A Survey of Technologies for the Implementation of National-Scale Road User Charging

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Abstract

This paper surveys the technologies available for constructing a pervasive, national-scale road pricing system. It defines the different types of road pricing, the methods by which a vehicle's position can be determined, and then examines possible pricing regimes in the context of their technological requirements and implications. The issue of enforcement and the distribution of pricing policies are considered, and further complexities are outlined. An examination of the security aspects of such systems is made, focusing particularly on the need to ensure privacy using technological, rather than solely procedural, methods. The survey concludes that a pervasive, national-scale deployment is unlikely to be technically achievable in the short term.

1. Introduction

Since the inception of mass production motor vehicles in the late

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1800s, road transport has come to dominate modern-day life. Vehicle ownership has exploded and there are indications that the road network has not developed at the same pace. Within the UK alone, the number of vehicle kilometres travelled by road in the UK has doubled in the last twenty-five years (see figure 1). Road congestion is strongly correlated with increased road usage and is now rife across the world — the UK estimated a £12 billion cost from congestion in 2004 (2004, Devereux et al), whilst the USA estimated $63.1 billion for their network in 2003, a five-fold increase since 1982 (2005, Schrank and Lomax).

Governments' interest has shifted from expanding the capacity of the road networks to encouraging more efficient use of the present network. Incentives to use car-pooling schemes and public transport have shown some improvements, but they are insufficient to counter the present trends. With recent advances in technology, governments have identified a new usage model around which to base the road networks of the future. The model is to make road usage service-based, charging for specific usage, and is referred to as "road use charging", "road user charging", or "congestion pricing".[1]

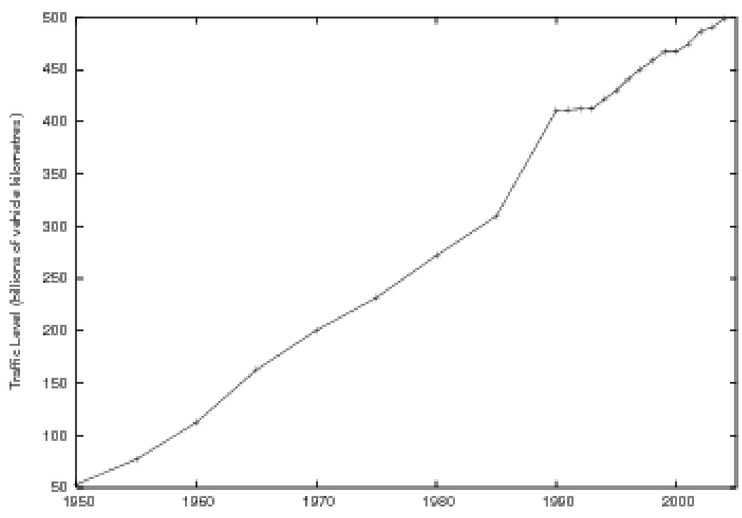

Figure 1: Traffic Levels in the UK 1950 – 2004 (2005b, DfT)

There is a significant body of literature on the economic and social implications of road pricing, ranging from Morrison's seminal survey of the area (1986, Morrison) to Lewis' comprehensive description of the many schemes worldwide (1994, Lewis). However, there is almost

[1] In this paper we use the terms interchangeably, though some authors distinguish between them (2005, Walker).

no work outlining the technical implementation details and failure modes of such schemes: most authors make the assumption that this is an area without difficulty. For example, Nevin and Abbie concluded that the main barriers to implementation were social (1993, Nevin and Abbie); the European Federation for Transport and Environment noted that the technology was mature enough, but the legal framework was not (2000, Kågeson and Dings); the UK government's position is that lack of standardisation and social resistance are the key factors (2005, Pendlebury *et al.*). Other authors have described existing schemes and their implementations for survey purposes (2004, Porter *et al.*) (1994, Gómez-Ibáñez and Small) or outlined a cost-based evaluation (2004, Ukkusuri *et al.*). Previous work on available technologies, such as (1995, Venable *et al.*) does not evaluate the usage of satellite or cellular networks for tracking, whilst (2005, Blythe) does not consider the implications of technology on payment models or privacy. In this paper, we provide an up-to-date survey of the technologies available and their feasibility for congestion charging, and argue that the technology is not yet mature enough to charge for the use of any road at a national-scale. We survey the present schemes, derive from them the practical challenges inherent in a national-scale scheme, and demonstrate the need to balance a secure charging system against a privacy-preserving system for law-abiding users.

2. Types of Charging

The aim of road user charging is to reduce congestion on a road network by charging the vehicles that use it. The usage cost needs to be set carefully: too low, and the cost will not act as a sufficient deterrent and congestion will remain; too high, and the road network will be under-utilised, which has a negative economic impact. Revenues from the charge must be sufficient to fund the scheme itself, as well as associated public transportation improvements, whilst not being perceived as another "tax". Such considerations require detailed economic studies to calculate the optimal tariff structure.

The types of charging available to motoring authorities are manyfold. Gómez-Ibáñez and Small (1994) make seven classifications:

- **Point pricing:** vehicle charged when passing a given point; e.g. a toll booth.
- **Cordon pricing:** vehicle charged when crossing a cordon or border.
- **Zone pricing:** vehicle charged for entering/exiting a self-contained zone.

- **Distance-based charging:** vehicle charged per-mile travelled.
- **Time-based charging:** vehicle charged when travelling at specific times.
- **Time- and distance-based charging:** a per-mile rate, varying with time.
- **Parking charges:** vehicle charged for parking.

As an additional classification we add the notion of *location-based* charging. Here a vehicle is charged according to where it is – a motorway may incur a fixed charge, whilst an arterial road may not. This then allows for *time-, distance-, and location-based charging*. Such a scheme would be a powerful deterrent to congestion, and The UK Department for Transport (DfT) has cited it as a goal, indicating that

> "...the key to a fully national road pricing scheme is a technology which can charge by time, distance and place to target the costs, including environmental costs." (2004, Devereux *et al.*).

We will therefore focus on the technologies necessary to implement such a location-based charging scheme at a national level, a goal shown to make good economic sense (2005, Glaister and Graham). Herein, we use the term "road pricing" to refer to any combination of time-based, distance-based or location-based charging.

2.1 Small Scale Implementations and Trials

There have been many implementations and trials of road user charging across the world. Here we summarise the major contributors to the field and classify the schemes according to the definitions given above. We omit examples of parking charges as these are not overly relevant to our discussion of technologies for national-scale congestion charging, but note that they have an important effect on urban congestion and the level of charge in cordon or zone pricing (2000, Calthrop *et al.*).

2.1.1 Point Pricing

The most familiar implementations of point pricing are tolls. Toll roads and bridges are common in many parts of the world, including many EU member states. Although the majority operate with manual fee collection at toll plazas, many now also offer a means of electronic payment. One such scheme is DART-Tag[2] at the Thames river crossing between Dartford and Thurrock in the UK. Regular users of the crossing may install a radio transceiver tag in their vehicles which enables automated payment when driving beneath an augmented gantry. Similarly, the E-ZPass[3] system (2004, E-ZPass) in the United States operates within a subset of the states and provides point-based charging on the road network, whilst the Melbourne City Link[4] in Australia is used for fully electronic tolling of 22 km of arterial highway (2005, CityLink Melbourn Ltd.).

