followed by a more detailed discussion of the navigation and emissions monitoring functions. Finally we offer some perspectives on the development of technologies to support a comprehensive, variable road user charge.

2. Variable Road User Charging Indicators (VRUCI)

A VRUC scheme must be based on quantities that are readily and accurately measurable as well as directly variable to the characteristics and travel of a given vehicle. The factors that one may use to determine the charges for road use are referred to here as Variable Road User Charging Indicators (VRUCI). In order to derive an appropriate set of VRUCI, the costs associated with a trip made by a motorist should first be considered. When a driver decides to make a trip, he imposes additional costs on the infrastructure providers (local and central authorities), other fellow road users, and the rest of society (DfT, 2004). The associated costs of using a road can then primarily be categorised into four classes: (1) road damage costs, (2) congestion costs, (3) environmental costs, and (4) accident costs. Figure 1 shows some of the negative effects of these costs on the environment and society as a whole.

The second step to investigate potential VRUCI is to examine the operational requirements that a comprehensive road pricing scheme should satisfy. The Smeed Report (1964) considered the economic principles underlying the pricing of the roads and compiled a list of necessary operational requirements. Their list was divided into two groups; the first group contained nine requirements which they regarded as important if the method was to be workable and close to its objectives; and a further eight requirements which were also considered desirable. Table 1 shows this list with an additional three requirements based on the findings of Khan (2005), May (1992) and the IHT (1997).

By considering both the associated costs of a trip (see Figure 1) and the operational requirements for a feasible road pricing scheme (see Table 1), five types of VRUCI are identified as shown in Table 2. These are: (1) spatial factors, (2) temporal factors, (3) vehicle related factors, (4) driver characteristics, and (5) road network conditions. Each indicator has been defined as either variable or static. This is based on whether the indicator is likely to change as the trip progresses and whether measurement is required when the vehicle is in motion. While some of the indicators identified as variable could be measured in the static state, it is the in-motion variability that makes them suitable for direct charging based on the amount of road use.

In general the aim of a comprehensive road pricing scheme is that motorists should be encouraged to choose whether to drive, when to drive, and where to drive more selectively and that the costs borne by the motorists should relate directly to amount of use[2]. With this as the overarching principle, each indicator was assessed in terms of the number of operational requirements it addresses, and the extent to which it contributes in each case.

All "Variable" indicators judged to be of significant relevance were then reviewed to identify those that require "real time" measurements from either the vehicle or roadside infrastructure (see Table 2). This process identified a set of nine variable indicators (highlighted in bold) that represent the main cost elements a road user imposes on society, while being directly related to the operational requirements identified in Table 1. These indicators were then assessed to determine the type of measurement required to accurately calculate a charge.

Measurement of navigation data that includes simultaneous vehicle location and time allows the evaluation of *geographic area*, *road class, distance* and *time* (Indicators 1, 2, 3, 20 and 21). This shows that the ability to locate and track a vehicle in space and time is fundamental to charging for true road use. Charges that vary according to the current level of *traffic density* (Indicator 24) may also be considered if a suitable interface to roadside infrastructure is available. Evaluation of *pollutant emissions* (including noise)*, driving behaviour*, and *vehicle occupancy* (Indicators 9, 14 and 18) may require additional data from on-board sensors.

All these indicators are variable, measurable, and could be derived in-motion from actual driving conditions. Technologies to support each of these functions are discussed in the next section.

3. Technologies to measure the selected VRUCI

Table 3 shows the nine selected VRUCI with examples of possible indicator values for each category, and feasible technologies that may be used to measure the VRUCI in real time. More precise definition of the appropriate indicator values must be made with reference to available technologies, and the policy objectives of the charging program.

