Simulating Complex Traffic Intersection Dynamics using an Agent-Based Modelling Framework on the NetLogo Platform

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1. ABSTRACT

This paper proposes a simple agent-based model for traffic intersection dynamics in urban Bangalore, India. Traffic flow dynamics have been studied through the employment of several toolkits such as fluid and nonlinear dynamics, network theory, computer and information science etc. However, the study of phenomena such as congestion necessitates the recognition that each of the agents involved are heterogenous and that collectively their individual behaviours lead to systemic outcomes at the macro level. Agent-Based Models (ABMs) are particularly well equipped to handle inquiries into problems of this nature. Although the model proposed here is specific to a certain intersection, it can be extrapolated to similar settings fairly easily. The presence of jaywalkers in the model is shown to have an adverse effect on the number of vehicles waiting at the intersection.

Keywords: agent-based modelling; netlogo; traffic dynamics; dynamical systems

1.1. INTRODUCTION

The presence of free flowing traffic within networks characterised with high degrees of complexity are essential for an efficient functioning of modern society (Zhao et al., 2005). This idea of free flowing traffic are not however constrained solely to road networks, but are sought in several network settings such as internet traffic, power grid networks etc. Several studies have explored the emergence of congestion in complex networks as being related to the topology of the networks, information parameters, network constraints, critical thresholds within the system, etcetera. The interest of this paper is in the simulation of a complex traffic intersection with a focus on the heterogeneity of individual agents within the network. The Agent-Based Modelling (ABM) framework allows for a decomposition of systems to a collection of the agents or classes of agents that populate or characterise them (Crooks, 2012). The ABM framework is particularly equipped to deal with large scale individual heterogeneity and associated emergent phenomena in complex systems and thus will be employed for the purposes of this simulation. In the realm of economics, traffic congestions are known to be quite a typical example of a coordination problem among multiple agents within the system (Tumer et al., 2009, Gartner et al., 1975, Kuyer et al., 2008). However, the ABM framework allows for us to investigate this coordination problem when the multi-agent system is characterised by individual agent/group heterogeneity rather than blanket assumptions.

The Koramangala 80 feet or Sony Signal intersection is put under investigation for the purpose of this study, which resides within the urban part of Bangalore, India. The city of Bangalore is well known for its severe traffic congestion problems that characterise most all intersections and junctions in the urban regions of the city. Cumulative road lengths in Bangalore amount to about 10,000 km, for which the number of registered vehicles currently approaches 8 million. This is a severe cause for concern not only for traffic flows but also for health hazard risks by way of noise pollution as well as dangerous particulate matter levels (Nagendra, 2007). Open data provided by the Bangalore Transport Information System (BTIS) shows that the spatial grid within which the Sony Signal is in very rarely sees traffic movement in excess of 30 to 40 km/h owing to high levels of congestion. Additionally, the signal is characterised by the routine takings of non-permissible U-turns, two-wheeler traffic on the footpaths, as well as frequent jaywalking, thus providing us with a complex systemic set up to work with.

1.2. AIMS AND QUESTIONS

The questions this paper seeks to explore are in relation to the simulation of traffic flows in a complex intersection network in urban Bangalore, India. While there exist several models on the mitigation of congestion via novel traffic signalling mechanisms and algorithms (Cetin et al., 2003, Srivastava and Sudarshan, 2013, Hassan, 2015), this paper will aim to investigate if mitigation to congestion is possible by some alterations to the individual components of the system. With that being said, an attempt at a wholly exhaustive representation of the intersection network is not within the scope of this paper. Section 3 of the paper will look at the methods employed in constructing the simulation environment as well as its individual components. In Section 4 the assumptions of the model will be stated explicitly as well as the simulations agents, globals, and other entities, stated within an adaptation of the ODD (Overview, Design Concepts, and Details) framework in Section V5(Grimm et al., 2006). Section 6 presents the results of the simulation along with some variations to the parameters and state or global variables of the system. The final section will conclude with some of the key results and then discuss the possible extensions to the model proposed within this paper.

1.3. METHODS

Noble (1985) notes that, much like any other metropolis, Bangalore has fairly consistent peak and lull traffic times during the day. Within the purview of this model, we will run simulations on the intersection wherein the environment is akin to one with peak traffic hour conditions. Figure 1 provides a schematic of the Sony Signal intersection with legally permissible routes indicated by arrows.

