From chaotic road traffic to cooperative opportunistic percolation using cellular automata

Stuart J Clement[1], Michael AP Taylor[1], KV Krishna Rao[2], Tom V Mathew[2], Pradip J Gundaliya[2],
[1] University of South Australia, Adelaide, SA, Australia
[2] Indian Institute of Technology, Bombay, India

1 Introduction

There have been few attempts to describe traffic behaviour in highly-congested urban road environments characterised by a wide range of vehicular types. Such environments can be found in many Asian cities where user behaviour is perceived as more 'chaotic' than that occurring in countries such as Australia and New Zealand where adherence to rules, such as keeping to a lane, is seen as a basic premise for road design and traffic operation. Each type of system achieves its main goal - to move people and goods about - but it is only the latter, heavily-structured type that has been modelled with any degree of success.

This paper describes some first steps to modelling the ‘less-structured’ road traffic environment using cellular automata. The approach is to view user behaviour in terms of ‘cooperative opportunistic percolation’ rather than ‘chaotic movement’. The paper discusses car-following models, briefly describes cellular automata, looks at some CA models that have been applied to somewhat self-structuring movement (eg pedestrians), and offers suggestions about and looks at some of the constraints of applying a CA to bi-directional, mixed-user road traffic systems exhibiting the characteristics of cooperative opportunistic percolation.

2 Two structure levels of road traffic

Driving behaviour in highly-motorised, ‘developed’ economies such as North America, Japan, Australasia and (most parts of) western Europe is characterised by drivers adhering to rigid lane discipline and conforming to a set of rules applicable to almost every situation encountered in the driving task. With such seemingly well-defined boundaries of behaviour in a highly-structured environment, there have been many attempts in the last half-century to develop models of the interaction between consecutive vehicles in the same lane through car-following models and to describe the propensity and method of changing lanes through models of lane-changing behaviour. Brackstone and McDonald (2000a) give an overview of the types of models available, describing their features and failures. They remark that such an overview has been due for many years and prompted by the increasing availability of desktop computing power that has enabled the development of microsimulation packages of road networks. These packages use many interacting models, including car-following models, as a means of describing and controlling the motion of the vehicles in the network.

The key point made by Brackstone and McDonald (2000a) about the evolution of car-following models is that ‘little concerted work has been performed since the early sixties on the establishment of a “complete” (basic) driver model.’ No explanation is given for this though a good bet is that the cost of data gathering for such an exercise has been – and probably still is – prohibitive. They assert that some vehicle manufacturers are investing heavily in this area due to the wave of interest in so-called in-vehicle driving aids that is sweeping through vehicle manufacturing R & D functions on the back of developments in Intelligent Transport Systems (ITS). These developments include increasing the on-board intelligence of vehicles by installing systems that use data from a variety of sources. A significant result of these developments is to increase the amount and range of information available to drivers.

A basic assumption of the models of multi-lane traffic flow is that drivers will adopt a significant level of regular behaviour with regard to lane discipline, speed, following distance and in overtaking manoeuvres. Taking the first of these, almost all models in current use assume that drivers will drive in marked traffic lanes. In conventional models drivers may have different physiological and psychological characteristics, may exhibit stochastic variations of perception and behaviour, and may change from one lane to another, but they are generally assumed to follow a regular single file behaviour whilst in a given lane. Such behaviour is what is found in general driving conditions in much of the developed world, especially North America, Japan, Australasia and much of western Europe, and particularly in traffic regimes where the overall proportions of two wheeled vehicles (motor cycles, scooters and bicycles) are small – as is the case in Australia.

In contrast, in many of those parts of the world now experiencing rapid urbanisation and motorisation (eg the cities of south east Asia) and those cities where two-wheelers are a significant part of the general traffic streams, ‘lane discipline’ as practised in highly-structured road environments is often non-existent! This behaviour has led many observers to the conclusion that such environments are ‘chaotic’ when in reality they are fundamentally self-structured and function through ‘cooperative opportunistic percolation’ (COP).

In a COP environment, the philosophy concerning road space is to use whatever part is most convenient. Cooperative action is required as sometimes this means a road user will be 'persuaded' (or forced) to undertake a 'lane change' or a braking manoeuvre which directly impacts the progress of other users; flexibility is the key. A COP environment is opportunistic as evidenced by the meaning behind the use of the horn in a vehicle. It is not solely a warning device (or indication of frustration and sometimes rage) as practiced in highly-structured road traffic environments. In a COP environment the horn also announces: ‘I am here and I will have a go at moving ahead of you given any opportunity that presents itself’. (Interestingly, the absence of a law in Australia requiring motor-vehicles to announce their presence with a light beep on the horn when approaching cyclists from behind can be viewed as a lack of advancement when compared with activity in a COP environment.) Maximum use of road space, cooperation and opportunism therefore result in percolating traffic.