Other more complex schemes include the the SR-91 express lanes[5] in California (2000, Sullivan), where variable pricing is used to regulate congestion on two lanes in either direction of 10 miles of expressway, and the A1 autoroute in France (1998, Small and Gómez-Ibáñez).

2.1.2 Cordon Pricing

In cordon pricing, vehicles are charged when they cross a particular boundary line. Commonly, this is on entry to a heavily congested area such as a city. Cordon pricing is distinct from zone pricing in that vehicles already within the cordon are not charged, and that vehicles traversing the boundary more than once are charged per crossing. In many cases cordon pricing only acts on one direction of traffic flow at any given point during the day.

The most well known cordon pricing schemes are the Norwegian toll rings. In Norway, these were originally set up to generate revenue for other road improvements such as tunnels, rather than to alleviate congestion. The Bergen and Trondheim rings (2000, Wærsted) and the Oslo cordon were set up in 1986, 1991, and 1990 respectively, as temporary (15 year) schemes, that have since had their lives extended. Technology has moved from a windscreen sticker system in Bergen to fully electronic tolling in all the cities. In 1998, Trondheim moved to a multi-sector cordon scheme (revised again in 2003), and Oslo is now looking to use time-varying prices as a demand management scheme (2001, Larsen and Østomoe). Once various road improvement schemes had been paid for by the Trondheim ring, it was closed at the end of 2005. Meanwhile, various other toll rings have been constructed in Kristiansand (complete ring in 2000), Stavanger (2001), and

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[2] http://www.dartfordrivercrossing.co.uk/dart-tag/
[3] http://www.ezpass.com/
[4] http://www.citylink.vic.gov.au/
[5] http://www.91expresslanes.com/

Namsos (2003).

The city of Stockholm, having in the past proposed a scheme that was not implemented, has recently, (August 2006) finished trialling congestion charging based on a cordon scheme with time varying prices (2005, Schelin). The primary technology was a 5.8 GHz Dedicated Short Range Communications (DSRC) microwave tag, however, users also had the option of paying after their passage through the zone, using Automatic Number Plate Recognition (ANPR) cameras for detection. The primary objectives of the scheme were reduced congestion, increased accessibility, and an improved environment, rather than solely revenue generation. The results were promising, with inner city congestion reduced by 22% (2006, Eliasson *et al.*) (2006, Söderholm) during working hours. The Swedish government, in the light of a positive result in a referendum on the charge, has decided to re-introduce the scheme in early 2007. A portion of the revenue will finance a new Stockholm bypass.

Other schemes that are designed to charge for entering particular areas include the (twice failed: 1985 and 2001) Hong Kong system (1988, Borins), and the unimplemented cordon pricing schemes in the Randstad area of the Netherlands (Rekeningrijden) (1999, Boot *et al.*). These systems used dedicated toll plazas. Such schemes are now being updated to have smaller sub-areas associated with different charges, and distance-based charges (2001, Pieper) respectively. This requires either the construction of further toll plazas, or a more complex technological solution. A comprehensive, if somewhat dated, survey of schemes can be found in (1994, Lewis).

2.1.3 Zone Pricing

Zone-based pricing consists of charging a fee for entry to a particular area, and over the subsequent day levying no further charges no matter how many entries or exits from the zone take place, or what distance is travelled in the zone. It is therefore a cruder form of cordon-pricing, as it does not increase the marginal cost per journey, but instead introduces an extra fixed cost per day. Singapore was a pioneer in this area; a more recent example is the London congestion charging scheme.

Singapore has a long history of road pricing (1997, Seik). In 1975, it instigated its Area Licensing Scheme (ALS) as one of a number of measures to curb congestion in its central business district. The scheme was zone-based and required drivers to display a paper-based license to drive within a 5.59 km^2 area at peak hours. Entry to this zone was limited to 22 points. The scheme was shown to reduce the number of cars in the zone by 76.2% at peak times, and considerably increased the use of car pooling.

In 1998 Singapore dropped ALS in favour of the more advanced Electronic Road Pricing (ERP) scheme (2002, Keong). This requires each vehicle to have an on-board unit that accepts a prepaid smart card. When passing under a gantry, the card is debited over a short-range DSRC radio link, making this a cordon-based approach compared to the zone-based one of ALS. These charges are on a per-pass basis and are dynamic—the amount charged is based on the prevailing traffic conditions at the seven pricing points. The in-vehicle units can be swapped to minimise the impact on personal privacy.

In 2003 London became a pioneer in implementing a form of zone pricing that is also time-based (2005b, Transport for London). Drivers within central London are charged a fixed fee for travelling in a particular geographical region during the working day. Drivers can pay by telephone, in shops, or over the Internet. On entering a charging zone, a vehicle's number plate is photographed by roadside cameras and the registration checked against a payment database. Cameras are also present within the zone to record vehicles that remain within it. Despite its apparent success (a 30% reduction in congestion within the charging zone, with no discernible adverse effects (2005a, Transport for London)), the current system is not seen as sufficiently scalable to cover the rest of London, due to its requirement for resource-intensive image processing, a high capacity backbone network, and an extensive back-end customer billing system. The Western Extension Zone of the congestion charging scheme in London will make use of an updated ANPR system (with processing of images at the roadside, linked to a central office over standard broadband Internet connections rather than dedicated optical fibres), but "ongoing trials are developing tag and beacon technology for use in an extended congestion charging zone" (2005c, Transport for London). Transport for London's latest technology trials have therefore concentrated on DSRC-based systems, using ANPR for enforcement (2006a, Transport for London).

2.1.4 Distance-based Charging

Charging users on the basis of the distance travelled, i.e. per kilometre, is seen as one of the most equitable and yet complex schemes. Consequently, few implementations exist on a small scale, and those that do are charged per segment, rather than per kilometre. A recent example is the Westlink M7 motorway[6] in Sydney, Australia, where vehicles have an On-Board Unit (OBU) that utilises DSRC technology

[6] http://www.westlinkm7.com.au/

in order to charge for known distances between entries and exits to/from the motorway. Section 2.2 describes more complex versions of distance-based charging that operate on a national basis.

2.1.5 Time-based Charging

A few existing toll schemes operate variable pricing related to the time of day, such as the SR-91 express lanes in the US (2000, Sullivan), or the A1 autoroute in France (1998, Small and Gómez-Ibáñez). In addition to time-variable pricing, charging on the basis of the length of time spent on the roads is another scheme that has been proposed. A small scale trial was conducted in Cambridge, UK, involving on-board units with pre-paid cards (1996, Ison). The user's balance was decremented at a known rate when it was determined that they were in a congested area, inferred from the length and number of stops the vehicle made. The scheme was to be operational in the Cambridge area, but met with significant opposition not least because it would have prevented a vehicle from starting if there was no credit remaining on the card, and was therefore never implemented (2005, Ison and Rye).