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[2] Pay As You Drive (PAYD) insurance schemes are beginning to do this, primarily through consideration of static factors such as driver and vehicle age, combined with the time of day of the journey. The car insurance company, Norwich Union UK, is currently using GPS satellite-based navigation technology and road network maps (integrated by a map matching algorithm) to track cars as part of a new PAYD insurance scheme. The in-car GPS device (acting as a black box) stores information on every car journey and each customer gets a monthly itemised insurance bill based on how much they used their car, what time of day they used it, what type of road it was driven on and how many miles they drove. The in-car device is the size of a DVD case and is fitted

This section discusses the technology options in more detail with specific reference to the development and testing of a technologically feasible navigation module and of techniques to assess tailpipe pollutant emission rates.

All indicators apart from *traffic density* can be measured using a self-contained On Board Unit (OBU) installed on each vehicle. The only data that must be periodically communicated to the regulator is the aggregated charge due from this vehicle, with more detailed examination of the vehicle activity only conducted at the owner's request (e.g. in the case of querying a charge). Such considerations may have a strong impact on the acceptability of a charging system (Ison, 2004). Nevertheless, exchange of data with a Central Data Server (CDS) may offer operational advantages in allowing more flexible charge structures to be implemented and adapted, regular update of maps, in terms of traveller information or for location-based services (LBS). However, such data exchange requires that a wireless communication system (e.g., DSRC, GSM, GPRS, WLAN, or a combination) be incorporated in the OBU to exchange data when required. Inclusion of time-varying information on actual *traffic density* levels would require some form of communication system and interface with network management data, although an approximate measurement may be made by comparing the current vehicle speed to historically expected values contained in an on-board database.

A positioning and navigation module in the OBU can quantify the derivation of all spatial, temporal, and derivative data from the vehicle including position (i.e., coordinates), time, speed and acceleration. This enables calculation of the total *distance travelled* by the vehicle, the *time of trip*, and the *duration of the trip*. Consideration of *driver behaviour* may include the need for detailed measurements of longitudinal and lateral acceleration. These may be combined with measurements of speed and with information about the local vehicle position (e.g. *road class*) to provide an appropriate assessment for different traffic situations.

If provided with an accurate position, information describing the *geographic area* and the *road class* can be obtained from a digital land-use database and a digital road network database respectively. Accuracy is linked to both the spatial resolution of the database, and the frequency of database updates. These databases can be included either within the OBU or at a CDS. Inclusion in the OBU may reduce day-to-day data transmission costs, but this may be outweighed by licence costs of the data, or by the need for regular database updates.

Second-by-second vehicle *exhaust emissions* (CO, CO_2, NO_x, HC, and PM) and other *driver behaviour* factors (such as gear changes, clutch and pedal presses, engine speed,

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with an emergency button that allows drivers to alert someone in the event of a breakdown or accident. The black box also allows Norwich Union to track and locate stolen vehicles.

vehicle speed, and acceleration) can be measured using a range of sensors installed on each vehicle and the information from the Engine Management System (EMS). A number of such devices have been developed in recent years (Frey et al., 2001, Ochieng et al., 2003) and might feasibly be incorporated into an OBU. The *vehicle occupancy* can be measured using a set of occupant sensors (able to detect the weight of any passengers) installed in each vehicle. Most vehicles equipped with an air bag system are fitted with these sensors and thus the relevant data may also be obtained via an OBU connected to the vehicle EMS. Emissions of *noise* might be evaluated by careful location of an on-board microphone, or through the use of calibrated models based on measured vehicle operating parameters.

The extent to which a given OBU can support the implementation of a VRUC scheme depends on the accuracy and reliability of its measurement of the VRUCI identified in Table 3. The performance of a potential navigation module and a range of techniques for exhaust emissions measurement are now examined in the next two sections.

4. Navigation Module Assessment

The policy objectives of a proposed VRUC scheme define the Required Navigation Performance (RNP) of the Navigation Module (NM). For instance, if one desires to know when and where a vehicle is located on a specific road link, the horizontal accuracy, the availability of the navigational information and its integrity are critical factors. For example, horizontal accuracy may be set at 5m (95%) with an availability of 99.9%.