The cities with COP road traffic environments require valid analytical procedures and models as tools for their traffic planning and management needs (Bang and McLean, 1997). The established tools are flawed for use in those environments and whereas it is largely appropriate to label a model of vehicle behaviour in a road system of significant levels of lane and rule discipline ‘car-following’, it is inappropriate to apply the same label to a complete model of COP road traffic that includes mixed-user behaviour. Of course another solution is to change COP road traffic environments to highly-structured environments. This approach (as evidenced by the building of infrastructure and the ‘Lane driving is sane driving’ campaign in Delhi, India) can be debated with regards to its benefits and disbenefits and is outside the scope of this paper, suffice to say that the development of analytical procedures and appropriate models may show that in terms of people and goods, the increase in speed, coupled with an increase in the buffer zone around individual vehicles may be less efficient than the current COP environment.

The behaviours inherent in the car-following models described by Brackstone and McDonald (2000a) are essentially a part of the behaviour model one would expect to find in a description of road traffic applicable to southeast Asia. Clement and Taylor (2003) provide a review of the state-of-the-art in car-following models with the view to ascertain if any characteristics of the models themselves are worthy of consideration in the vehicle-percolating models to be developed for applicability to COP road traffic systems.

While the first part of developing a vehicle-percolating model is to extend elements of models that have been built for and validated in the car-following environment, the second part concerns the method by which any theoretical model is expressed. Clement and Taylor (2003) proffer cellular automata as a likely method. This paper briefly describes cellular automata (CA) and reviews their previous use in transport modelling while highlighting the features and likely pitfalls in the development of a CA-based vehicle-percolating model.

1 The cellular automaton method

1.1 Basics

A cellular automaton (CA) is a method of modelling a (usually) physical system into a grid-like structure of cells where each cell or group of cells represents an element of the system being modelled. At each time step in the running of the cellular automaton, the update value of each cell depends on the values of its surrounding cells (ie its view of its neighbourhood) and the set of rules governing the update process. In the simplest implementations of CAs, each cell is given one of two possible values at each of a series of time-steps. In more sophisticated implementations, each cell is given one of a range of possible values at each time-step.

Allinson and Sales (1992) firstly give a potted history of the development of CAs attributing the seminal work to John von Neumann whose attempts to model self-reproducing systems were never completed. They also report on the development of a dedicated CA machine built on a plug-in board for IBM PCs. Their vision was for CA machines based on multiprocessor technology. A good, brief introduction to the basics of cellular automata is given by Rucker and Walker (1989, Chapter 5). They describe a computer program as a cellular automaton when the updates are:

- parallel;
- local; and
- homogeneous.

Parallel in the sense that each cell update from one time-step to the next is performed independently. That is, all the cell updates are conceptually performed at the same time. In computer applications this corresponds to the use of a buffer to store the new values of all the cells in the grid before the old cell values are over-written with the new.

Local concerns the new state of the cell being dependent on the state of the cell and of the state of its neighbouring cells in the previous time-step. A neighbourhood is defined by Walker (Rucker and Walker, 1989) as 'the set of cells whose state can affect a given cell at one instant'. The range of the neighbouring cells can vary and depends to some extent on the shape of the individual cells. In most implementations the shape of the cells is square or rectangular but some are different shapes. See Section 2.2 for a description of some types of neighbourhoods.

Homogeneous refers to the condition where the same set of update rules applies to each and every cell of the model. Schreckenberg, Schadschneider, Nagel and Ito (1995) also note that in some applications (theirs was a CA applied to traffic flow) the order of the update rules 'is crucial'. That is, the order in which they are applied in the update processing period can have a significant effect on the outcome of running the model.

A further set of principles is reported in Ceccini and Rinaldi (1999): these are described as 'principles of stationarity' and are reported as being defined by Tobler (1979), Couclelis (1985) and Batty and Xie (1997). The first principle, 'spatial stationarity of neighbourhoods' states that each cell has the same type of neighbourhood. This has a different implication to the notion of 'local' as defined by Rucker and Walker (1989) as the type of neighbourhood for a cell may well differ over time while the update regime remains the same. In some senses this difference is a precursor to the construction of multicellular automata (see Section 2.4). The second principle, 'spatial stationarity of rules' is essentially the same as the notion of homogeneous update of Rucker and Walker.

An interesting view of CAs is provided by Rucker (Rucker and Walker, 1989) when he suggests that CAs represent the bottom/up approach to building intelligent artificial life in contrast to the top/down approach of artificial intelligence (AI) techniques. The idea is that the (often simple) interactions of many small cells operating under a few seemingly simple rules can be combined to produce a totality of action that is not explicitly described by any of the individual cells or the range of actions they can perform. This is precisely the idea behind using CAs to model traffic flow.