2.2 National Charging

2.2.1 Existing Schemes

The aforementioned implementations are all on a relatively small scale, designed for local authorities to combat localised traffic problems. There is a growing desire to integrate these schemes under national (or even international) control. Few of the current systems scale easily beyond their deployments and thus more aggressive and challenging implementations are required. Two implementations that currently do work at a national level are the Swiss and German Heavy Goods Vehicle (HGV) charging schemes.

In Switzerland, HGVs pay per kilometre travelled in the country, regardless of road type (2004, Krebs and Balmer). This functions by means of an on-board unit with a smart card, connected to the vehicle's digital tachograph, with a GPS unit as backup (i.e. not for precise location). The unit is switched on by roadside DSRC units when the vehicle enters the country, and switched off similarly on exit. The distance is recorded on the smart card. On leaving the country, the driver inserts the smart card in a roadside terminal, and pays the charge due. Vehicles without on-board units can make a declaration of their mileage on entry and exit to customs authorities.

The German scheme for HGV charging (2005, Toll Collect GmbH, 2005, Jung) is more complex, as the charge only applies on motorways, and is also time-based. All motorways are divided into logical segments, with the on-board units (OBUs) storing the geographical co-ordinates of these segments. GPS is then used to ascertain what segments (i.e. not exact per kilometre location) the vehicle has travelled on, with the digital tachograph as a backup. In addition, in locations where the GPS signal is unreliable (e.g. where two roads run closely in parallel), DSRC beacons provide backup location information. On exit from the motorway network, the OBU transmits details of which segments have been traversed to the toll operator over an encrypted cellular GSM link. Similar to the Swiss scheme, drivers without OBUs can use the Internet to declare an exact route in advance.

Two further national schemes are the recently installed (January 2007) Czech HGV charging system (2006, Feix), which makes use of gantries over key roads, and the proposed Swedish HGV charging scheme (2006, Sundberg), which hopes to use a GPS-based onboard unit.

Also of note is the paper-based Eurovignette (2006, European Parliament & Council) scheme that allows HGVs to pre-pay for the period of time (days, months, years) that they spend in a particular nation state. This relies on a driver making a declaration at a point of sale, and being issued with a receipt. Due to its low technical complexity, we will not discuss this scheme further in the remainder of this paper.

2.2.2 Proposed UK Scheme

The UK Government has proposed that the country move to a national road user charging scheme for all vehicles by 2030 (2004, DfT). It is felt that the fixed costs of motoring constitute the majority of the total costs, (e.g. road tax, insurance and vehicle depreciation), while the variable cost per kilometre (e.g. petrol, wear and tear) is significantly less for drivers with an average mileage (2005, Automobile Association). Therefore the public have little incentive to be prudent in their driving habits, and this explains the multitude of single-occupant vehicles congested along arterial roads of cities at peak hours. The goal is to introduce variable (i.e. per kilometre) costs to change social attitudes and promote public transportation.

Such a comprehensive and large scale road pricing scheme will require much more accurate positioning than is currently achieved in the German initiative. The system must not only be aware of the area the vehicle is in (as in zone based charging), but exactly which road, with all roads being possibilities (unlike the German system of only motorways), and the distance travelled on each. It is of limited use to report that the user may have been on any one of a motorway, a main road in a city, or a quiet residential street. As figure 2 demonstrates, many UK roads are close to, or even overlap one another. Downtown roads in the US are typically grid-based, resulting in ambiguity between neighbouring roads unless the positioning is highly accurate (a significant technical challenge, see Section 3). In addition the location technology used must be secure and reliable, since a national scheme may wish to use position for both enforcement *and* charging (see Section 4). This is another difference from the German or Swiss schemes, where the tachograph can be used to prove the distance travelled, and the location is of a lesser importance.

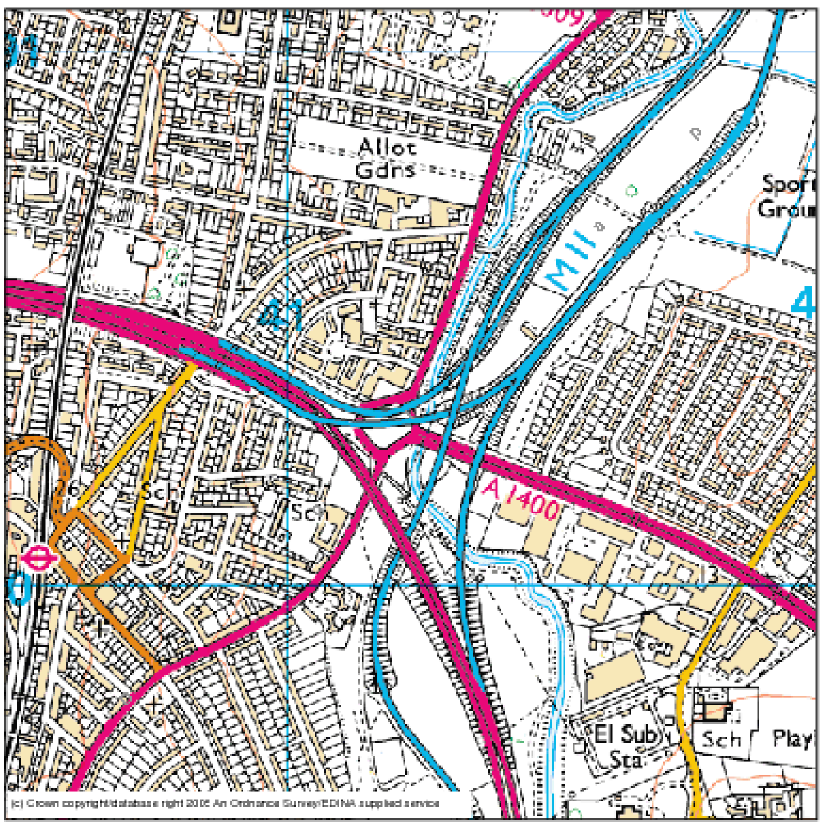

Figure 2: Potentially confusing road topology.

3. Vehicle Tracking Technologies

Various technologies can be used to locate vehicles. In this section we outline how several existing technologies work and discuss their suitability for use in road pricing schemes. In particular, we consider satellite-based positioning, location data from cellular networks, and finally the usage of more traditional gantry-mounted schemes such as cameras for Automatic Number Plate Recognition (ANPR), and Dedicated Short Range Communications (DSRC). Previous work has concentrated on ranking these technologies according to their ease of implementation, cost, enforcement difficulty and privacy. Ukkusuri *et al.* concluded from a study of various schemes that, overall, systems based on Radio Frequency Identification (RFID) are most suitable, followed by ANPR, GPS, and then DSRC (2004, Ukkusuri *et al.*). Instead, we focus on the technological suitability of each for a national congestion charging scheme, describing the benefits and faults of each system in detail. A summary of our analysis can be found in Table 1.

3.1 Global Positioning System

The Global Positioning System (GPS) (2004, ARINC) is the most ubiquitous positioning system presently available. A GPS radio receiver listens to transmissions from a visible subset of 24 GPS satellites orbiting the earth. The receiver can calculate the difference between arrival times of signals from each visible satellite and thus estimate its current position. The positioning calculation is performed solely on the receiver.