A NM consists of three essential component groups: 1) a set of positioning sensors to determine the geometric location of the vehicle; 2) a road network database to provide the physical context of the vehicle; and 3) a map-matching algorithm to integrate the data provided by the navigation sensors with the road network database. The specification of each of these groups can have a large impact on the ability of the system to satisfy the RNP.

For a wide area (e.g. nationwide) scheme, a system that uses a Global Navigational Satellite System (GNSS) (e.g. GPS) as the core positioning sensor technology is attractive. However, standalone GPS has been observed to offer poor performance in certain contexts (e.g. urban areas or tunnels). Deduced Reckoning (DR) motion sensors such as an odometer and a gyroscope may be used with an Extended Kalman Filter to augment the GPS solution and achieve the required availability (e.g. 99.9%) in such areas (Zhao et al, 2003). This is known as an integrated navigation system (GPS/DR).

Since land vehicles primarily travel on known road networks, a digital road map is used as a spatial reference to locate them. However, digital road maps contain errors arising from the processes of creation and digitization of maps. The errors can be estimated using either the scale of the map or field experiments. The integration of GPS, DR and digital map data can be used to enhance geometric positioning capability (Ochieng et al., 2004, Quddus et al., 2006). A map matching algorithm can then be formulated to integrate the positioning data with the digital road network data (White et al., 2000, Greenfeld, 2002). However, traditional algorithms have a number of limitations, including:

- Unreliability, especially at junctions and in the vicinity of parallel roads.
- Inaccurate positioning in urban road networks.
- No method to determine the accuracy offered by the algorithms.
- No assessment of the level of confidence (integrity) of the map-matched locations.
- No sensitivity analysis to assess how the navigation sensors and the digital map quality affect the performance of map matching algorithms.
- Error sources associated with the navigation sensors and the digital maps are often ignored.

As a result, most of the existing map matching algorithms are not capable of satisfying the requirements of many road pricing systems. The fuzzy logic map matching algorithm developed recently by Quddus et al. (2006) takes into account the limitations outlined above and is also capable of providing high positioning accuracy. Field trials were conducted to assess the performance of this, and other, map matching algorithms. The results are summarised below.

A vehicle was equipped with a navigation platform consisting of a 12-channel single frequency (L1) high sensitivity GPS receiver (for C/A code-ranging), a low-cost rate gyroscope and the interfaces required to connect to the vehicle speed sensor (odometer) and the reversing light. In order to obtain the reference (truth) trajectory by GPS carrier phase observables, the vehicle was also equipped with a 24-channel dual-frequency geodetic receiver consisting of L1 and L2 with C/A code and P code-ranging. Navigation data was obtained from a series of comprehensive field tests in London between 2002 and 2005 over a range of geographic areas. The total duration of field campaigns was about 20 hrs. Figure 2 displays the routes taken.

To account for the effects of poor satellite geometry, reflected signals (multipath error) or insufficient availability of satellites a series of indicators are used to determine whether the raw GPS position or the calibrated DR position should be used (Quddus et al, 2006). These position data were then combined with digital map data from a map of scale 1:2500 to test the fuzzy logic map matching algorithm for various scenarios with different network characteristics and with different traffic manoeuvres.

The test road network can be divided into two classes: (1) a suburban road network (2040 position fixes), and (2) an urban road network (60 000 position fixes). For the suburban road network, the results suggest that the fuzzy logic-based map matching algorithm is capable of identifying 99.2% of the links correctly with a horizontal positioning accuracy of 5.5 m (95% confidence interval). For the urban road network, the algorithm can identify 98.5% of the links correctly.[3] However, the performance is sensitive to the types of positioning sensors and spatial road network data used (Quddus et al., 2005). For instance, the fuzzy logic-based map matching algorithm only identifies 93.1% of the links correctly when the positioning data come from stand-alone GPS. This is due to inherent problems associated with the satellite signal masking along the urban test route where the stand-alone GPS is unable to provide position fixes 4.5% of the time. More detailed results describing how navigation sensors and spatial road network data affect the performance of a map matching algorithm can be found in Quddus et al. (2006).