Allinson and Sales (1992) also add to the principles of parallelism, locality and homogeneity evident in CA systems. They include the attribute of scaleability which posits that expanding the physical size of the CA is easily done. Their notion of self-organisation means that a CA system can start with a 'disordered configuration' of cell values in the lattice structure but then can evolve towards a system where cells are ordered in either a temporal or spatial sense. Allinson and Sales point out that the CA is essentially non-reversible. That is, due to the 'chaotic' nature of the update process, the previous configuration of the cells cannot be determined by inspection of the current state. There are times when the previous state can be deduced but these are generally limited to trivial implementations.

1.2 Neighbourhoods

There are many different types of neighbourhood that can be used in cellular automata. Allinson and Sales (1989) describe three types of neighbourhoods: the Moore; the von Neumann; and the Golay.

The *Moore* neighbourhood is where the central cell and all eight adjacent cells in a two-dimensional array of square cells are involved in the evaluation of the rules to update the value of the centre cell.

The *von Neumann* neighbourhood is where only the centre cell and its four directly-adjacent cells take part in the update process.

The *Golay* neighbourhood consists of hexagonal cells and hence each central cell has six surrounding cells. The advantages of this form is that there is more scope for growth of the CA grid as there are three axes of symmetry compared with the two of the rectangular or square cells. In addition each neighbouring cell actually borders the central cell whereas in the Moore neighbourhood, four of the cells only have an intersection boundary point in common. Allinson and Sales consider the Golay neighbourhood a subset of the Moore neighbourhood but if we treat the Golay and Moore neighbourhoods as different, and consider each as a possibility of implementation in the CA to model a COP road traffic environment, the apparent motion will be somewhat different. For example, the Moore neighbourhood could describe longitudinal progress of a vehicle accurately whereas the lateral progress would be of the quantum jump nature. In the coarsest implementation where one cell-width describes a lane width, a lane change would be either completed or not. The Golay neighbourhood may well describe the lane change manoeuvre more adequately but the progress longitudinally would appear as a series of lurches. Examples of how these hexagonal neighbourhoods operate in a CA can be seen on Tim Tyler's web page on hexagonal engineering (Tyler, 2002a).

The Margolus neighbourhood is where the grid is divided into groups of four cells and the update is applied to each cell completely on each iteration. A distinguishing feature of the Margolus neighbourhood is that the grouping changes in successive update iterations meaning that the same operation is not performed at every time step. Hence situations of no change to the grid structure between iterations can easily be avoided. This is illustrated at Tyler (2002b). The disadvantage with this scheme is that knowledge of which partitioning grid was used to update the cell is needed for continual correct updates to be performed.

The Q*Bert neighbourhood (Tyler, 2002c) has the same characteristics of a changing partitioning scheme as does the Margolus neighbourhood only the Q*Bert partitioning scheme is applied to the hexagonal grid of the CA.

The Star of David neighbourhood (Tyler, 2002d) is a hexagonal neighbourhood scheme that subdivides the hexagonal cell into its triangular components. The operation of such a CA revolves around the notion of a 'domain' and its 'co-domain'. The Star of David scheme updates uniformly at every iteration.

The Necker neighbourhood (Tyler, 2002e) is an extension of the Margolus neighbourhood. into three dimensions.

1.3 Update possibilities

Schreckenberg *et al* (1995) describe four types or styles of update algorithm (or 'dynamics') for cell values in a CA. These are:

- parallel (as described above);
- sublattice parallel – where all the cells of a certain site are updated in parallel (at the same time);
- sequential – where the cells are updated in a certain order; and
- random-sequential – where the cells are updated in turn but in a random order.

They report conditions where each of these can have a different effect on the outcome of a CA model. They further note that 'in the case of asymmetric update rules and sequential dynamics' differences exist if the update is performed in the direction of traffic flow or opposite the direction of flow.

1.4 Multicellular automata

Ceccini and Rinaldi (1999) use the concept of multicellular automata (MCA) to describe the spread of urban development on the fringes of a city. They expound that an MCA is useful when applied to a phenomenon or system that is so complicated and/or large that a single CA implementation is impractical in terms of the size of the description (rule-base) required for each element in the system and/or the computational requirements. Hence they use a system where two or more CAs are linked together in sequence. Hence the final configuration of CA i is the initial configuration for the next CA in the sequence, CA (i + 1). The MCA idea is further developed in that the CA sequence could be circular so that CA n is employed as the starting configuration for CA 1. This allows great flexibility. For example the number of circuits of the MCA through each component CA can be altered; the number of iterations for each individual CA can be varied; in some circuits of the MCA one or more of the CAs can be included or excluded and the order of the component CAs can be changed. What this implies is that the rules applied to a specific cell can vary depending on which CA is operating.