The accuracy of a GPS receiver is associated with its quality, the accuracy of the almanac it has (which describes the orbital paths of the GPS satellites) and the accuracy of its model of the atmosphere (layers such as the ionosphere can lead to diffraction and spurious signals due to multipath). The location accuracy of a modern GPS receiver is usually modelled as a bivariate normal distribution, with a standard deviation of 4.25 m, resulting in approximately 95% readings from the receiver falling within 8.5 m of its true position (2005, Prasad and Ruggieri). Higher accuracy results can be achieved by combining many results taken over a period of time, a promising technique known as High Sensitivity GPS (2005, Basnayake *et al.*).

Four systems exist to help increase GPS accuracy without resorting to time averaging: Differential GPS (a network of accurately-located ground stations transmitting corrections to the timing signals); the Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay System (EGNOS), and the Japanese Multi-Functional Satellite Augmentation System (MSAS), all of which use geostationary satellites to transmit differential corrections.

A key problem with GPS for road pricing is the *urban canyon* effect, where the presence of tall buildings minimises the visibility of satellites and prevents a position fix (2004, Appelbe). Ochieng and Sauer present results for central London that suggest that a position fix can only be obtained for 38% of a representative journey (2002, Ochieng and Sauer). Similarly, Transport for London have assessed GPS performance and found that to obtain 99% accuracy in determining whether a vehicle is within the congestion charging zone, a buffer zone of average width 60 metres (maximum 250 metres in parts) is required (2005b, Transport for London). Technology trials in several European cities as part of the PRoGRESS project have concluded that satellite positioning is not yet a mature enough option for urban congestion pricing (2004, Lundberg (Ed.)).

In order to (partially) solve this issue, the European Space Agency is currently embarking on a programme known as *Galileo* (2002, European Space Agency), scheduled to be in service by 2010. This will provide a service similar to GPS, but of greater accuracy, whilst still remaining interoperable with GPS. It remains to be seen, however, whether the accuracy that can be achieved in urban canyon situations increases to a high enough level: simulations comparing GPS, GPS with differential corrections, and Galileo and GPS combined have concluded that even the latter will in some cases only provide an accuracy of 25 metres, and an availability of 90% (2002, O'Donnell *et al.*). Transport for London also conducted simulations of satellite visibility in London, and concluded that even with a Galileo fully operational, there would be some areas of the city where fewer than 4 satellites would be visible, and hence a position fix would not be possible (2006a, Transport for London). In the future, the original GPS system will be updated to GPS-2, which will have similar accuracy to Galileo. The performance benefits of this are as yet unknown.

The accuracy of GPS positioning in vehicles can be improved in two ways by utilising sensor data fusion. Firstly, the usage of gyroscopes, accelerometers, and a connection to the vehicle's odometer can allow relative position to be calculated. This means that if infrequent absolute positions can be obtained, approximate positions can be calculated based on distance and direction travelled in the mean time. Secondly, if the receiver is interfaced with a road map database, position readings can be taken that give a good indication of which road the vehicle is on (map matching). This of course does not work well when roads run side by side (see figure 2), and matching can therefore give plausible yet incorrect results. It is also of note that current digital maps do not have sufficient accuracy to guarantee correct map matching even with a perfect GPS reading: these systems are expected to incorrectly identify the road a vehicle is on 13-27% of the time, depending on road type (2006, Cheng *et al.*). It remains to be seen whether a court of law would accept the results of map matching algorithms for enforcement of charges.

Map matching not only carries the risk of not identifying the road that corresponds to a position fix, but also the risk of incorrectly attributing a fix to a road that was not travelled on. Recent trials (2006b, Transport for London) by Transport for London of various GPS units showed that in the best case, with vendor supplied map data, 96.8% of roads in an average journey were correctly identified, 3.2% were not identified, and a further 6.4% (of the length of the journey) were incorrectly deemed as having been travelled on. Using highly accurate map data surveyed by Transport for London, these figures decreased to 98.6%, 1.4%, and 1% respectively. The same study considered billing error due to these errors in matching, which had a mean financial cost inaccuracy in the best case of 0.8%, and 5.7% mean inaccuracy over all the units tested. However, this does not consider the spread of the inaccuracy values; in the very best case, inaccuracies of up to 4% were recorded, whilst other units gave spreads of 10% to 60% inaccuracies.

Finally, another concern with GPS is the relative ease by which the publicly-available signals can be jammed. A transmitter with a power of one watt has been shown to be capable of disrupting positioning over a 10 kilometre radius (2001, John A. Volpe Transportation Systems Center). Such jamming could be used to disrupt any charging scheme significantly, whilst unintentional interference from civilian sources such as amateur radio can also severely affect GPS performance (1999, Butsch). One further step is the spoofing of signals to cause a device to obtain an incorrect position fix. Such spoofing is difficult to solve without modification of the GPS protocol (2004, Kuhn), and could cause users of a road pricing scheme to be charged incorrectly.

3.2 Cellular Networks

There is a great deal of publicity in the media about how cellular telephones can be used to locate their owners. This is achieved through a number of methods (1998, Drane *et al.*)(2004, Raja):

Serving Cell. A handset communicates primarily with the cell with the strongest signal (its *serving cell*). Assuming that strength is correlated with distance (an unreliable assumption at best), this localises the handset. Unfortunately the coverage area of a cell is ill-defined. In rural areas a single cell can cover many square kilometres, whilst urban cells may cover a much smaller area. One improvement is to use the *timing advance* value for a handset (used to coarsely define the reception delay). This can localise a handset to an annulus centred on the serving cell, of approximately one kilometre in width. These systems have been trialled for congestion charging (2004, Birle), but there are few reliable performance figures.

Propagation Time. Given sufficient timing measurements from different cells (requiring extra Location Measurement Units to be installed at the base stations), a handset can be located to approximately 100m using multilateration techniques[7] . Unfortunately, the accuracy has a high variance (2000, Zhao), and also has the major disadvantage that it requires full duplex (i.e. two-way) link between the handset and the base stations. Additionally, for GSM, a handset in stand-by mode may only register with a base station every few hours, and therefore the update frequency can be very low.

Time Difference Of Arrival. If a handset is receiving signals from three or more base stations, it can calculate the difference in time of arrival from the signals from each pair of base stations. Each measurement will generate a hyperbola on which the handset must lie, and therefore the point at which the hyperbolae intersect is the location of the device. An important issue with the Time Difference Of Arrival method is that it relies on the base station being in the line of sight of the handset. If it is not, the timing estimates are subject to error due to reflection and multipath. In urban environments this method gives a location accuracy of approximately 215 metres of error within the 67th percentile (2003, Ahonen and Eskelinen).

Angle of Arrival. Using relatively sophisticated receiver equipment, the angle of arrival of an incoming transmission can be determined. If two base stations are available, the location of the handset is simply at the point where the two straight lines drawn from the base stations intersect. The key issue with Angle Of Arrival (AOA) is that it assumes line of sight, i.e. no multipath effects. In a city environment AOA was shown to have an angle estimate at the 67th percentile of within an angle error of 30 degrees (1998, Owen and Lopes), thus rendering it highly inaccurate.

