GNSS-based Dynamic Road User Charging System

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ABSTRACT
Most current road user charging systems have a static charging structure. Under the ‘Polluter Pays Principle’ vehicles that cause more road damage, congestion and pollution should pay more. Until recently, technology was not available for dynamic appraisal of user charging. However, satellite based road user charging technology provides an efficient, dynamic and sophisticated charging mechanism. In this research, a Global Navigation Satellite System (GNSS) based dynamic road user charging system architecture is demonstrated. The proposed system could consider a range of dynamic variables such as (e.g., distance travelled on a chargeable road, pollutant emission and vehicle occupancy level etc.) to appraise the road user charge. Finally, key technological, user accessibility issues and feasibility of implementation of the proposed dynamic road user charging system is examined through focus groups with experts.

1. RESEARCH MOTIVATION AND OBJECTIVES
Some fifty years ago in the early 1960s, a panel supported by the UK Ministry of Transport and chaired by Professor R. J. Smeed, prepared guidelines for implementing a successful national road user charging (RUC) scheme [1]. A key element of the Smeed report was that RUC should be dynamic spatially, temporally and modally, and the level of charges should be based as much as possible on the amount of road damage (the wear and tear to a road due the passage of a vehicle varies according to vehicle size, type, and class for example), congestion and environmental pollution caused by a vehicle. However, despite technological advances, systems for direct charging road users have not yet fully assimilated the equitable principles set out in the Smeed Report. A recent study by Ochieng et al. critically reviewed previous studies such as Smeed, May, IHT, and Khan [2, 3, 4, 5]. They identify indicators for national-level dynamic RUC and assess vehicle location systems and sensors (e.g., vehicle emission monitoring unit) suitable for GNSS-based dynamic RUC. The latest advances in transport telematics that encompass a range of advanced information and communication technologies (ICT), vehicle sensing, emission monitoring, digital technologies, and navigation and positioning systems may help in deploying a national-level dynamic RUC system [6, 7]. As the technology has developed implementation cost becomes a significant reason for this comparative rarity. Further, a critical factor for deploying such a national-level dynamic RUC is public, and hence political, acceptability [8, 9]. Therefore the main objectives of this paper are (a) to review and critically compare existing charging types and technologies to develop a typology (b) to demonstrate a national level GNSS-based fully dynamic RUC system architecture and (c) to highlight key technological and user accessibility issues with the proposed GNSS-based dynamic RUC, supported with the findings of a pilot focus group.

2. PROPOSED GNSS-BASED DYNAMIC RUC SYSTEM
The components of a GNSS-based dynamic toll collection system are: an on-board unit (equipped with a GPS and a Deduced Reckoning (DR) sensors), a wireless communication system (e.g., Dedicated Short Range Communication, Global System for Mobile Communication, General Packet Radio Service (GPRS), Wireless Local Area Network, or a combination), a vehicle emission monitoring unit, a sensor-based vehicle occupancy monitoring unit, and a base station (see Figure 1 at the end of this paper).

System inputs combine a digitised GIS map with traffic information for each link/corridor, such as traffic density or speed from the Area Traffic Management System (ATMS), and the user charging structure (i.e., the rules concerning when and how much a vehicle should be charged). The On-Board-Units work via GPS and DR sensors serve as a back up to determine how far the vehicle has travelled by reference to a digital map provided to the system. A Map-matching algorithm integrates vehicle positioning data with GIS road map to identify the road segment on which a vehicle is travelling and the vehicle’s location on the selected road segment. The GPS/DR records road usage data (i.e. distance travelled on a particular road class / geographic area) as well as temporal information, like the time and duration of the trip, and vehicle-specific information such as unique identification, vehicle class, vehicle occupancy, pollution emission, vehicle weight, or vehicle configuration. This information is then transferred to a base station through wireless communication system such as GPRS. At the base station, the information is used to calculate the charge which is then billed to the vehicle owner. Finally, users are supplied with the detailed information about their charges and road usage (e.g. distances and emissions).

GNSS-based road charging systems have many advantages such as: more flexibility in charging, a minimum need for external roadside infrastructures and hence less environmental impact. In addition, the level of feedback about personal road usage to drivers offers the type of personalised information necessary for behaviour-based policy interventions, as users are directly supplied with the information required to alter behaviour to control costs. Moreover, the proposed system not only fully assimilates the equitable principles in charging mechanism, but it also has additional benefits for implementing and controlling various ITS systems (e.g., real time traveller information and route guidance, incident or accident management, traffic speed control, stolen vehicle recovery etc.). Nevertheless, in order to implement the proposed variable RUC system at national level there are still some technological and acceptability issues; these are discussed in the next section.