2 The CA method in road traffic applications

2.1 The Nagel-Schreckenberg model

The Nagel-Schreckenberg model (Nagel and Schreckenberg,1992) is a one-lane traffic flow model which can be attributed as spawning development in the two-lane models of Rickert, Nagel, Schreckenberg and Latour (1996) and Nagel, Wolf, Wagner and Simon (1998) and in the two-dimensional models of Cuesta, Martinez, Molera and Sanchez (1993), Nagatini (1993) (these reported by Simon and Gutowitz (1998)) and Molera, Martínez and Cuesta (1995). Krauss, Wagner and Gawron (1996) developed a generalised view of the Nagel-

Schreckenberg model so that continuous values of vehicle speed and spatial coordinates could be represented.

The Nagel-Schreckenberg model provides a useful initial example of the application of the CA approach to road traffic streams, albeit for a relatively simple case (eg flow in a single lane). The simple CA framework is to use integer variables for space, time and speed (the basic descriptors of vehicle performance and location). The space along the road is divided into cells, which can either contain a vehicle or be empty. The length of the cell (Δx) is set by an assumed minimum spacing between vehicles in a traffic jam (the 'jam density'). For normal passenger car traffic this means a cell length $\Delta x \approx 7$ m though there is room for some variation in this value. Akçelik, Besley and Roper (1999) found that the range of mean jam spacings in their study of queuing and discharge behaviour at eleven intersections in Sydney and Melbourne was from 7.3 m to 4.6 m. An update time step (Δt) is also set and the location of a given vehicle at time $t + 1$ (time in integer time steps) is computed from its position at the previous time t, according to a set of rules describing vehicle performance and progression in the presence of other traffic. The time step size Δt may be set to any suitable value, and usual practice is to do so according to an assumed driver reaction time (typically $0.6 < \Delta t < 1.2$ s). Δt may then be estimated for a specific model, to optimise the performance of that model (in terms of model error and computational speed). Vehicle speed v ranges between $0 \leq v \leq v_{max}$ where v_{max} defines a maximum number of cells that the vehicle can traverse in the time step.

This approach simulates the dynamics of driving, along the line 'go as fast as you can and as the vehicle in front allows you to, decelerating when necessary to avoid collision with the vehicle in front' (Nagel and Schreckenberg, 1992). This can be modelled using simple calculations and thus at very fast computational speed – an advantage for simulations approaching (or surpassing) realtime comparability.

Typical performance rules could be expressed as follows, given that x and v are the actual position and speed of a vehicle in the CA framework, and G is the number of free cells in front of the vehicle,

1. *if the present speed is less than the desired speed, accelerate*: if $v < v_{max}$ then $v \leftarrow v + 1$
2. *avoid hitting the vehicle in front*: if $v > G$ then $v \leftarrow G$. [This is an unrealistic braking rule in terms of deceleration capability but is a logical rule to implement to avoid collisions]
3. *include an allowance for random variability of behaviour between individual vehicles*: in the simple Nagel-Schreckenberg model this is expressed as a possible random deceleration by any one vehicle, if $v > 0$ then $v \leftarrow v - 1$ with probability p_b
4. *move the vehicle forward v cells in the next time step*: $x \leftarrow x + v$

This simple model has produced reasonable simulations of traffic flows and queues at, for instance, signalised intersections. It is simple, but limited: it only accounts for vehicle flow in a single lane, and is restricted to a single vehicle type. Note that the concepts above are similar to the three basic rules of behaviour expressed by car-following models. Bham and Benekohal (2004) express these in a nine-rule matrix for the behaviour of a following car. On the side of the matrix are the three possibilities of the relationship between the space gap observed by the driver and the desired space gap – greater than, equal to, and less than. On the top of the matrix are the three possibilities of the relationship between the velocities of the lead and following vehicles – greater than, equal to, and less than.

Schadschneider and Schreckenberg (1993) expand on the concepts of the Nagel – Schreckenberg model by generating a graph of traffic flow, q, versus vehicle density, ρ and observing the theoretical behaviour of the CA in the transition 'from laminar to start-stop waves'. Their approach was of single-lane traffic on a ring geometry but even with this synthetic environment they were able to show that a change in the order of application of the update rules can significantly affect the CA outcome.

2.2 Numerical example of CA traffic flow modelling

A numerical example of a CA road traffic flow model is shown in Figure 1.

