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A framework for simulating large-scale complex urban traffic dynamics through hybrid agent-based modelling

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ABSTRACT

Urban road traffic dynamics are the product of the behaviours and interactions of thousands, often millions of individuals. Traditionally, models of these phenomena have incorporated simplistic representations of individual behaviour, ensuring the maximisation of simulation scale under given computational constraints. Yet, by simplifying representations of behaviour, the overall predictive capability of the model inevitably reduces. In this work a hybrid agent-based modelling framework is introduced that aims to balance the demands of behavioural realism and computational capacity, integrating a descriptive representation of driver behaviour with a simplified, collective model of traffic flow. The hybridisation of these approaches within an agent-based modelling framework yields a representation of urban traffic flow that is driven by individual behaviour, yet, in reducing the computational intensity of simulated physical interaction, enables the scalable expansion to large numbers of agents. A real-world proof-of-concept case study is presented, demonstrating the application of this approach, and showing the gains in computational efficiency made in utilising this approach against traditional agent-based approaches. The paper concludes in addressing how this model might be extended, and exploring the role hybrid agent-based modelling approaches may hold in the simulation of other complex urban phenomena.

1. Introduction

It may be said that urban systems are a function of the behaviour of its citizens. Whether one is concerned with short-term or long-term dynamics, the actions and interactions of thousands, possibly millions of individuals shape the way in which urban systems change and evolve. Through the decisions and activities of its citizens a city's complex dynamic structure is defined, transformed and disintegrated. While institutional interventions can play a role in constraining and influencing behaviours, urban systems – in terms of transportation, migration, economics, and a swathe of other phenomena – remain strongly influenced by the actions of the collective. Therefore, understanding this link between the microscopic behaviour of individuals and complex macroscopic patterns in the city is central to predicting how urban systems may shift and respond to new events and influences.

Attempts to understand and predict urban transportation dynamics have been on-going for some considerable time, with a great deal of research and development being carried out within the field of traffic simulation. However, representations of driver behaviour have generally followed a consistent path. The vast majority of conventional traffic simulation tools – be them microscopic, macroscopic or agent-based in focus – replicate the principles of equilibrium in traffic distribution as described by Wardrop (1952). According to this principle, individuals will always seek to reduce their journey time, until no vehicle may reduce their own journey time unilaterally. This principle carries an underlying assumption that all individuals maintain a complete knowledge of the road network, and knowledge of the prevailing traffic conditions upon it. It furthermore assumes that the minimal journey time route will always be selected by the individual regardless of alternative preferences or an inability to do so. This approach enables the distribution of traffic to be managed from a macroscopic perspective, assigning traffic according to an optimisation of journey times and calculating traffic flows according to the level of traffic saturation of each link. As a result this approach is mathematically tractable and computationally efficient, meaning it can be extended to a wide spatial area and large number of individuals. The approach remains popular and is widely used by city planners

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in the prediction of traffic flows across cities worldwide (Aimsun, 2012; PTV, 2012).

Yet the aforementioned underlying assumptions proffered by these models do not fall in line with conventional thinking from the fields of spatial cognition and psychology in respect to human navigation in urban areas. Rather, it has been demonstrated that individuals rarely do take a least journey time path from origin to destination, as their ability to identify such a path is limited (Golledge, 1995; Wiener, Schnee, & Mallot, 2004; Zhu & Levinson, 2010), and are highly unlikely to maintain a comprehensive knowledge of the road network structure, instead being bounded by an individual's prior experiences and their ability to remember the world around them (McNamara, Hardy, & Hirtle, 1989). It is evident, therefore, that in order to more completely and correctly predict the evolution of the traffic system, particularly in respect to the formation of congestion, one must better represent the true nature of driver behaviour on the road network.

With respect to this challenge, agent-based modelling (ABM) represents a highly promising platform for the representation of macroscopic phenomena as a product of individual behaviour. By modelling individually the most significant influencing elements of a system, ABM enables one to examine how the behaviours of individual entities impact in influencing global patterns, moving beyond any impositions of an assumed equilibrium state. Furthermore, in enabling the representation of a population of agents, one can explore how inter-population heterogeneity can shape global dynamics. This discretisation of the modelled scenario allows the richer representation of the behaviours impacting within a given scenario, and thus enables potentially a more detailed examination of system-level outcomes. This approach has been used in the prediction of wide number of urban phenomena, notably land-use dynamics (Bretagnolle & Pumain, 2010), housing (Schelling, 1978), crowd movements (Torrens, 2012) and crime patterns (Malleson, See, Evans, & Heppenstall, 2012). In each of these examples, macroscopic patterns emerge through the interactions of many autonomous constituent individuals. Within the context outlined in this work, agent-based modelling represents a potential route forward in the simulation of global traffic dynamics as a product of the behaviour of multiple individual drivers.