Enhanced GPS. Whilst GPS functions well in open areas, in urban environments its performance is poor. However, in cities, there is generally a high density of cellular base stations. These can be used to aid the location of the handset, using one or more

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[7] Multilateration is the calculation of the position of an object by measuring the time difference of arrival of a signal that the object emits at three or more separate receivers.

of the above techniques, or by transmitting location signals as aids (e.g. E-OTD for GSM, and OTDA for UMTS). More recently, work such as Matrix (2003, Duffett-Smith and Hansen) has been carried out utilising timing estimates from more than one handset to ascertain the position of a target handset. This method has an error of approximately 50 to 100 metres within the 67th percentile with a GSM system, and is expected to double in accuracy with W-CDMA (3G, or UMTS) systems.

Cellular systems have the advantage that the vast majority of people in developed countries already possess a handset. Therefore the cost in implementing road pricing based on this hardware could be relatively low. However, there are several issues:

- Accuracy, as described above, is not, as yet, high enough. Transport for London found that the performance of GSM location was quoted by operators as having a resolution of 800 metres, but in practice yielded 2.4 kilometres (2005b, Transport for London). Clearly this is not accurate enough for distance-based charging as opposed to zone based schemes.
- A handset must somehow be associated with a particular vehicle. Whilst this is by no means an insurmountable problem, it requires that a service be provided to perform the registration (e.g. by SMS), or that hardware be installed in the vehicle to perform the association. Enforcement must still take place to ensure that those vehicles with which a handset has not been associated are caught. This is certainly not trivial.
- Handset identity spoofing is possible, but it does require expensive equipment. Cellular operators are incentivised to minimise tampering, since spoofing can give access to free and anonymous calls.

3.3 Automatic Number Plate Recognition

A growing number of localised schemes make use of cameras and sensors mounted on gantries for locating cars as they enter or exit a zone. Deployment and, in particular, maintenance (as this requires road closures for health and safety reasons) of such gantries is very expensive, and each requires a connection back to a central processing authority.

Camera-based systems, such as that used in the London congestion charging scheme, use ANPR on photographs of vehicles passing under the gantry. ANPR systems in London have an accuracy (i.e. percentage of correctly recognised number plates) of at least

85% (2005b, Transport for London). With multiple sightings of a vehicle, this can be increased to above 90%, while some manufacturers are now claiming a 95% recognition rate from a single sighting (2003, Appian Technology). Where the recognition confidence level falls below a defined threshold, manual processing of the image can be used.

ANPR systems are not suitable for accurate location at all times, since the required camera density is infeasible. It also does not function well if a number plate is obscured by another vehicle, or by dirt, and it requires significant processing power to execute the recognition algorithms. It has the final disadvantage that its robustness is not as high as for other identification technologies (e.g. both microwave and infrared DSRC were found to have a 99.5% recognition accuracy in London trials (2005b, Transport for London)).

However, related uses of ANPR are increasing, with data being captured from CCTV cameras in cities and dedicated police intercept teams. Coarse-grained tracking of vehicles can be carried out in the using CCTV images from the motorway network. This allowed police intercept teams to make 13,499 arrests in the 12 months to June 2004, resulting in an arrest rate per officer of 10 times the national average. Drugs and weapons were also recovered (2004, Henderson *et al.*). This demonstrates ANPR's utility as a crime reduction technology.

3.4 Microwave & Infrared

The remainder of the systems based on gantry mounted "tag and beacon" sensors are short range microwave- (DSRC) or infrared-based. A tag is placed in the car and queried as the vehicle moves past a gantry. Some tags are passive, and are powered by the gantry transmission, others are active. Some tags are also able to perform two-way communication, such as that necessary for registering a new account balance on a tag having ascertained its identity (1994, Wiggins). A tag costs approximately £15, and has a lifetime of several years.

In the United States, DSRC is governed by the IEEE 802.11p standard, and has an assigned frequency band at 5.9 GHz. In Europe, there is no comparable standard, and many proprietary protocols exist, all utilising the 5.8 GHz band. Confusingly, these are frequently also referred to as "DSRC" systems. Consequently interoperability between microwave-based toll systems is a key issue at European Union level (2003, Commission of the European Communities).

Microwave-based systems have a recognition accuracy above 99% (2003, iPico South Africa), and are in use in several locations around the world (e.g. Australia, Austria, Chile, Germany, Switzerland, UK, USA). They do not, however, provide any better location data than any other gantry-based system, which renders them unsuitable for national congestion charging schemes, unless sensors were placed in great density on every road, at high cost.

3.5 Future Developments

The state of the art of all of the technologies mentioned in the previous sections is constantly advancing, and in the medium term will allow types of charging scheme that are not currently possible. In this section we outline our own views on how such technologies will develop in the next decade.

Satellite navigation units will continue to increase in precision, as the number of correlator circuits used in them increases due to their falling cost. Greater numbers of satellites visible at any one time will aid performance in cities. However, urban canyons where very little of the sky can be seen will always present a problem. Dead-reckoning (inertial) systems will be deployed more commonly on vehicles, and will accurately deduce location relative to the last GPS position fix obtained. Progress will continue to be made with High Sensitivity GPS (2005, Basnayake *et al.*), and with TV+GPS systems; in the latter, unmodified signals from broadcast television stations are used in cities to obtain position fixes where GPS is unreliable (2005, Rabinowitz and Spilker Jr.). Vision systems fitted in cars may also derive their location from inexpensive marker tags affixed to street furniture. With systems of this complexity, the possibility that they could be tampered with increases.

Cellular networks have also bettered their ability to deduce handset location. However, positioning information is unlikely to become any more accurate using current methods. Hence, operators are now integrating GPS units into cellular phones, in order to have more accurate location information. Federation of position fixes provided by cellular multilateration and satellite navigation systems will increase, but it remains to be seen if this could provide the high enough accuracy information at all times required for distance- or location-based charging. It is likely that using cellular positioning for analysing large-scale people or traffic movements will continue in the medium term, as there are no other methods of sensing that are ubiquitously deployed, whereas cellular phone coverage essentially is. In the long term, if a national scheme is deployed, more accurate data on where each vehicle is located is likely to be available.

ANPR systems continue to increase their recognition success rate. However, it is unlikely that this will equal the read rate of DSRC tag and beacon technology, due to the problem of number plate obscuration (by other vehicles, dirt, or deliberate tampering). Hence, it is unlikely that it will be used for both billing and enforcement. However, it is the only system that does not require any equipment to be installed in a vehicle, and is therefore required for enforcement purposes. In the medium term, ANPR will continue to be the enforcement technology of choice, until all vehicles have a unique identification device that is installed at time of manufacture and can be read remotely.

Microwave (DSRC) systems are currently the technology of choice for road tolling. Read rates are already very high (>99.9%), and will increase. Interoperability of tags and readers from different manufacturers is a major concern. Steps are being taken by various bodies to develop interoperability standards – examples are the DIRECTS project (2005, Jones at al.) and the documents formerly known as the Open Minimum Interoperability Specification Suite (2006, Mackinnon) in the UK, and the European Electronic Toll Service (2004, European Parliament & Council) by the European Commission). In the medium term we are likely to see toll schemes that utilise incompatible DSRC implementations, whilst in the longer term standards will prevail; the technology has matured, but the legislative framework to support it has yet to.