After determining the correct link and the location of the vehicle on that link, the total distance travelled by the vehicle on the road network for a particular trip can easily be calculated. The time of the trip (from a GPS receiver) and the duration of the trip can also be determined. The duration of the trip (in seconds) is equal to the number of total position fixes for a sampling rate of 1Hz. If a land-use database is integrated with the navigation module, the geographical area on which the vehicle is travelling can be identified by converting both the land-use database and the road network database into the same coordinate system.

These experiments demonstrate that an NM supported by an integrated GPS/DR, a high-scale digital map and a sophisticated map matching algorithm may allow sufficient performance to support the RNP of a VRUC system. However, the performance limitations of such a system must be explicitly considered in designing the charging scheme.

5. Measurement of Exhaust Emissions

The environmental impact of road transport is felt at both a local and a global scale. It is important to consider the mechanism of how these pollutant emissions contribute to societal costs in devising an appropriate charging scheme. Table 4 summarises the characteristics of the two major pollutant categories alongside a set of proposed metrics and performance criteria.

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[3] Due to the lack of reference positioning data in the urban road network, it was not possible to determine the performance of the algorithm in terms of positioning accuracy.

The aggregate level of CO_2 emissions are of concern (IPCC, 2007). These may be approximated by an evaluation of the amount of fuel consumed by the vehicle. The application of a “carbon tax” on fuel at the point of purchase may therefore be an appropriate means to charge for CO_2 emissions from road transport. Alternatively, an estimate of the instantaneous CO_2 emission rate may be calculated alongside the local air pollutants. Existing fuel taxes are a very effective means of currently taxing CO_2 emissions, especially in Europe, although they may not be based on the carbon content of alternative fuels (petrol versus diesel and biofuel blends).

Concern about the impact of local air pollutants is dominated by human exposure considerations. In particular many studies have demonstrated strong links between air pollution and cardiovascular and respiratory complaints (WHO, 2005). Some studies suggest that short-term, peak exposure levels are of greatest significance (e.g. Englert 2004). Costs to society are therefore strongly dependent not just on the amount of pollution, but also on *where* and *when* the pollutant is emitted.

Pollutant emission rates from motor vehicles vary greatly according to their operating mode with relatively short, high emitting “episodes” dominating the overall emission rate (Frey et al, 2001). Consequently, accurate assessment of a road-user’s environmental impact requires a method to measure or estimate the emission rate of pollutants from the vehicle at high temporal resolution, and to link these estimates to the local geographical environment at the moment of emission.

Studies using data obtained during real world field trials have revealed vehicle emissions profiles to be highly variable between different vehicles with high emissions episodes corresponding to high accelerations (e.g. Frey et al, 2001). An accurate assessment of emissions therefore depends on monitoring each vehicle individually. This may be achieved either through direct measurement of the pollutant emissions on-board the vehicle, or through the measurement of other, proxy, variables and the use of a calibrated emissions model.

The Vehicle Performance and Emissions Monitoring System (VPEMS) project explored the potential for existing sensor technologies to provide continuous, high-resolution measurements of tailpipe emission rates of CO_2, CO, NO and HC from a simple on-board unit (North et al, 2005). While accuracies to within 10% of laboratory reference values were achieved for the aggregate emission over a test cycle, the measurements were sensitive to instrument calibration and required regular servicing. System reliability was also limited. Consequently, long term (e.g. months or years) continuous operation is currently infeasible. This suggests that the use of similar direct measurement technologies for wide-scale VRUC initiatives is not appropriate.