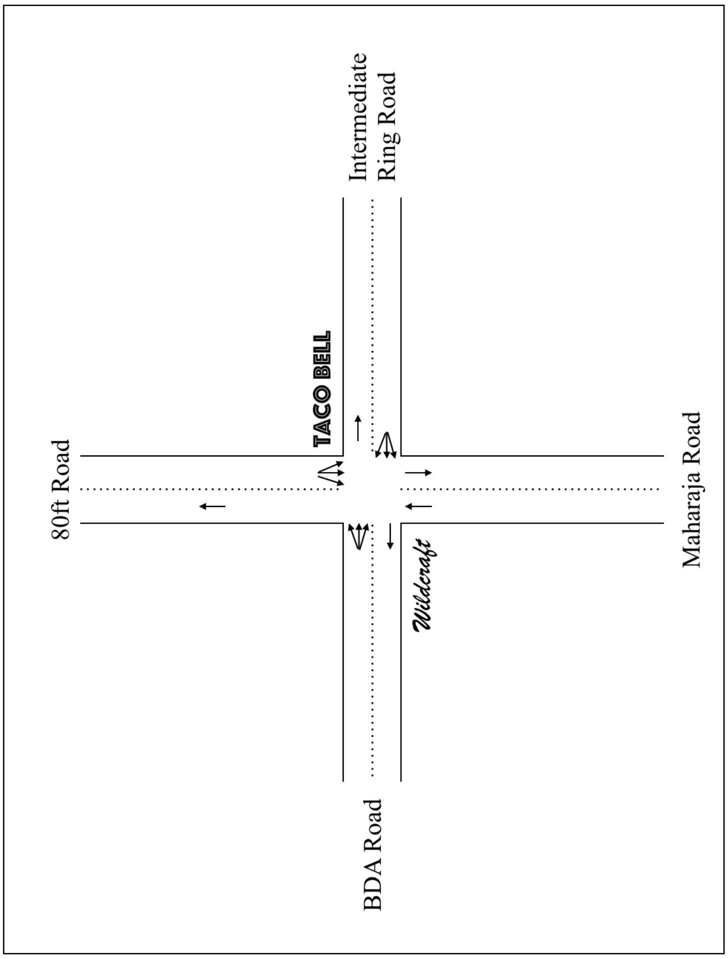

Figure 1. Koramangala 80ft Sony Signal Intersection Schematic

The four main roads are the 80 feet road, the BDA road, the Intermediate Ring road, and the Maharaja road, with the intersection at the middle. In keeping with the on road vehicle proportions, cars, two-wheelers, and auto-rickshaws rank among the higher proportions in the simulations, while buses and cycles follow respectively. However, these proportions can be changed as and when necessary. The signal works on a fixed signal time based mechanism where the signal times rotate on a cyclic basis (Open City, www.opencity.in). The simulation will be run on the *NetLogo* agent-based modelling platform, which provides an environment where we can visualise our simulations as well as collect some statistics (Wilensky, 1999). Finally, a lane utility function is established and computed after each simulation which will be used to assess the quality of flow.

1.4. AGENT-BASED MODEL PRETEXT

For the purpose of a robust approximation of the intersection system, an inclusion of all significant agents is necessary. The key agents for the simulation of a high density or congested traffic intersection are as follow:

1. **Four and Three-Wheelers:** Includes cars, cabs, auto-rickshaws and buses. Buses can further be classified into government, school, or corporate transportation. However for the purpose of this model, buses and cars (auto-rickshaws, cabs) will fall under separate categories.

2. **Two-Wheelers:** Bikes/scooters and cycles.

3. **Pedestrians:** Jaywalkers.

The aforementioned classes of vehicular transportation and pedestrians constitute primary players in the urban roads of Bangalore, India. Further, some assumptions are necessary to base the model on, particularly regarding the behaviour of these different agents. Some of these assumptions will take on a parameterised form and can be tweaked as and when necessary. Thus, the following assumptions will be made within the purview of the model and its environment:

4. Pedestrian zebra crossing behaviour will not be included in the model as their crossing time will not alter outcomes for traffic that would be halted by the light regardless. However, this model accounts for a 'jaywalker' cohort of pedestrians, that may cross the road abruptly should the opportunity present itself. This abrupt crossing will alter traffic outcomes for those vehicles affected by the jaywalker, who may cross at any point orthogonal or tangent to a lane of flow.