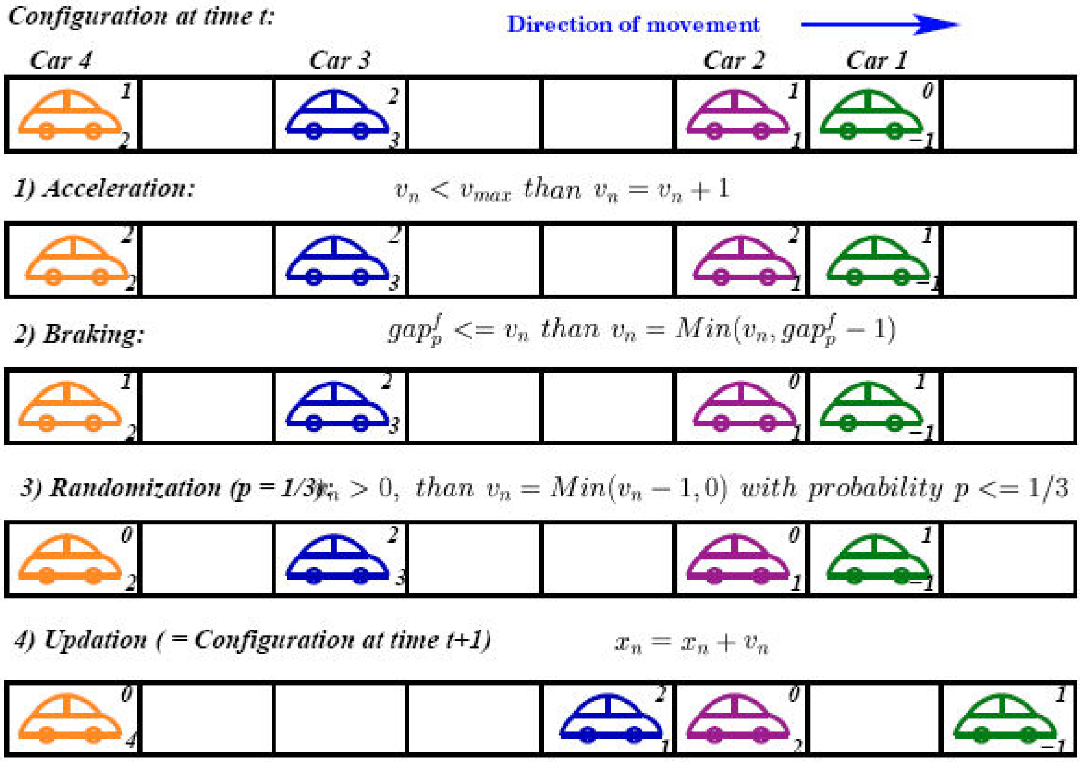

Figure 1 Example of CA traffic flow modelling

In this example all vehicles are assumed to be light passenger vehicles with a maximum speed (v_{max}) of 2 cells per time-step. The vehicle speed is indicated in the top right corner of the cell. The initial speed of vehicles 1, 2, 3 and 4 are 0, 1, 2, and 1 respectively. The front gap (distance headway) of the vehicle is indicated in the bottom right of the cell and is taken numerically as the number of empty cells ahead plus one. The headway of vehicles 1, 2, 3, and 4 are -1, 1, 3, and 2 respectively. The headway of the first vehicle is -1, meaning that there is an infinite forward gap and the vehicle can therefore attain its desired maximum speed. All vehicles update their speed step by step at every time-step in parallel.

The driver behaviour probability ρ is 1/3, meaning that 'on average' one third of the vehicles qualify to slow down in the randomization step. The updation of vehicle speed is indicated after applying each rule shown in Fig. 1. After applying the acceleration rule, the speeds of vehicles 1, 2, 3, and 4 are 1, 2, 2, and 2 respectively. Vehicle 3 is already moving at maximum speed hence its speed remains unaltered. This reflects the general tendency of the drivers to drive as fast as possible, if allowed to do so, without breaking the maximum speed limit.

After applying the braking or deceleration rule, the speeds of vehicles 1 through 4 are 1, 0, 2, and 1 respectively. Vehicles 2 and 4 reduce their speeds by the available front gap in terms of the number of cells as 0 and 1 cell per time-step respectively. After applying the randomization rule, the speeds of the vehicles are 1, 0, 2, and 1. After applying this rule vehicle 4 has its speed reduced by 1 due to the probability ρ. This step takes into account the different behavioural patterns of individual drivers in particular non-deterministic acceleration and overreaction while slowing down; this is crucially important for the spontaneous formation of traffic jams.

The vehicles then move forward with a speed in terms of the number of cells as shown in the updation step 4 of Figure 1. After applying all the rules, the new speeds of vehicles 1 through 4 are 1, 0, 2, and 0 respectively. The front gaps of the vehicles are then updated to -1, 2, 1, and 4. This procedure is again repeated for another time-step. It is to be noted that even changing the precise order of the steps of the updated rule stated above would change the properties of the model. This model may be regarded as a stochastic CA.