Table 1 goes about here.
Table 1: Comparison of Vehicle Tracking Technologies.

4. Enforcement

With any congestion charging scheme, we must ensure that there exists the capability of detecting vehicles that do not pay, or have tampered with on-board equipment. It is crucial to realise that implementing a system such as DSRC or number plates containing RFID tags, will not solve this problem: if a vehicle does not have a tag installed it will not be detected. In the same way, an on-board GPS unit can be disabled by removing or covering its antenna, or a tachograph may be periodically disconnected from the drive-shaft (1998, Anderson). Equipment failure must be distinguishable from malicious tampering, and such equipment must not rely absolutely on being tamper-proof. Other mechanisms must be in place to verify (albeit approximately) that the on-board technology has not failed, and that the user has not wilfully disabled it. As an example, the Swiss lorry charging system makes use primarily of a digital tachograph, but this is supplemented by a GPS unit to calculate the approximate distance travelled (2004, Krebs and Balmer).

Another observation concerning the use of DSRC is that a reduction in privacy only takes place for those vehicles that have a tag installed, i.e. those who are law abiding. In contrast, charge evaders are not detected, and therefore their movements remain entirely unknown. Cameras solve this problem by capturing all vehicles, and discarding images of those who have paid the charge. However, a more optimal solution would be to devise a system that reduced privacy only for those who had not paid. One such a system is described in (2006, Beresford *et al.*).

The London congestion charging scheme functions by photographing the majority of cars that enter the zone, and performing ANPR on their number plates. Vehicles that have not paid are then fined accordingly. The economic incentives are engineered such that it is not worth failing to pay the congestion charge and risk being caught by the cameras. Users therefore pre-pay and the cameras are simply an enforcement mechanism.

For a national congestion charging scheme, it is unlikely to be feasible to have cameras on every road. In any case, depending on the mechanism used, there may be no use in having cameras, as the system will not know which vehicles are carrying the equipment until these are serviced (in the case of post-payment systems). To perform camera-based enforcement there is a need for vehicles that have the equipment and/or that have paid to be identifiable by a unique ID to the system, that can be linked to the car number plate. This then allows ANPR to be used on the number plates to find those vehicles that are committing an offence. At present, the only unique externally visible identifier a vehicle has is its number plate; changing to a different system will be costly and time consuming.

Enforcement requires a technology that can be used in multiple locations and does not require properly functioning hardware in the vehicle. Spot checks are of course possible (as are those at annual vehicle roadworthiness tests), and indeed, should be used whatever the enforcement mechanism implemented. This is an open question, but for the present it appears that cameras are the only feasible method for enforcement, but are not deployable nationwide. We note however, that it might only be necessary to deploy them in strategic locations, on the assumption that offenders will have to pass through one or more of these locations on any significant journey that they make, as is the case with the German lorry charging system (2005, Jung). Checks at such locations could include verifying the vehicle was in the payment database, and interrogating an on-board unit via DSRC to ascertain whether its GPS receiver was functioning. The density of such checkpoints that would be required, and the optimal locations for these, is unknown for a national scheme covering all roads, and requires urgent research using network modelling techniques.

One solution to this problem involves the transfer of enforcement duties from apparatus placed in the environment onto the vehicles themselves (2005, Harle and Beresford).

5. Pricing Models

There are various different types of pricing mechanisms for implementing road pricing. The simplest, *static pricing*, involves a fixed schedule of distance-based prices announced in advance of any travel. A government could update these prices on, for example, a yearly basis. There may be different pricing bands for different times of day, but these would be well known. In contrast, *dynamic charging* is a closed loop system, where charges depend on the current level of road congestion. Such a scheme is therefore more flexible but the charges are less easily predicted by the user. Another alternative is *slot reservation* pricing, which takes advantage of the flexible nature of dynamic pricing, but allows users to book their journeys in advance for a price agreed at the point of sale. This gives drivers greater control over costs.

Detailed travel data can contain a great deal of sensitive personal information. Therefore a strong guarantee of privacy is highly desirable for any charging scheme: technically, all the schemes outlined below, if implemented in a suitable way, can provide some guarantee of anonymity and therefore privacy. Enforcement generally requires some loss in anonymity: what we require is that those whose privacy is invaded are those who are attempting to evade a charge. It is, however, interesting to note that the population's concerns over privacy appear to be lessening (2004, Lyons *et al.*), and that therefore robust enforcement with some privacy loss might receive a warmer welcome than a weaker system that provided increased privacy (see Section 7).

5.1 Static Pricing

Road users are currently accustomed to paying a high fixed cost of car ownership and a relatively small per-mile (fuel, tyres, servicing) charge to travel. On the rare occasion that their journey involves a toll road, they pay a fixed fee, often known in advance. National road pricing will modify this by making a larger proportion of costs to be per mile. The UK government has indicated (2005a, DfT) that they would set a price that would lead to an average driver paying annual charges approximately equal to (and replacing) the present road tax.

In recent UK Government proposals (2004, Devereux *et al.*), the price for using a particular road will depend on its utility to the driver. For example, a motorway will be deemed of greater utility than a dual carriageway, which in turn will be charged at a higher price per kilometre than a country lane.[8]

Static pricing is relatively easy to implement once a sufficiently accurate positioning system is available. Because users would be aware of charges for each type of road (in the same way that they are aware of the speed limits in force), there is no requirement for an additional in-vehicle user interface.

Critics of static pricing complain that if a tax on fuel is reduced or dropped in favour of road pricing, drivers will have no incentive to purchase fuel efficient or low-emission vehicles. Clearly this can be solved by setting road prices which take the size of vehicle engine, or EU emissions class into account (as in Germany and Switzerland). It is also important to note that a tax on fuel is insufficient to avoid congestion, given that congestion is time-variant, whilst tax is not, in the short term, time-variant.

5.2 Dynamic Pricing

Greater flexibility can be achieved using a dynamic pricing model, where charges are based on present road network conditions. The goal of such a system is to keep the road network just below a state of congestion, therefore maximising throughput. Singapore again provides a good example, providing financial incentives or a disincentive to use roads depending on their present state.

The biggest issue with dynamic pricing is the need to inform users of charges in a timely manner. Is is not acceptable for a road user to commit to using a road at one price only to be charged another within seconds of committing. The model we envisage assumes that charges are published globally to all users (see Section 6 for network infrastructure considerations). Charges are varied throughout the day, but are normally fixed, i.e. there is one price for rush hour, another for midday, another for overnight, etc. There is a key issue as to whether these charges would be further dynamically varied depending on day-to-day incidents: for example, a popular football match may require an increased charge to avoid gridlock. Accidents are another interesting problem area: if an incident occurs on a road of high utility, should people be discouraged from using it by increasing the

[8] We note that it may not be economically viable to charge for countryside roads, depending on the technology used. However, this might push traffic on to them. Any scheme should take this issue into account.

charge? It is not clear what effect this might have.