An alternative approach is to continuously model the pollutant emission rates on the basis of measured vehicle operating conditions. This may be on the basis of the speed and acceleration measured by the NM, or by using data from the EMS if a connection is available. Models based on polynomial terms of speed and acceleration have been found to agree to measured aggregate emissions to within 15-20%, although discrepancies in the instantaneous measurements are apparent (North, 2006).

The simplicity and stability of the modelling approach is attractive, especially if sufficiently representative models may be derived from data measured by the NM. Periodic recalibration of the models would be necessary to account for changes in the emissions behaviour of the vehicle over time. This could be incorporated into an annual test which is common in many countries. However, in breaking the link between the actual emissions from the vehicle and the charging regime, it becomes possible to subvert the system (e.g. by detuning the vehicle for the emissions tests). Consequently, careful consideration of how the system may be enforced is necessary.

A third alternative is also apparent. Given the dependence of aggregate emission levels on short duration, high-emission episodes, it may be that continuous monitoring is unnecessary. A charge could be based on the frequency and duration of emissions episodes where the exhaust concentration of a particular species exceeds a limit value. This may allow the use of a simpler, but more robust measurement system. Nevertheless, the addition of an exhaust sensor system imposes a significant increase in the complexity of fitting a vehicle with an OBU, and may be vulnerable to tampering.

In all cases, it is important to carefully consider the extent to which the implementation of a monitoring and charging system can contribute to societal benefits. It may be that an imperfect, but simple solution based on a modelled emission rate, provides the best compromise between reliability and accuracy.

6. Perspectives on technologies for VRUC

The question of technologies for road user charging is inextricably bound with policy and economic considerations. The definition of a viable scheme must therefore include an iterative assessment of what is desirable from an economic perspective, what is feasible from a technology perspective and what is acceptable from a political perspective.

This paper has identified a set of nine variable indicators that can assist in the implementation of a comprehensive, variable road user charge. These consider both the costs imposed on society by a road user, and the operational requirements of a feasible road user charging system. Technologies to support the measurement of these indicators were then examined.

The importance of the ability to continuously locate and track a vehicle in space and time is seen to be fundamental to charging for road use. While the exchange of activity data with a central data server may offer additional benefits and services, it should be emphasised that the majority of the charging functions may be implemented without these data being transmitted outside the vehicle – it is only necessary to transmit a charge.

The technology to implement a link-by-link charging scheme is now available through the use of an integrated GPS-DR navigation system, large-scale digital maps and advanced map-matching algorithms. Nevertheless, it will be important to evaluate the local effects of road topology to ensure that the RNP parameters are met. In certain situations it is possible that additional augmentation will be required, e.g. to distinguish between adjacent links. Such technologies have the possibility to be deployed on a large scale, at reasonable cost and would provide a flexible tool for the management of road use.

A substantial burden on society is created by the health impacts of road transport. These include costs associated with accidents and with the effects of poor local air quality on health. Measurement of vehicle operating parameters may offer the opportunity to encourage safer driver behaviour; however explicit links between vehicle dynamics and accidents have yet to be established.

Assessment of the pollutant emission rates from vehicles is possible using on-board emission monitoring systems with sufficient resolution to support a detailed charge. However, current systems are not well adapted to long-term continuous monitoring and require considerable effort to ensure that reliable data is measured. Consequently, the estimation of pollutant emission rates using a well-calibrated model is an attractive option. Such models have been shown to provide a reasonable level of accuracy when compared to direct emission measurements, however, more extensive development and validation would be required prior to inclusion in a viable road user charging system.

To guide the development of technologies to support a road user charging system the policy objectives and constraints must be clearly defined. The technologies required to support the measurement of different aspects of a comprehensive VRUC are at different stages of maturity. Consequently, it may be that the ability to implement a system and then adapt and extend it in the future is an important design criterion.