5. Traffic signals, within the purview of this model, will possess two states only that indicate '*GO*' and '*STOP*' respectively. Traffic signals will work only on a fixed timing mechanism and are not be subject to change owing to the density of traffic etcetera.

6. Vehicular traffic moves primarily in lanes, with low amounts of stochasticity in individual vehicle movement. Thus, there exists a high degree of lane discipline within the simulation environment.

1.5. MODEL DESCRIPTION

A detailed description of the model is given below in an adaptation of the ODD protocol format proposed by Grimm et al (2006). The ODD format has been shortened here to Overview and Design concepts alone because an exhaustive description of this base model is not required at this stage (Grimm and Railsback, 2010). The model was based on the 'Traffic Intersection' model proposed by Wilensky (1998).

1.5.1. Overview

A. **Purpose:** The primary purpose of the model is to present a model with reasonable approximations of the dynamics of traffic in the Koramangala Sony World junction in urban Bangalore, India. The model does not present an exhaustive picture of the intersection dynamics, but provides a strong basis for which additional complexity can be built upon in further research.

B. **Entities, State Variables, and Scales:** The primary entities in the model include the different classes of vehicles, jaywalkers, the traffic signals that govern the flow of traffic, the patches that populate the environment, which may or may not be traversable, and the global environment. The state variables include the respective speeds of each vehicle, the waiting time of vehicles (ticks), their maximum acceleration and break parameters, and whether they have been in an accident or not. The global environment keeps count of the number of vehicles and their positions and headings.

C. **Process Overview and Scheduling:** First, within the *setup* procedure, the world is populated with permissible and non-permissible patches, in black and grey respectively, which set up the intersection environment. Then traffic signals are then added in, all initially in the STOP state, followed by the addition of the initial vehicles on empty patches at the edges of the models environment and pedestrians at random points on the dividers or grey land patches. The *go* process initiates the simulation, which consists of the following scheduled procedures. First, as and when patches on the edges of the world clear up, new vehicles are spawned and added to the flow. This process continues for as long as the tick counter progresses, constantly creating new vehicles as the intersection is assumed to be in peak traffic hours. As soon as vehicles are spawned into the system, their movement protocol is initiated. Vehicles check subsequent patches for space and adjust their speed and break time accordingly, while adhering to a global speed , break, and acceleration limits. Additionally, vehicles also check for accidents on subsequent patches and adjust their speed and break in a similar fashion to blocked patches. The signal mechanism starts after one hundred ticks and changes after every two hundred ticks. The vehicles, however, do not respond directly to the signal mechanism, rather, vehicles right at the front move when the signal permits and thus create a chain reaction downwards on the lane by clearing up patches.

1.5.2 Design Concepts

A. **Basic Principles:** The model was built upon a single lane traffic intersection model proposed by Wilensky (1998) on the NetLogo Modelling Commons library (Wilensky, 1999). Some key elements of Wilensky's model are preserved such as the speed adjustment and accident mechanisms as well as the direction maintenance in vehicles. The movement mechanisms are similar to car-following theories proposed in the works of Zhang's (2005) multi-vehicular traffic flow research. Additional factors included such as jaywalking have been well established in characterising already complex Indian traffic dynamics.

B. **Learning and Adaptation:** Each subsequent iteration of the model does not result in any adaptive or relatively more successful behaviour on the part of the agents. The adaptive properties of the agents in relation to themselves and their environment are mentioned in the sub-section on 'Process Overview and Scheduling'.

C. **Objectives:** A key objective that alterations to the simulation seeks to mitigate is the number of waiting vehicles within the time frame of the simulation. The adaptive behaviour of the agents is not explicitly designed as an attempt to minimise waiting, however the alterations to adaptive behaviours will try to do so, either directly or indirectly.

D. **Sensing:** Vehicular and pedestrian agents have a local sense of their physical environment, in that, they are able to ascertain primarily the number of free patches ahead of them and move accordingly. Additionally, vehicles adhere to global parameters such as the speed limit and constraints on acceleration and breaking.

E. **Interaction:** Agent to agent interactions are of a direct nature only in the event of a collision/accident. Indirect interactions are in the form of speed adjustments resulting from patch availability sensing among individuals and jaywalking tendencies among pedestrians.