2.3 Other models and further considerations for CAs

Nagel (1996) defines and dissects the various implementations of particle hopping models. As in other approaches (Nagel and Schreckenberg, 1992; Tadaki and Kikuchi, 1994; Nagel and Paczuski, 1995; Molera *et al*, 1995; Simon and Gutowitz, 1998; Esser, Neubert, Wahle and Schreckenberg, 1999; Wahle, Neubert, Esser and Schreckenberg, 2001) a major emphasis of the model development is to reproduce traffic jams and the kinematic waves occasionally evident in freeway vehicle flow. Most of these CA implementations use discrete integer velocity steps of either zero or '1' – Wahle *et al* set a $v_{max} = 5$ – and while this tends to produce the desired behaviour in freeway traffic, the modelling of urban, dense network traffic may well require a more realistic spread of velocity steps. White, Garside and Whittaker (1999) formulate the Statistical Traffic Model (STQ) with the aim of providing motorists with accurate travel times allowing them to make route-choice decisions and furnishing them with realtime information during the journey.

Nagel *et al* (1998) point out that the lane discipline evident in German drivers is particularly strong where at very low densities, all traffic is in the right (kerb) lane with increasing usage of the median lane as densities increase. In addition, passing on the right in Germany is not allowed but in the US this manoeuvre is possible. It is also possible in Australia (on the left) provided the road is marked with lanes and that lane discipline by the vehicles is predictable. Nagel *et al* constructed two sets of CA rules for their two-lane model: one based on the German driver behaviour and the other based on US driver behaviour.

For example the rule for passing considers that German drivers tend to immediately return to the right lane as soon as the speeds of the vehicles in both lanes ahead are sufficiently large. For the US case, a return to the right lane will occur when there are either no vehicles in the right lane or the vehicles in the right lane are travelling faster than the overtaking vehicle. Such cultural differences will need to be considered when developing rules for vehicle-percolating models. In addition the local area of interest is likely to have a profound effect on the behaviour of road users and hence differentiation between mid-block progression and pre-intersection manoeuvring and queuing will likely produce alternative sets of rules or at the least a sophisticated set of rules designed to have specific outcomes when applied to specific areas. In terms of mid-block passing on streets more than two lanes wide, in some circumstances the tendency for road users in Thailand is to keep the density of vehicles high in both the longitudinal and lateral directions.

Rickert *et al* (1996) describe a two-lane CA model that is essentially two single-lane models juxtaposed in parallel. The CA has several extra rules to allow lane-changing behaviour to be modelled effectively. They split the update step into two: the first as a strictly parallel update as per the classical CA and the second step is to run the single-lane update rules independently on each lane using the results of the first step. Their approach for lane-changing considers variability in how far the vehicle 'looks ahead' in the lane in which it is travelling and in the other lane and also how far back the vehicle 'looks behind' in the other lane. This is a method of implementing gap-acceptance into the lane-changing mechanism of a CA.

2.4 Bi-directional traffic modelling using CAs

Simon and Gutowitz (1998) continued development of CA applications to road traffic by developing a model for two adjacent, opposite-direction lane flows. They developed their models with different passing restriction regimes:

- passing was allowed in both directions;
- only one lane could perform the passing manoeuvre (either direction); and
- no passing at all.

Their model included rules such as that where a vehicle would not be allowed to decelerate while passing and that a passing vehicle would immediately return to its lane when an oncoming vehicle was 'seen'. This was to ensure a level of safety usually observed in driving behaviour though they point out that seldom do drivers begin a passing manoeuvre unless it can be completed. They also introduced to the model the concept of vehicles not passing due to a high local density. This is the situation where there are many vehicles travelling in a platoon and passing is rare even when the density of oncoming traffic is low. They point out that the lanes therefore 'become effectively decoupled'.

Their results indicated that allowing of passing 'dramatically' improves the fluidity of traffic because there is a significant reduction in the number of start-stop waves even when the densities of traffic were 'chosen to maximize the effects caused by interactions between two lanes in opposite directions'.

2.5 On-line modelling using CAs

Wahle *et al* (2001) developed a method for using realtime data as inputs to an online CA simulating the road traffic in Duisburg, Germany. Realtime data obtained from 750 inductive loops in the network was relayed to the central microsimulation computer every minute. The types of data used are the flux (flow rate), the density of vehicles and the types of vehicles. These data are used for estimating the turning probabilities on 56 driving directions and as such are used to calibrate the CA. Wahle *et al* found that tuning the simulator for either flow or density achieved the same simulation results. Their method would appear to be computationally expensive and though valid as a traffic-state forecasting tool at the dense network level requires a considerable level of infrastructure to detect road users.

1 Pedestrian modelling approaches

Andreas Schadschneider (Schadschneider, 2001a) modelled pedestrians as a herd with attractive forces by utilising the biological process of chemotaxis to introduce the idea of a floor field to model the movement of pedestrians in congested conditions. His example was pedestrian movement towards the exit in a large room such as a lecture theatre. In this cellular automaton simulation, the floor field is a virtual field that modifies the probabilities of pedestrian movement in a particular direction; essentially the floor field modifies the transition rates to neighbouring cells. Hence the pedestrians gain information from their herding instinct (interactions between pedestrians) and also from their position in the theatre relative to the exit (the floor field). Schadschneider reported that the model reproduced much of the self-organising behaviour observed in pedestrian dynamics such as lane formation and flow oscillations at doors.