Dynamic charging will require significant amounts of infrastructure and new user interfaces that clearly show the charges a user can expect to pay. It may seem unrealistic to change the tariff that a user pays per kilometre when the user is on a road, but we accept such price changes on telephone calls that span both rate bands. Not doing so would almost certainly cause more harm than good, as users would attempt to get to particular roads just before the charge rate changed (as took place in Singapore (1997, Seik)), to avoid paying a high tariff. Such dynamic changes will require user interfaces that are clear and simple, whilst providing all the necessary information in a safe manner to the driver (Section 5.4).

5.3 Slot Reservation

In slot reservation, a user purchases, in advance, the right to travel on a particular route at a particular time (1997, Wong). The price of the route can be dynamic, but the user knows the cost in advance of travel. In this way slot reservation retains much of the flexibility of dynamic pricing, but with less complexity and also reduces the need for adaptive route planning systems. However, enforcement mechanisms are still needed to ensure that vehicles travel on the correct route.

The pricing system for slot reservation can take advantage of pre-travel purchase requirement to enable capacity planning. For example, the pricing mechanism can limit the number of slots available (1999, Koolstra), and therefore early reservation may cost less than bookings near the time of travel. This pricing model is similar to the those used by low-cost airlines now operating in Europe. Alternatively, each user may bid for one of a limited number of slots, as proposed by the Foresight project (2007, Markose *et al.*).

5.4 User Interfaces

When using a static pricing scheme, there is often no need for a separate user interface in any vehicle: prices vary over long timescales, not by the hour. Nevertheless, given that many higher end vehicles now come with on-board GPS units that provide suggested routes, pricing information could be incorporated into these units to plan routes based on absolute cost or the quickest route available for a particular price.

With a dynamic pricing scheme it is likely that the resulting optimisation problem will be too complex for a human driver to realistically perform whilst travelling. It will therefore be necessary for drivers to rely far more on on-board route planning software, which will calculate optimal routes based on distance, time, and prices. This will result in a significant departure from the current situation where drivers are able to ignore their GPS route finding units if they so wish (perhaps because the unit is not aware of the prevailing traffic conditions).

For slot-based reservation, auction systems have been proposed, where vehicles could be fitted with units that allowed the driver to specify a personalised strategy for how the unit should bid for time slots on road segments (2003, Iwanowski at al.). The maximum and minimum bids that a unit might make could be specified, as well as limits for the bids for each road segment from any vehicle. A central co-ordinator would be used to run the auction and keep track of each vehicle's balance. Although such a system is likely to be successful from an economic perspective, the authors concede that incentivising the fitting of such a system would be difficult, and in our opinion users would be likely to find such a system overly complex.

In the light of the above, we propose that a congestion charging system should not necessarily take the form of the most effective theoretical solution, but instead should be shaped by the need for a simple user interface. A case in point was the unpopular and unimplemented Cambridge Congestion Metering Scheme (1996, Ison). Although the system had a simple mental model, users did not like the unpredictability of the price, which depended on the degree of congestion they were currently experiencing. This was despite the fact that such a solution corresponds closely to the idea of users paying for the real cost of their journeys.

If users are to rely on their in-vehicle units, several aspects need further development:

Positioning The accuracy of positioning systems must be improved, (See Section 3).

Real-time information Up to date information on the state of the roads is required. Such congestion-aware systems exist, e.g. Traffic Master[9] or systems based on it (2000, Fawcett and Robinson), but they only provide coverage on major roads. Various schemes have been proposed to collect data with a greater coverage, such as utilising cars as mobile congestion measurement sensors (2005, Cottingham *et al.*), or "traffic spies" (2004, Guizzo). Simulations indicate that this approach is a possibility, and in Singapore this system has been implemented using the city's taxi fleet.[10]

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9 http://www.trafficmaster.co.uk/

10 http://www.onemotoring.com.sg/publish/onemotoring/en/traffic/traffic_management0/intelligent_t

Map updates There must exist a mechanism for maintaining detailed map data in the unit. There are currently cases where emergency vehicles attempt to use roads suggested by their on-board units only to find that a crucial 100 metres of which do not exist. Such faults should be corrected on all units, even when in motion. This requires mobile connectivity (perhaps over the Radio Data Service channel). Data quality is also an issue: a detailed map should include up-to-date information such as lane closures or variable speed limits, which will require much greater information sharing and distribution than currently takes place.

Standard OBU There must be a single on-board unit that is interoperable with all charging schemes. The European Commission has issued a directive (2003, Commission of the European Communities) stating that microwave-based schemes should be phased out by 2012, and a single satellite-based system used in their place. This will alleviate the current situation where vehicles that regularly traverse several countries are required to install a 1-2 kg OBU for each territory's charging scheme, clearly a concept that is unsustainable.

6. Networking Issues

If charging is to be performed in an on-board unit, or if dynamic charging is to be implemented, charging policy data must be downloaded onto each vehicle's on-board unit. There are various existing mechanisms to perform this: Radio Data Service (RDS) channels and satellite feeds (similar to the GPS almanac download) are both near-ubiquitous, and with specialised broadcast techniques such as fountain codes (2004, Mitzenmachert), charging data could be easily distributed. Fortunately, the distribution of charging data need only be one-way. However, a certain degree of system intelligence is required if pricing is to be dynamic and location-based, and there is a need to keep policy updates small.

In schemes that involve data transmission from the car as well as reception, a more advanced wireless network, capable of high data throughput, will be necessary. Collation of this data may also be problematic. For example, in order to report vehicle position at 100m intervals, a vehicle travelling at 100 km/h would report its position every 3.6 seconds. For a country with 20 million active vehicles travelling at an average speed of 100 km/h, a 32 byte position message per vehicle would result in a total data rate of 1.42 Gbits/s. In principle, this is achievable, but account must be taken of the overhead

ransport_systems/traffic_scan.html

per message.

To achieve location independence in throughput, satellite communication is attractive. The expense and limited capacity of satellite links, however, makes them unsuitable for individual transmissions from vehicles. Cellular networks are a possibility, but present designs do not cope well with large volumes of short messages, which can cause a denial-of-service attack[11] on the network (2005, Enck *et al.*). Operators are now increasing throughputs using W-CDMA technology (known as UMTS or "3G" in Europe), and making their networks more suitable for handling data streams. It is therefore likely that initial systems will use cellular links.

In contrast, short range networks have been proposed, such as transmitters on each lamp post on a road (2005, Tully and Blythe), or simple base stations using millimetre radio over fibre technology (2005, Kim *et al.*). Whilst this is potentially feasible on a motorway or a major road, it is unlikely to be so on many less well used roads, resulting in reduced coverage. This is for purely economic reasons: mounting large numbers of sensors on poles or gantries and interconnecting them using a backbone network, along with the high probability of vandalism, make the costs prohibitively expensive for roads with low volumes of traffic. Many systems proposed thus far have not considered these issues.

7. Security and Privacy

Achieving social acceptance of a national road pricing scheme is likely to be harder to achieve than it has been for localised charging. There is significant concern among the public that the introduction of any nationalised congestion charging scheme will mean that the government will be aware of exactly where each vehicle has been at all times (2001, Ogden), and might possibly be able to query its current location. Any such system must therefore ensure that these privacy concerns are addressed.

