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Integrated GNSS/DR/road segment information system for variable road user charging

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ABSTRACT

Road User Charging (RUC) is designed to reduce congestion and collect revenue for the maintenance of transportation infrastructure. In order to determine the charges, it is important that appropriate Road User Charging Indicators (RUCI) are defined. This paper focusses on Variable Road User Charging (VRUC) as the more dynamic and flexible compared to Fixed Road User Charging (FRUC), and thus is a better reflection of the utility of the road space. The main issues associated with VRUC are the definition of appropriate charging indicators and their measurement. This paper addresses the former by proposing a number of new charging indicators, considering the equalization of the charges and marginal social cost imposed on others. The measurement of the indicators is addressed by a novel data fusion algorithm for the determination of the vehicle state based on the integration of Global Navigation Satellite Systems (GNSS) with Dead Reckoning (DR) and road segment information. Statistical analyses are presented in terms of the Required Navigation Performance (RNP) parameters of accuracy, integrity, continuity and availability, based on simulation and field tests. It is shown that the proposed fusion model is superior to positioning with GPS only, and GPS plus GLONASS, in terms of all the RNP parameters with a significant improvement in availability.

1. Introduction

Severe road congestion resulting from rapid urbanization, motorization and poor urban planning has many social, economic, and environmental consequences (Boquet, 2011; Hu et al., 2015, 2016a,b). While there are multiple means to address urban congestion at strategic, tactical and operational levels, Road User Charging (RUC) has been widely recognized as an effective way to alleviate congestion and raise revenue (Newbery, 1988b). RUC can be categorized as Fixed Road User Charging (FRUC) and Variable Road User Charging (VRUC). FRUC charges each vehicle for using specific road segments or subnetworks regardless of the time spent in the charging zone and/or the travel activities; examples include tolled highways or bridges, and the Congestion Charging Zone (CCZ) in London (Ison and Rye, 2005; Richardson and Bae, 2008; De Palma and Lindsey, 2011). VRUC, on the other hand, considers the specific road usage and related environmental and social impacts (Ochieng et al., 2010). Typical variable charges include distance-based road charging schemes for Heavy Goods Vehicles (HGV) (Cottingham et al., 2007; De Palma and Lindsey, 2011).

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For RUC to better reflect the utility of road space and its impact on the environment and society, Ochieng et al. (2008, 2010) proposed the concept of Variable Road User Charging Indicators (VRUCI). These indicators should be measurable with the required levels of accuracy and integrity in order not to result in incorrect charging (e.g. overcharging and under-charging), missed detection and false detection.

Currently, advanced technologies including networks of sensors and communication devices are widely applied in Intelligent Transportation Systems (ITS). These technologies including GNSS based positioning systems can be applied to meet the positioning and timing requirements of the location based indicators for RUC (Velaga and Pangbourne, 2014; Toledo-Moreo et al., 2010). In GNSS based RUC systems, the vehicle state (Positioning, Velocity and Time – PVT) or location determination function forms the basis for charging. In particular, the 4D positioning accuracy is a critical factor for identifying a vehicle's physical position (Zabic, 2009). This is because the positioning ambiguity arising from height inaccuracy could lead to incorrect physical location of a vehicle, especially for the vehicle on or beneath the viaduct. The quality of the state determination can be assessed based on the RNP parameters of accuracy, integrity, continuity and availability (Feng and Ochieng, 2007; Salós et al., 2010; Velaga and Sathiaseelan, 2011).

Research carried out by Transport for London (TfL) showed that only 58% of all the positioning data collected from GPS were adequate for RUC (TfL, 2006), significantly below the requirement. However, the exploitation of new GPS signals and the addition of the Russian Global Orbit Navigation Satellite System (GLONASS) and in future the European Galileo and China's BeiDou systems have the potential to improve performance through improved satellite coverage, visibility and redundancy for the positioning (GINA, 2010). However, as evident from extensive field tests by Zabic (2011) in Copenhagen, Denmark, the improvements from new signals and multiple constellations are unlikely to meet the requirements for RUC particularly in built environments. In such environments GNSS signal errors, weak geometry, road map errors and map-matching process errors have the potential to lead to vehicles being assigned to the wrong road segments with the consequences of incorrect charging (Velaga et al., 2012; Quddus et al., 2007; Toledo-Moreo et al., 2010).

In order to address the issues of Variable Road User Charging Indicators (VRUCI) and inadequate vehicle state estimation performance, this paper proposes a new definition of VRUCI and an integrated Particle Filter (PF) based GPS/GLONASS/DR/road segment information data fusion algorithm for VRUC.

2. Variable Road User Charging Indicators

The RUC indicators should capture all aspects of the utility of road space. Furthermore, they should as far as possible be independent and measurable. Using these criteria, Ochieng et al. (2010) identified the nine indicators listed in Table 1.

The geographic area and road class data are required to capture the spatial variations in the utility of road space. The real time travel information including travel distance, time of trip and duration of trip account for the temporal aspects of the use of road space. The traffic density data are needed to charge vehicles according to real network conditions (i.e. free flow or congested). The pollutant emissions are required to capture the impact of emissions on the environment and health. The effect of noise pollution should be included in addition to exhaust emissions. Furthermore, the indicator 'driver behavior' cannot be measured directly as it is affected by many factors, such as speed, acceleration, braking, gear changes, clutch pedal press. And these factors can be detected and measured related to the state of the car (Rendon-Velez et al., 2011). In practice, therefore, the factors that influence driver behavior should be measured separately. Furthermore, as the VRUC should be related to the amount of road use at the vehicle and traveler levels, vehicle occupancy should be included as an indicator. Therefore, Table 2 presents an improved list of indicators.

Besides the requirement for the indicators to be measurable, correlation should be accounted for in order to ensure independence. Therefore, two or more correlated variables can be combined into one factor in order to create an improved set of uncorrelated indicators. The approach based on the consideration of marginal social cost (Newbery, 1990) is used here to select independent indicators. According to Newbery (1990), there are four types of costs when a vehicle is traveling: road damage, congestion, accident externalities and environmental pollution. Therefore, the best charging scheme is where the charges equate to the marginal social cost each driver imposes on others. Based on this assumption, a charging scheme should be considered to be justified if the indicators influence these four costs.

Table 1
Variable Road User Charging Indicators (VRUCI).

VRUCI
Geographic area
Road class
Distance traveled
Pollutant emissions
Vehicle occupancy
Driver behavior
Time of trip
Duration of trip
Traffic density