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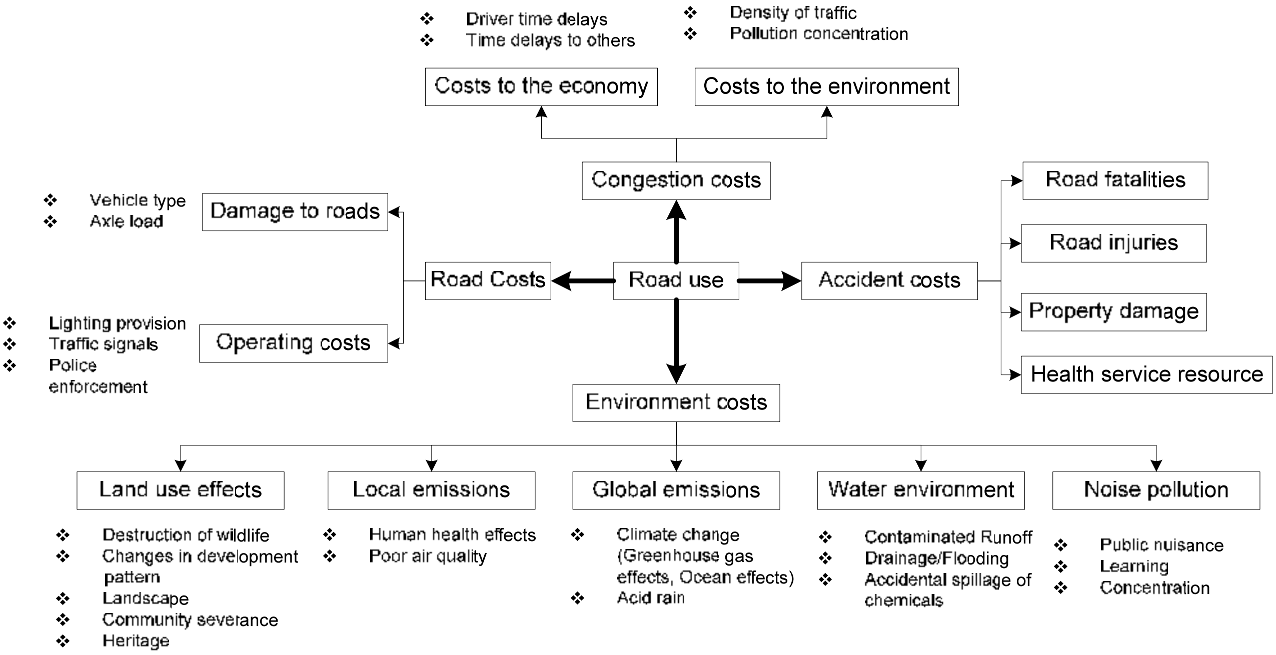

Figure 1: Negative effects of road use after Khan (2005)