Yet there exists an important challenge that must be considered in the development of any agent-based simulation. This is the challenge of managing limited computational resources. Increased model complexity, with increased numbers of agents can potentially lead to significantly rising memory usage and subsequent processing speeds. In many cases, particularly where large-scale models are required, or results required at a near real-time basis, such performance levels may be prohibitive (Castle & Crooks, 2006). This challenge is particularly pertinent where considering the prediction of traffic flows within the urban realm. In these cases, the agents are complex, they are cognitive in their actions, and within the agent population there will be a large degree of heterogeneity in individual preference, knowledge and behaviour. Such representations will also require the simulation of thousands, possibly millions of cognitive individuals across a large spatial scale. Equally, a simulation must capture the role of physical actions and interactions between agents on the roadway, as it is at this level where frictions occur and congestion ultimately begins. Therefore, in coping with this level of complexity, one must carefully consider the deployment of computational resources, specifically the relative importance of simulating in fine detail (or otherwise) each aspect of the simulated scenario. Traditionally, modellers have been left with the decision of modelling many individuals in little detail or few individuals with high levels of detail.

This paper presents a framework for an agent-based model of urban traffic flow that maintains a high degree of behavioural complexity, across a wide spatial scale, whilst remaining computationally efficient. To achieve this agents are granted advanced cognitive abilities, but are constrained in their movement behaviours by a macroscopic model of traffic flow. In incorporating the important capabilities of agent-based modelling in more fully representing the behaviour of a population of individuals, this work aims to move beyond existing traffic simulation models that model behaviour in a simplistic fashion.

The paper is presented as follows. In the next chapter, an exploration of the relevant literature that has informed the development of this framework – both in terms of driver behaviour and roadway dynamics – is laid out. Following this, the modelling framework is presented in depth, detailing how both the behavioural and physical models are implemented, before outlining how these models are integrated. Following this a real-world case study is presented, describing an application of the frameworks outlined here, with the computational performance of the model assessed against a traditional agent-based modelling approach. The paper concludes in highlighting the ways in which this approach may hold wider significance for existing agent-based modelling research, particularly research into complex urban systems, and identify ways in which this framework may be developed in the future.

2. Literature review

As described above, much of the conventional thinking surrounding the simulation of urban traffic flow follows clear principles of how a traffic system arranges itself. Agent-based modelling potentially offers a way forward in the more accurate representation of the behaviours that contribute to the evolution of such systems. The following review first highlights recent developments with respect to conventional transportation modelling, before addressing the application of agent-based modelling towards transportation simulation, and specifically the relative benefits it offers toward this domain.

2.1. Conventional road transportation simulation

Conventional simulations of traffic flow have traditionally consisted of two core models of driver behaviour – one describing inter-vehicular dynamics on the roadway, the other describing the distribution and route selection of vehicles across the entire network. The nature of traffic simulation is usually defined in terms of how the former of these two processes is represented – broadly, from either a microscopic or macroscopic perspective – with the latter process following principles common to both approaches.

The microscopic representation of traffic flow describes vehicles on an individual level, modelling movements and speeds on the roadway and interactions with other vehicles in a broadly realistic fashion. These models are able to effectively replicate common roadway phenomena such as traffic jam waves (Helbing, Hennecke, Shvetsov, & Treiber, 2003) and junction-level congestion. While conceptually similar to agent-based simulation, these models represent individuals in a broadly homogenous fashion, with behavioural heterogeneity introduced only through stochastic variation. Alternatively, macroscopic traffic models do not seek to replicate the movement of the individual vehicle but rather the collective movement of traffic flow across the road network. In order to achieve this, equations simulating the collective impact of inter-vehicular friction and interaction are implemented, varying in their scale and complexity. These models, derived from physics-based models of inter-molecular dynamics, are capable, in their most advanced form, of replicating physical phenomena and behaviours observable in real traffic systems (Daganzo, 1993; Helbing et al., 2003). Macroscopic models generally enable,