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Exploring the role of spatial cognition in predicting urban traffic flow through agent-based modelling

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ABSTRACT

Urban systems are highly complex and non-linear in nature, defined by the behaviours and interactions of many individuals. Building on a wealth of new data and advanced simulation methods, conventional research into urban systems seeks to embrace this complexity, measuring and modelling cities with increasingly greater detail and reliability. The practice of transportation modelling, despite recent developments, lags behind these advances. This paper addresses the implications resulting from variations in model design, with a focus on the behaviour and cognition of drivers, demonstrating how different models of choice and experience significantly influence the distribution of traffic. It is demonstrated how conventional models of urban traffic have not fully incorporated many of the important findings from the cognitive science domain, instead often describing actions in terms of individual optimisation. We introduce exploratory agent-based modelling that incorporates representations of behaviour from a more cognitively rich perspective. Specifically, through these simulations, we identify how spatial cognition in respect to route selection and the inclusion of heterogeneity in spatial knowledge significantly impact the spatial extent and volume of traffic flow within a real-world setting. These initial results indicate that individual-level models of spatial cognition can potentially play an important role in predicting urban traffic flow, and that greater heed should be paid to these approaches going forward. The findings from this work hold important lessons in the development of models of transport systems and hold potential implications for policy.

1. Introduction

Cities are archetypal complex systems, combining dense mixtures of infrastructure, people and systems that together are capable of increasing productivity, reducing environmental impact and improving the health of its inhabitants (Glaeser, 2011). Understanding cities, and helping them to operate to their most efficient capabilities, represents one of the most pressing challenges of the 21st Century. While the emerging availability of new, rich datasets enable the improved explanation of cities, it can be argued that there remains a fundamental shortage in our ability to predict the future of cities. This situation is no truer than in transportation modelling (Cascetta et al., 2015). Many transportation modelling methods were born in a ‘data poor’ era, where detail around the heterogeneity and diversity of behaviour was unavailable. These models served cities well for some time, but continuing inefficiencies and the persistence of poorly planned infrastructure indicates that improvements are possible (Flyvbjerg et al., 2005; Bartholomew, 2007).

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Any modelling of cities – be it relating to transportation, housing, the economy, or crime – should build from a deep appreciation of their complexities. Urban systems are a product of the behaviour and interactions of many – sometimes millions – of autonomous individuals. Understanding how these actions coalesce and influence the formation of complex dynamic patterns is therefore vital in sustaining the prosperity of the urban centre. Recent years have seen a growing utilisation of practices and models relating to complexity theory in the explanation of urban systems. In employing this approach, it has been demonstrated how urban systems – rather than defining system behaviour through their physical structure alone – are in fact *defined by* the behaviour of their constituent entities (Batty, 2007). The whole system, in this sense, is 'greater than the sum of the parts' (Von Bertalanffy, 1972), and thus to understand a system one should endeavour to understand its individual components. Yet further than merely a static representation of a system, one should equally seek to identify how a system changes state. In this one must seek to identify how individuals interact with each other and with their wider environment in dynamics of both local and global scale. In many cases the origins of these patterns may be not clear and may demonstrate non-linearity in evolution. It is these dynamics that influence how we view and experience the system in space and time; these are the by-products of the existing organisation of and interaction between individuals.

Urban road traffic networks are a very strong example of this type of highly dynamic, non-linear and complex system. The process by which the system changes state in this way is strongly influenced by the actions of the individual and of the collective. The behaviours of travellers, and their fluctuation as a collective drives the evolution of congestion effects. Congestion is not simply a product of network engineering and hyper-demand, but is driven fundamentally by facets of human behaviour. The emergence of a *Science of Cities* (Batty, 2013), accompanied by new, rich sources of data and improved simulation methods opens up new opportunities for understanding the inherent complexity of traffic congestion. Today we are granted, more than ever before, significant potential to re-examine conventional assumptions around the fundamental bases of these systems.

This paper will argue the case that transportation modelling should better incorporate the facets of human cognition that contribute to the inherent complexity of transportation dynamics. In particular, we focus on behavioural elements of driver route selection and bounded knowledge of space, modelling these behaviours at the individual traveller level. Whereas, in recent years, there has been considerable advancement with respect to the context within which travel takes place (Arentze et al., 2000; Bowman and Ben-Akiva, 2001; Miller et al., 2005), the incorporation of elements of cognition and complex decision-making has been less well served. This shortfall is well highlighted by Portugali in *Complexity, Cognition and the City* (Portugali, 2011), where it is claimed that advances in cognition science have been 'ignored' within the wider domain of urban complexity theory, and that existing applications of these approaches remain insufficient (p. 103–104). There is a strong opportunity for developments in cognitive science to help to more comprehensively describe individual travel behaviour, and subsequently allow us to better model and explain the dynamics of the wider transport system.

This work will aim to address one further outstanding issue around whether more descriptive models of cognition are truly necessary in explaining complex systems. In opposing that described above, it could be argued that while cognitive models may appear more realistic in principle, the added value they offer to prediction system behaviour is negligible. This may be deemed particularly true within the context of urban traffic systems, where trip distributions are broadly constant and strict movement control mechanisms are in place. In this context, it may be argued that the interpretation of behaviour is less important than the engineering of the system itself. Through a series of simple, exploratory agent-based simulations, the paper seeks to address the verity of this argument.

In achieving these aims, we will first seek to identify the gap between representations of behaviour within conventional urban traffic models and research findings from within the cognitive science domain. The findings from this review are then incorporated into a simple agent-based model environment, with the aim of addressing the relatively influence that behavioural definition has on predicting traffic flows. The paper will conclude in addressing the most important findings from this study, highlighting some the wider lessons learnt through this work and identifying areas for further investigation.

2. Models of route choice in urban transportation

For over fifty years, the interpretation and representation of route choice and urban navigation has been an important research area in disciplines of both transportation modelling and cognitive science. Yet, as the literature reflects, there is a significant difference between the approaches taken by the respective disciplines in exploring this shared objective.

Transportation modelling, in respect to the movement of traffic on an urban road network, continues to be heavily influenced by the 'first principle of traffic equilibrium' laid out by Wardrop in 1952 (Wardrop, 1952). This principle states that on a road network loaded with traffic no single vehicle may improve their journey time through unilateral action. Underlying this principle, it is assumed that each driver has considered all of their route options, with a complete knowledge of the road network structure and prevailing flow conditions, and have subsequently selected their path of least journey time. This approach found favour, and has seen a range of approaches developed that conform to the general principle of user equilibrium. More advanced incarnations of this approach incorporate dynamic elements to traffic flow distribution (Merchant and Nemhauser, 1978), varying, stochastic distributions of perceived journey times (Bell, 1995), or flexible 'indifference' to journey times (Mahmassani and Chang, 1987), but rely on the same assumptions around a system-level traffic organisation. Importantly, with respect to transportation policy, equilibrium models are widely used, and are implemented within the most popular commercial tools for traffic flow simulation.

Simple intuition presents some notable challenges to the equilibrium paradigm. Equilibrium models make simplistic assumptions about the basis of individual route choice, assuming pure rationality in preference for the quickest path with little or no consideration for alternative route characteristics. They do not consider the influence of partial route knowledge, and how individuals may be