3. ISSUES TO IMPLEMENT GNSS BASED DYNAMIC RUC
3.1 Issues with vehicle position and location
The main function of a GPS in a road user charging mechanism is to provide position and time information to the system [10]. Due to GNSS signal errors (that include atmospheric effects), multipath errors and errors with GIS road map, vehicles might sometimes be assigned to the wrong road segment [11]. A lack
of positioning accuracy may lead to charge users erroneously [12]. For example, the GNSS-based variable road user charging scheme may charge users erroneously in situations where two adjacent roads are priced differently (i.e., charge for a motorway is £1.50 per mile and charge for a minor road parallel to the motorway is £0.25 per mile or even zero).

3.2 Reliability and security issues
In the proposed GNSS based road user charging system, there are two possibilities of erroneous charging: (a) Missed recognitions/charging and (b) False recognitions [13]. Missed recognitions represents although a vehicle is travelling on a chargeable road or area, the system wrongly identifies the vehicle and keeps it on a non-chargeable zone. On the other hand, false recognitions indicate over charging of users. The false recognitions make the system un-acceptable to the public and may further lead to legal consequences. Missed recognitions may create loss to RUC agencies.

In addition to the system's reliability, system's security is also an important issue in both users and operators point of view. The system security includes users' privacy and toll operator's tamper protection. Moreover, Smeed's guidelines also indicate that road user charges should possess a high degree of reliability, free from the possibility of fraud and evasion, and protect road users' privacy [1, 14]. Therefore, security and reliability issues need to be addressed to deploy a GNSS-based variable road user charging.

3.3 Technology integration
In the proposed variable road user charging system, the measure of user charges is based on exact distance travel on a chargeable road/area, time of travel, road class, geographic area (urban or semi urban), traffic density (congestion level), vehicle class, pollutant emission and vehicle occupancy. A range of equipment need to be tightly integrated in the proposed dynamic road user charging system; the equipment are: vehicle positioning systems (e.g., GPS), vehicle emission monitoring unit, a microphone to measure noise, air bag sensors to measure vehicle occupancy etc. Moreover, the road user charges also incorporate other information from various sources (e.g., real time traffic density (congestion level) on road where vehicle is travelling) to calculate the user charges. It is challenging to integrate different equipment to on-board unit and use a range of real-time information (e.g., road segment level traffic density) obtained from other sources.

3.4 Scalability and cost
To introduce or deploy the proposed GNSS-based dynamic RUC, based on integrating different equipment and sensors to on-board unit, might be costly. Moreover, in order to deploy this system at national or regional level (a metro city), it might be difficult to practically introduce such system at large scale and also replace the existing road user charging systems. However, the growth of intelligent vehicles and built in navigation and positioning systems on vehicles may support the proposed GNSS-based dynamic road user charging.
4. ADDRESSING ACCEPTABILITY ISSUES

In order to scope potential acceptability issues of the proposed GNSS-based fully dynamic RUC system, a pilot focus group was conducted with experts in transportation, policy and social scientists. Seven experts participated in the focus group. The focus group lasted approximately 60 minutes. Participants were provided with a brief description of existing RUC systems and a detailed explanation of the proposed GNSS-based dynamic RUC system architecture. Further, various potential issues with the proposed RUC system were flagged. The participants were then asked to discuss the topic, around key themes. The key points noted in this focus group are:

• Participants agreed with the issues we have identified in this paper and it was mentioned that before deploying such system these issues would need to be adequately addressed.
• The revenue that comes from such RUC should be allocated to public transport (PT) development and be used to make the PT cheaper. This may lead to mode change and further influence the carbon footprint.
• In the proposed system, all users will be tracked throughout their journeys; user privacy issues were main concerns; participants were concerned that the public might not accept the system if users are fully tracked. If such full tracking of users was necessary to operate the system, there should be high-level safeguards to protect user privacy. It was suspected that there will be challenging issues of information storage, data processing and transaction processing.
• It was agreed that this type of high-tech system might be acceptable in high charging zones, where static RUC is already in implementation (e.g., London congestion charging). However, participants felt that deploying this type of system at national level would be socially regressive, benefiting the rich more than the people less well off; if it had the effect of discouraging car use amongst the lowest income groups, it could exacerbate social exclusion.

5. DISCUSSION AND CONCLUSION

National-level RUC ideally needs to replace most, if not all, other forms of indirect vehicle taxation, to avoid some segments of society effectively paying twice, and to address the types of issues the public finds unpalatable if it RUC is perceived as additional taxation. For example, in the UK this would mean reducing the level of fuel duty, and changing or abolishing annual vehicle excise duty. The system proposed here also does not consider ability to pay, as that is a social issue that is generally outside the scope of transport network management. However, there is already a wealth of evidence that access to annual vehicle excise duty. The system proposed here also does not consider ability to pay, as that is a social issue that is currently proposed [18]. The political difficulty of such a move provides a good justification for undertaking more detailed research to understand public sentiments regarding the basis for full pricing of mobility.

6. REFERENCES