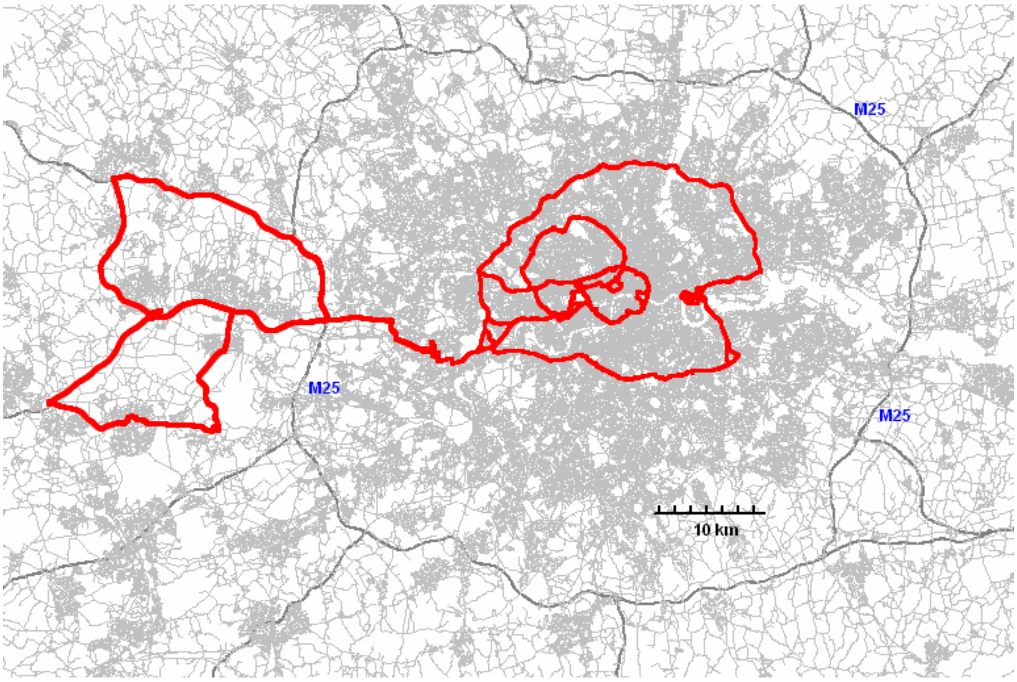

Figure 2: The test routes from all field campaigns

Table1: RUC operational requirements

ID	Description	Rating (Source)
1	Charges should be closely related to the amount of use made of the roads	*Important* (Smeed, 1964)
2	It should be possible to vary prices to some extent for different roads (or areas), at different times of day, week or year, and for different classes of vehicle.	*Important* (Smeed, 1964)
3	Prices should be stable and readily ascertainable by road users before they embark upon a journey.	*Important* (Smeed, 1964)
4	Payment in advance should be possible, although credit facilities may also be permissible under certain conditions.	*Important* (Smeed, 1964)
5	The incidence of the system upon individual road users should be accepted as fair.	*Important* (Smeed, 1964)
6	The method should be simple for road users to understand.	*Important* (Smeed, 1964)
7	Any equipment used should possess a high degree of reliability.	*Important* (Smeed, 1964)
8	It should be reasonably free from the possibility of fraud and evasion, both deliberate and unintentional.	*Important* (Smeed, 1964)
9	It should be capable of being applied, if necessary, to the whole country and to a vehicle population expected to rise to over 30 million.[4]	*Important* (Smeed, 1964)
10	Payment should be possible in small amounts and at fairly frequent intervals	*Desirable* (Smeed, 1964)
11	Drivers in high cost areas should be made aware of the rate they are incurring.	*Desirable* (Smeed, 1964)
12	At the same time the attention of drivers should not be unduly diverted from their other responsibilities.	*Desirable* (Smeed, 1964)
13	The method should be applicable without difficulty to road users entering from abroad.	*Desirable* (Smeed, 1964)
14	Enforcement measures should impose as little extra work on the police forces as possible and should therefore lie within the capacity of traffic wardens.	*Desirable* (Smeed, 1964)
15	It would be preferable if the method could also be used to charge for street parking.	*Desirable* (Smeed, 1964)
16	The method should, if possible, indicate the strength of demand for roadspace in different places so as to give guidance to the planning of new road improvements.	*Desirable* (Smeed, 1964)
17	The method should be amenable to gradual introduction commencing with an experimental phase.	*Desirable* (Smeed, 1964)
18	Charges should reflect the amount of negative external effect on the environment.	*Important* (Khan, 2005)
19	Charges should reflect the amount of negative external effect on medical costs caused by road accidents.	*Important* (Khan, 2005)
20	Charges should ideally operate without interfering with flow or speed	*Desirable* (May, 1992; IHT, 1997)

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[4] Since the publication of the Smeed Report the UK vehicle population has exceeded this limit (DfT 2005). Clearly, the need to monitor all vehicles will require much larger capabilities if a European or North American system is implemented.

