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A novel peer-to-peer congestion pricing marketplace enabled by vehicle-automation

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ABSTRACT

This paper proposes a novel concept of congestion pricing based on voluntary peer-to-peer exchange of money between motorists in exchange for one ceding priority to another in a traffic stream. While in the classical congestion charging paradigm payments are compulsory and flow only towards the system operator, in the proposed marketplace participation is voluntary and motorists directly compensate each other. A particular motorist may find that he/she is a 'payer' at certain points in a given journey and a 'payee' at others.

Humans would not be expected to successfully seek, negotiate and execute a continuous series of peer-to-peer trades involving micro-payments while also handling the cognitively-demanding task of driving; real-world implementation will therefore require vehicles operating under fully-automated control in both the longitudinal and lateral dimensions during the time periods that they seek and engage in trades. The automated vehicle control algorithms must be sufficiently intelligent and adaptable to enable alternative maneuvers on short timescales, given the inherent uncertainty of whether or not a potential trade will in fact be executed. The peer-to-peer trading would be executed algorithmically, subject to strategic-level guidance given by a vehicle's occupant(s) regarding the occupant's relative valuation of money and priority in the traffic stream.

In this paper we detail the prospective marketplace and present a simple simulation model to expose its properties. We show that the proposed peer-to-peer marketplace could lead to both desirable and undesirable outcomes; which of these would be predominant is a matter requiring empirical study. The paper concludes with a discussion of further research needs to refine and develop these concepts into practice.

1. Introduction

The notion of charging motorists to occupy space on congested road networks has been a longstanding part of mainstream transportation research (Pigou, 1920; Walters, 1961; Vickrey, 1963; Johnson, 1964). Congestion charging on a road network is typically designed to be implemented by the responsible public-sector entity. Except for special cases where parallel 'charged' and 'free' lanes exist, in which the charge is set dynamically in response to real-time network conditions, congestion pricing as typically implemented on road network is a relatively blunt instrument for managing demand, for a variety of reasons. In many cases the price charged does not vary in real-time with demand, despite the fact that congestion does.

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The London (United Kingdom) congestion charge, for instance, is a fixed price during the time that charging is in operation, regardless of network conditions. Price discrimination between different travelers is also relatively uncommon in practice; variation in individual people's willingness-to-pay for priority through particular network paths at particular times is therefore not accommodated.

In this paper, we propose a novel form of congestion pricing based on a peer-to-peer marketplace that enables voluntary trading between adjacent vehicles of their relative position in a traffic stream in exchange for micro-payments. Such a system builds on earlier research into network governance strategies under high levels of vehicle automation. To the authors' knowledge, prior literature has not addressed peer-to-peer traffic-control mechanisms that can operate in the absence of intermediation via the road network manager.

The properties of the proposed peer-to-peer marketplace are exposed via a simple simulation analysis. The prospective system has both desirable and undesirable properties; undesirable properties arise due to the benefits of each trade accruing to the vehicles that are willing participants in the trade whereas some of the costs it imposes accrue to vehicles which are downstream of (i.e. behind) the vehicles participating in the trade and who do not choose whether or not to bear such costs. This paper presents a necessarily stylized and straightforward analysis of the issues raised by the prospective marketplace; a broader program of research will be required to better understand its likely operations and consequences.

The prospective marketplace requires that vehicles engaged in seeking and executing trades must be operating under automated control (i.e. not under real-time control by a human 'driver') in both the longitudinal and lateral dimensions. In the taxonomy developed by the US' National Highway Traffic Safety Administration (NHTSA, 2013), this is classified as 'Level 2' automation.[1] The system does not require vehicles that operate exclusively under automated control for an entire journey ('Level 4' automation), because a vehicle that transitions from automated-control to human-control would simply stop transmitting (and responding to) offers from leading and following vehicles.

The remainder of this paper is structured as follows: Section 2 presents background on congestion pricing instruments. Section 3 describes the simulation methods used in the quantitative analysis, the results of which are presented in Section 4. Section 5 concludes the paper with a brief summary and discussion of future research needs.

2. Background

Congestion pricing on road networks has traditionally been conceived of as a mechanism by which the system operator charges each motorist a fee, which must vary across time in some way to distinguish it from a classical road toll. In exchange for their payment the motorist is granted access to travel where and when the charging is operable (Pigou, 1920; Walters, 1961; Vickrey, 1963; Johnson, 1964; Teodorovic and Edara, 2007; Brownstone and Small, 2005; Gomez-Ibanez, 1992; Graham et al., 2008). Systems typically involve either charging motorists to travel on a specific linear corridor (e.g. the State Route 91 tolled lanes in Orange County, CA, cf. (Brownstone and Small, 2005) or a geographic area encompassed by a defined cordon line (e.g. the scheme in Central London, UK, cf. [TfL, 2014]). Price may vary temporally according to a pre-defined schedule, or may vary dynamically in response to real-time network conditions.

When a road network manager introduces classical congestion pricing, not all travelers will be made better off though the aim is that on balance there will be a net increase in welfare. A common strategy is for the entity that collects the revenues to agree to dedicate some or all of the net revenue in ways that compensate groups that are not directly made better-off through the implementation of pricing (King et al., 2007).

Credit-based congestion pricing, a relatively sophisticated form of congestion pricing, merits highlighting in this discussion. As proposed by Kockelman and Kalamanje (2005), such a system would involve a central system administrator allocating each driver with monthly driving credits that they then 'spend' on driving (with the 'costs' of driving being time- and link-specific). If they do not exhaust their allocation of credits, they can either carry them over to future periods or sell them to drivers that wish to purchase additional credits. The credits proposed by Kockelman/Kalmanje are a commodity product (i.e. not spatio-temporally heterogeneous); they are fungible in the sense that they can be 'spent' by driving on any link in the road network (albeit at variable rates).

Congestion pricing is one way of allocating priority through a traffic network to specific vehicles (those that have paid the charge), though in practice other mechanisms are more widely used to provide differential degrees of network priority. Police and other emergency vehicles use sirens and flashing lights to direct that other motorists cede priority (NB: Systems to draw on vehicle-to-vehicle communications to assist with path-clearing for emergency vehicles have been proposed, cf. [Jordan et al., 2013]). The use of sirens and lights is not in all cases limited to emergency situations; the motorcade of a government minister may, for instance, legally use sirens and lights to direct other motorists to give way. Vehicle design can also facilitate priority; motorcycles' narrow width enables them, in certain circumstances, to maneuver past standing queues of four-wheel traffic (Lee and Polak, 2012). Physical design is also used to give network priority to certain vehicle types; bus and bicycle lanes are common examples. Tolled road corridors frequently allow vehicle equipped with an electronic tag to bypass toll plazas at which cash-paying motorists must stop. Another example of network priority is the dedication of specific lanes

[1] We note that NHTSA uses the example of "*adaptive cruise control in combination with lane centering*" (NHTSA, 2013, page 5) to describe 'Level 2' automation. The prospective peer-to-peer marketplace presented in this paper would, however, require lateral control that is different than traditional 'lane centering', because the trading vehicles would each be required to occupy the margins (rather than the center) of a lane.