In contrast to the Schadschneider approach, Helbing Farkas, Fasold, Treiber and Vicsek (2001) modelled pedestrians as individual entities with driving and repulsive forces resulting in 'an optimal self-organization phenomenon.' This method specifically excluded the use of floor fields stating that 'virtual fields or other questionable model ingredients are not necessary to obtain realistic results.'

Schelhorn, O'Sullivan, Haklay and Thurstain-Goodwin (1999) review prior efforts to model pedestrian movements and suggest that the paucity of such activity was due to a lack of computing power and suitable data sets. Their agent-based model made full use of the data storage and retrieval capabilities of a GIS. They point out however that CA implementation does not really fit 'the agent modelling paradigm.'

Blue and Adler (2001) produced a CA microsimulation model of bi-directional pedestrian walkways and were inspired by the successes of CA implementations of vehicular flows on roadways. One of their aims was to find the most realistic expression of pedestrian behaviour with a minimal rule set. They found their focus was on the lane-changing rules that are necessarily more complex in pedestrians than they are in vehicular models.

A major part of the problem of modelling bi-directional pedestrian flow is that where there are no 'lane markings', pedestrians tend to form lines of flow that appear spontaneously and disappear (Helbing, 2001; Schadschneider, 2001b). No quantifiable research has been found to explain this behaviour though from discussions with Helbing and Schadschneider and the authors' own observations it appears that the phenomenon is due to a combination of congestion, desired speed of pedestrians, the mix of pedestrians (eg the number of leaders compared to followers) and the destinations of 'key' individuals.

2 Considerations for CA modelling of COP

2.1 Road users

A major consideration for using CAs to model cooperative opportunistic percolation in road traffic is in defining the various vehicles and road users both spatially and behaviourally. That is, how is a particular vehicle to be defined in terms of the number of cells it 'inhabits' and of course how it behaves when part of the road traffic stream.

It is common to find between 10 and 15 different classes of motor vehicles in ordered road traffic systems. Several of these classes may be similar in different regions but the different types of vehicles and the way the road space is utilised often defines a particular region.

For example, Thailand has a large range of vehicle types using the roads of its urban centres: some of the vehicles are found only in Thailand. A list covering most of the modes of transport found on their urban roads is given below along with a brief description of their physical characteristics. This is not an official list and like Australia may well have different sub-categories of 'heavy vehicles'.

1. Motorcycles
2. Cars
3. Bicycles
4. Light trucks
5. Heavy vehicles
6. Buses
7. Hoklor – 6-wheeled passenger vehicle smaller than a 'normal' bus.
8. Songtaw – passenger-carrying light vehicle. These are characterised by having a passenger canopy mounted on the back of a utility vehicle with bench seats mounted one on each side so that the passengers sit facing each other.
9. Sarmlor – 4-wheeled light passenger vehicle.
10. Tuk-tuk – 3-wheeled passenger vehicle most of which run on natural gas.
11. Motorcycle taxis – these are registered as passenger-carrying vehicles.
12. Pedal-powered rickshaws.

The list above contains some vehicles that are evident on almost any road traffic system in the world (eg cars, motorcycles, bicycles). One of the goals of this research is to produce a model or combination of models that describe the behaviour of as many types of vehicles as possible.

2.2 Spatial modelling

One of the biggest challenges facing a CA depiction of the above vehicles is to correctly model each spatially. The CAs reviewed in previous sections of this paper use a single cell for each vehicle and the updation rules are implemented to a grid-based approach where the vehicles are represented by different cells (Gundaliya, Mathew and Dhingra, 2004; Lawarence and Chang, 2004). This minimal modelling aspect gives computational advantages than the previous attempts of grid-based models where the vehicle movement is governed by car following concept. This modelling aspect is more realistic for the urban arterials where there is no lane discipline and a mixture of vehicles with wide variation of physical and dynamic characteristics. Increasing the grain of the grid representing the roadway over which the vehicle models would travel could enhance cellular automata implementation though may well prove computationally too expensive. Since this project is to model mixed-user behaviour, including pedestrians, it is appropriate that vehicles of different sizes inhabit a different number of cells in a particular configuration. As examples, a pedestrian could be defined as occupying a single cell, a bicycle occupying two cells longitudinally and a car four cells longitudinally and three laterally.

Larger vehicles such as buses and trucks would then occupy more cells longitudinally and laterally. For example in a simple model, a bus could be represented by an object covering a line of four (say) cells on a grid where each lane is represented as a single cell wide. Movement forward along the lane would be in single cell increments but lane-changing would be a movement sideways also of a complete cell. There would be no accommodation for the bus temporarily straddling the lane (cell) divider. A more realistic model would have the bus represented as (say) five cells wide and (say) twenty long with the width of the lane set at (say) seven cells. Such an arrangement would be necessarily more complex and more computationally intensive when running.