7.1 Privacy & Utility Tradeoffs

It is somewhat paradoxical that potential users should be so concerned with this new scheme, given that they are willing to make use of mobile telephones and debit cards, both of which can be used to derive

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[11] A situation in which an attacker floods a server with a large number of requests, causing there to be very limited resources for serving requests from legitimate users.

a great deal of information about the their locations and habits. Existing location data from the cellular network has uses in transportation. For example, mobile telephone data has been used to measure the level of congestion on the road network (2004, Applied Generics Ltd.). However, there are several differences between the collection of mobile telephone location data and the recording of position data for a national congestion charging scheme:

- There is currently no obligation for any person to carry a telephone handset, or to make use of a debit card. With a congestion charging scheme it would be a requirement for all vehicles. This obligation makes the population uneasy (2001, Ogden).
- Both mobile telephones and debit cards were novel technologies at the time of their introduction. This meant the public did not have any alternative system to compare the new offering against.[12] In contrast the road network is an existing technology which currently has a high level of anonymity.
- The quality of location data required for road pricing exceeds that required to enable mobile phone operation. For example, dynamic pricing requires a constant stream of accurate location data. In contrast, a mobile phone that is not currently taking part in a phone call only provides updates to the current cell, or radio mast, that the mobile phone is closest to at relatively infrequent intervals. Therefore the location of a mobile phone is not always accurately known.
- Current invasive technologies provide an immediate personal benefit to the consumer. Mobile telephones improve communication whilst on the move, and debit cards facilitate easier access to money. In contrast, road pricing incurs a financial cost on the consumer, rather than providing a tangible benefit (at least prior to implementation; the benefits of reduced congestion with the scheme in place should be tangible).

There exists a trade off between anonymity and the identification of offenders. In an ideal scheme, the system would only be able to identify the cars which have not paid. Achieving detection of offenders and, simultaneously, anonymity for paying vehicles is a difficult, but not insoluble problem (2006, Beresford *et al.*).

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[12] In the case of mobile telephony and debit cards, alternative technologies do exist, for example phone systems have been designed with anonymising proxies (1996, Kesdogan *et al.*), however they have not been made widely available as an alternative.

7.2 Legal Considerations

From a legal perspective, with any scheme that is implemented, the operator must ensure that any data that might be used for charging is admissible as evidence in a court of law. Transport for London noted in their report (2005b, Transport for London) that they could not make use of GPS with map matching algorithms as these were not yet accepted as valid systems in terms of positioning. In the same way, if digital images are taken from cameras, they are likely to require digital signatures at the point at which they are taken. Such considerations are not likely to be technically complex, but require the necessary legislation to ensure that the final system is legally robust.

8. Conclusions

This paper has examined the key technical requirements for the deployment of a pervasive, national-scale, congestion charging system. Section 2 compared existing congestion reduction schemes under five broad categories: point, cordon, zone, distance-based and time-based charging. We also reviewed the technological charging requirements for a new, national-scale system. In the UK at least, location-based charging, or, charging for use of a particular piece of road, has already been cited as a requirement. Yet, as seen in Section 3, many existing vehicle tracking technologies are not capable of accurately locating a vehicle on a particular road segment.

GPS and Galileo, whilst having ubiquitous coverage, fail to provide sufficient resolution to locate a vehicle on a particular road. Cellular networks also have good coverage, but have insufficient accuracy to provide a location-based charging solution. ANPR and microwave systems have excellent accuracy, but cannot provide global coverage in a cost effective manner.

Section 5 discussed the technical requirements involved in various pricing models. A static, or fixed price, scheme is easy to administer and requires little or no infrastructure in the vehicle itself. Unfortunately, it is unknown whether a static pricing scheme has sufficient control over vehicle usage to prevent congestion. In contrast dynamic pricing, which charges vehicle owners based on the current expressed need in the road network, gives the congestion charge operator greater control. However, it comes at a cost. Dynamic pricing will require additional equipment in the car to inform the driver of the prevailing tariff if the current price is to have any impact on driving habits.

Effective enforcement will be a major problem, irrespective of the mode of pricing or payment model. Any congestion charging scheme requires some infrastructure on the vehicle, even if it is only a visible number plate. Such infrastructure is then open to abuse by tampering. Protecting a complex combination of sensors, hardware and software against user modification is difficult, and is unlikely to be fully achievable in the near future. Therefore, congestion charging systems should minimise the incentive for a vehicle owner to modify any installed equipment.

In our view, a national-scale, pervasive, location-based congestion charging system is not technically achievable in the short term. This is in contrast to the many government and economic reports detailed in Section 1 that assume that it is. Cordon- or zone-based charging may be possible using GPS or cellular systems, but enforcement is likely to be difficult and problematic. ANPR and combined camera & microwave systems can be used to provide point-based charging and provide better enforcement guarantees, but are unlikely to be installed pervasively: it is simply too expensive to install such systems with sufficient density over the entire road network.

In the medium term, it is likely that a combination of technologies will be installed. In the UK, a comprehensive ANPR network on major roads is being used to track vehicles (2006, Evans-Pughe), whilst different cities have proposed or are trialling congestion charging schemes with various tag and beacon technologies, or ANPR. Charging for rural roads is unlikely to be implemented, though this may result in increased traffic levels as users avoid sections of charged major road. Without careful co-ordination, the result will be a confusing mix of solutions that will not be interoperable, nor have unified billing, along with worsening congestion in rural areas. This is a situation that governments must avoid if congestion charging is to gain wide acceptance, and something that technology must be developed to solve.

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Technology	Description	Accuracy (m)[a]	Unit Cost	Infra. Cost	Deployed?[b]	Urban?[c]
GPS	Uses differences in arrival times of satellite signals.	8.5-25[d]	Medium	In Place	●	○
Cellular Serving Cell	Infer from base station in use an annulus of possible locations.	1000	Low	In place	●	●
Cellular Prop. Time	Multilateration of timing measurements from different base stations.	100	Low	In Place	●	●
Cellular TDOA	Uses differences in time of arrival of signals; assumes line of sight.	470	Low	Low[e]	●	●
Cellular AOA	Uses angle of arrival of signals to two base stations.	Inaccurate in cities	Low	High		○
Cellular Enhanced GPS[f]	Timing differences from multiple handsets are reported back to a server.	50-100[g]	Low	Low		●
ANPR	Cameras record vehicle number plates	95% capture rate	Zero	High	●	○
DSRC	Microwave beacons on gantries with tags on vehicles.	99% read rate	Low	High	●	○

a Quoted as 95th percentile except where noted.
b Whether the technology is widely used for deriving the positions of vehicles.
c ● = Works well, ○ = Variable availability in urban environments.
d Highly variable; depends on receiver specification and number of satellites in view.
e Requires augmentation of existing base stations.
f Data quoted in this row concerns the cellular handset positioning element (such as Matrix) only; GPS performance is as given in the 1st row.
g 67th percentile.

Table 1: Comparison of Vehicle Tracking Technologies.