Table 2: Road user charging indicators for a comprehensive charging system

Indicator Type	Static/ Variable	RUCI	Operational requirements	Routinely Measured?
Spatial factors				
1	**Variable**	**Geographic area**	**2, 3, 6, 18**	**No**
2	**Variable**	**Road class**	**2, 1, 5, 15**	**Yes**
3	**Variable**	**Distance travelled**	**1, 5, 6**	**No**
Vehicle related factors				
4	*Static*	*Age*	*2*	*Yes*
5	*Static*	*Class*	*2, 18*	*Yes*
6	Variable	Noise	18	No
7	*Static*	*Engine size*	*2, 6, 18*	*Yes*
8	*Static*	*Type of fuel*	*2, 6, 18*	*Yes*
9	**Variable**	**Pollutant emissions**	**18,19**	**No**
10	Variable	Fuel efficiency	18	Yes
11	*Static*	*Annual mileage*	*1*	*No*
12	*Static*	*Vehicle safety rating*	*2, 19*	*Yes*
14	**Variable**	**Vehicle occupancy**	**1,5, 6**	**No**
15	Variable	Load	1	No
Driver characteristics				
16	*Static*	*Age*		*Yes*
17	*Static*	*Convictions*	*5*	*Yes*
18	**Variable**	**Driver behaviour**	**5, 18**	**No**
19	*Static*	*Income*	*5*	*No*
Temporal factors				
20	**Variable**	**Time of trip**	**1, 2, 5, 6, 15**	**No**
21	**Variable**	**Duration of trip**	**1,5**	**No**
22	*Static*	*Purpose of trip*		*No*
23	Variable	Frequency	1	No
Road network conditions				
24	**Variable**	**Traffic density**	**2, 18, 20**	**No**
25	*Static*	*Road accident rate*	*2, 19, 20*	*Yes*
26	Variable	Vehicle speed	19	No
27	*Static*	*Annual average daily traffic*		
28	*Static*	*Road quality*	*2, 5*	*No*
29	Variable	Traffic flow	2	No

Table 3: Selected VRUCI and required measurements

VRUCI	Example indicator values	Measurement technologies
Geographic area	City, urban, suburban, rural, unclassified	Land-use and population database
Road Class	Motorway, A-road, B-road, minor road	Digital road network database
Distance travelled	Actual distance travel (m)	Navigation module
Pollutant emissions	Exhaust mass emission rates (e.g. g/s of CO, CO_2, NO_x, HC, PM etc) Instantaneous noise level (dB)	On-board sensors: Tailpipe emission monitoring, modelling based on engine parameters or other proxies. Microphone or modelling
Vehicle occupancy	Number of passengers	On-board sensors: Airbag sensors
Driver behaviour	Bands of poor, normal, good	On-board sensors: Longitudinal and lateral acceleration
Time of trip	Actual time	Navigation module
Duration of trip	Total time (s)	Navigation module
Traffic density	% of road capacity at given time and location	Navigation module determines time and location, interface to real-time network information required

TABLE 4: Characteristics of road transport air pollution categories

Pollutant type (Species)	Global pollutants (e.g. CO_2, CH_4, O_3)	Local pollutants (e.g. PM, NO_x, CO, HC, O_3)
Impact	Climate change, global warming	Human health, local environmental damage
Spatial resolution required	Low (Regional/political boundaries for inventories)	High (Health effects dependent on peak exposures)
Temporal resolution required	Low (Accumulated concentrations over months and years)	High (Vehicle emission rates vary rapidly)
Proposed metrics	Aggregate fuel use to derive mass CO_2 equivalent (kg)	Tailpipe mass emission rates (g/s), vehicle speed and location
Comments	Charging time-scale depends on charging methodology to be adopted (e.g. per day or per tank of fuel)	Ambient concentrations cause health impacts, but individual vehicle emissions contribute. Multiplying factors may be applied based on proximity of emission to vulnerable populations (e.g. schools, hospitals)