1.6. SIMULATION RESULTS

The first simulation ran with standard conditions including speed limits set at a factor of 3, which was visibly the most reasonable limit in the context of the simulation time, and a maximum acceleration and break factor of 10. Additionally, jaywalking was not included in this first iteration of the model so as to introduce it as an added layer of complexity in a later iteration and to then gauge its effect on simulation outcomes. Figure 2 shows the uninitiated simulation environment on the NetLogo platform and Figure 3 provides satellite imagery of the intersection.

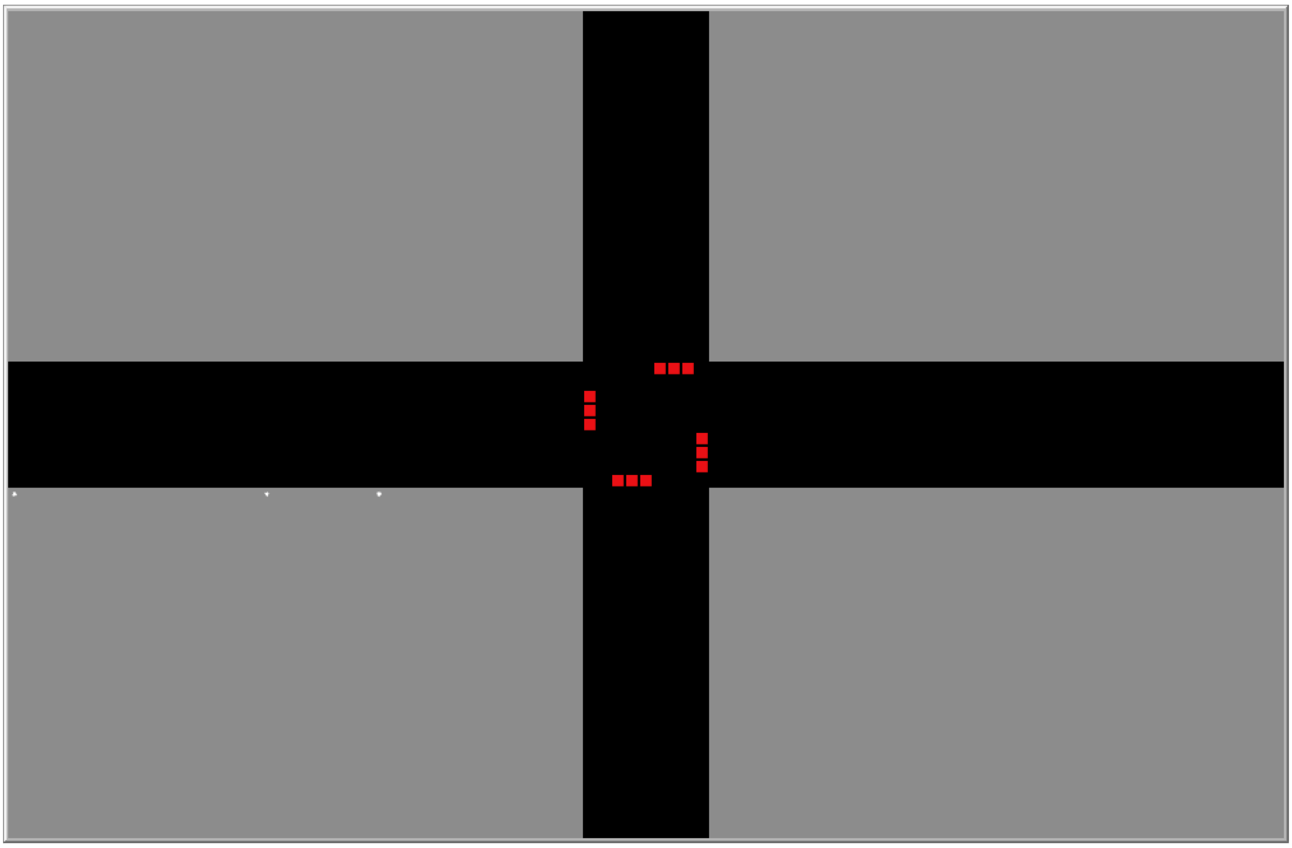

Figure 2. Initial Simulation Environment and Graphical User Interface on the NetLogo Platform (replace)

The average number of waiting vehicles for this first simulation stands at 234 ± 32 vehicles, where the total number of vehicles in the environment stood at 378, which holds for all the simulations. Increasing the speed limit to a factor of 5, the average number of waiting vehicles moves to 254 ± 47 vehicles and upon increasing the speed limit to a factor of 10, the average becomes 222 ± 36.

Figure 3. Koramangala 80 Feet Road Signal Intersection (Google Earth Engine)

Incorporating random jaywalking behaviour into the simulation, we see that lane traffic flows are visibly impeded. The mean number of waiting vehicles for the duration of the simulation stands at 253 ± 35 vehicles and flows on lanes that are empty are also affected by this behaviour, with and a maximum acceleration and break factor of 10 and a speed limit factor of 5. The aspect of pedestrian jaywalking is an important aspect to consider in this simulation as the behaviour is routine and highly tolerated. Increasing the number of jaywalkers in the system, averages for waiting time increase further to 295 ± 44 vehicles. Decreasing the speed limit to a factor of 3 and then increasing it to 10, we see that waiting vehicle averages stand at 269 ± 34 and 262 ± 46 respectively, with jaywalking present.

Simulation Settings	Jaywalking Absent	Mild Jaywalking	Heavy Jaywalking
Speed Limit set at 3 Maximum Acceleration and Brake set at 10	234 ± 32	269 ± 34	250 ± 36
Speed Limit set at 5 Maximum Acceleration and Brake set at 10	254 ± 47	253 ± 35	295 ± 44
Speed Limit set at 10 Maximum Acceleration and Brake set at 10	222 ± 36	262 ± 46	261 ± 41

Table 1. Simulation Results Summary Table

1.7. CONCLUSIONS AND FURTHER RESEARCH

The model, although a basic formulation of complex intersection dynamics, provides quite a flexible tool to then understand these dynamics. Moreover, the ODD formulation of this model makes any attempt at reproducing or modifying the simulation easier, as details and design concepts are laid out in a structured format. Added layers of complexity to the model such as the introduction of jaywalking, are shown to impede traffic flows and adversely affect systemic outcomes. This is key due to the fact that an investigation into these subtle complexities may yield a level of influence over the system that may have not been previously considered. The model, to a certain extent, follows car-following models of steady-state traffic flows (Gazis et al., 1959; Zhang et al., 2005). This theoretical framework however is one of several potential models concerned with traffic flows, which can be used as an underlying basis in simulating these flows. Models have been proposed towards an understanding of traffic flow dynamics in contexts of broadband and communications networks, fluid dynamics, micro and macroscopic environments, etcetera (Adas, 1997; Treiber et al., 2006; Helbing, 1998; Bretti, 2007).

Extensions to the model can be made by way of incorporating alternative traffic flow models atop the skeleton model proposed in this paper. Additionally, microsimulations can be added within the model to tend toward a better understanding, both of this system as well as similar systems wherein this model can be extrapolated to. For example, Gunay (1999) proposes a model for varying degrees of lane-discipline in traffic flows, which is an aspect that warrants further investigation, especially in the context of developing countries. While the zeitgeist for contemporary mathematical modelling primarily involves formulation by means of ODEs (ordinary differential equations), ABMs serve to overcome limitations such as emergence, heterogeneity, adaptation etcetera (Figueredo, 2013).

The modelling and simulation of novel complex dynamical systems has become quite the attractive endeavour of late. Traditionally, models of these systems would usually take the from of *ordinary* or *partial differential equations* (ODE's or PDE's). The use of differential equations, while very robust, are typically quite involved and hard to solve analytically. Solutions to these systems are usually obtained by way of *phase plane* diagrams or the obtaining of *fixed points* that represent equilibrium states in the system. Several systems have been modelled using differential equations such as the dynamics of population growth, dynamics of planetary motion, classical mechanics, thermodynamics etcetera. Systemic complexity is recognised in *complex systems theory* as an amalgamation of linear, non-linear, self-organising, evolving, adaptive, homogenous and heterogeneous relationships. The theory also notes that these systems are made up of several constituents or cogs that behave and interact in different ways, which give rise to phenomena at the systemic level.

Agent-Based Models serve as a powerful tool to model these complex systems, right from their individual constituents and upward. These models, at a base level, are populated with *agents* that own certain properties and which inhabit some *environment* which has some larger parameters that govern its constituents. The complexity of these models may be governed by some nuances in the system such as learning, constraints, heterogeneity, time, adaptability, etc.

DECLARATION OF INTEREST

None.

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