The behaviour of each vehicle (ie group of occupied cells) approaching an intersection would depend on its occupation of real estate and its knowledge of the vehicles around it as it would on its own behaviour such as acceleration and deceleration characteristics and propensity to change lanes. It may therefore be necessary to define the road space in terms of cells without regard to physical lanes. This would mean that the position of the cells in the lattice of the CA would determine the propensity for particular behaviour of vehicles occupying those cells. For example, if we define the road space at the approach to an intersection as fifteen cells wide, the behaviour of the vehicles occupying the cells towards the right (in a drive-on-the-left country such as Australia) would exhibit more of an inclination to turn right than the vehicles occupying the left cells of the road space. This extension is even more complex than the basic CA as it would require interaction between the vehicle behaviour and cell behaviour at another level again.

Gunay, Bell and Sung (1997) studied the behaviour of multi-lane unidirectional traffic flows on two- and three-lane highways. They introduced the concepts of ‘untidy traffic flow’ and ‘degree of untidiness’ in an effort to quantify the action of vehicles when not within the lane structures of multi-lane roads. Untidy traffic flow refers to ‘both low lane discipline and disorderly traffic flow’ where the number of vehicles that do not conform to travelling within a lane of a highway is relatively high. Degree of untidiness is the ‘lateral position of vehicles across the carriageway’ and is essentially the concept of lateral distribution of vehicles over the lane but with a finer granularity. That is, degree of untidiness quantifies the position without direct regard to the lane markings. Such concepts are central to the theme of vehicle-percolating models in sections other than at signalised intersections.

The work by Kwon, Morichi and Yai (1997) on the interaction between pedestrians, bicycles and cars in narrow urban streets of Japan could be helpful in determining parameters for modelling mixed-user flows. Their method of scoring the incidence of interactions may well prove suitable to this project.

Work on intelligent agent-based models applied to transportation problems is a relatively recent area of research. Dia (2002) reports on several approaches taken to a variety of transport-related problems. The action of an individual agent in a decision-making environment is a result of the set of goals with which it is programmed combined with the contents of its knowledge-base. Whereas the pure CA model has the cells in the grid iteratively changing their attributes solely through the influence of the attributes of their neighbouring cells, a combination of an intelligent agent-based model and the CA paradigm could increase the realism of the traffic stream model.

Both the Schadschneider (floor field) and Helbing *et al* (driving and repulsive forces) approaches to pedestrian modelling could have application to the modelling of a COP road traffic environment. This could be especially applicable to modelling the behaviour of pedestrians percolating perpendicular to stationary or congested stop-and-go vehicles. Extending the Schadschneider floor field approach to bi-directional pedestrian travel would likely involve an exponential leap in complexity from the single-exit theme of the original model. Applying this to perpendicular percolation around vehicles would make this more complex and may require a CA implementation combining parallel update with regard to the values of a parameter for drivers and pedestrians describing their propensity to give way. Even though the Helbing *et al* method is not specifically implemented using cellular automata the ideas behind the method – individual entities with driving and repulsive forces – could still be used in a ruleset of a CA. Such a contrast in approaches could produce interesting results when each is applied to a COP model of road traffic.

3 Conclusion

There have been many attempts in the last fifty years to model driving behaviour in environments exhibiting high conformity to an extensive set of road user behaviour rules. These models have been concerned with car-following and lane-changing behaviour. There have been few attempts to model road user behaviour where the range of vehicles – including pedestrians and bicycles – and behaviour are manifold. This paper looks at cellular automata as a possibility for modelling such systems and begins with a review of CA definitions and implementations.

CA definitions include the notions that updates are parallel, local and homogeneous. Varying forms of neighbourhoods (eg Moore, von Neumann, Golay, Margolus, Q*Bert, Star of David and Necker) have been developed by different researchers as have a variety of update algorithms (parallel, sub-lattice parallel, sequential, random-sequential) that extend the basic CA formulation.

Several implementations of CAs applied to road traffic systems are reviewed as are two novel approaches for modelling pedestrian movement.

From this review it appears that development of a CA to model bi-directional, mixed-user, cooperative, opportunistically percolating road traffic systems could start with the model of Rickert *et al* (based on the Nagel-Schreckenberg model). This could then be extended with a neighbourhood such as the Margolus neighbourhood that has the possibility of implementing the percolation behaviour of COP systems. The bi-directional qualities of the Simon and Gutowitz model show promise and as a final step, the implementation of pedestrian movement through stationary or near-stationary vehicle traffic could be achieved by using the ideas of either Helbing or Schadschneider or even a combination of both.

4 References

Akçelik, R; Besley, M and Roper, R (1999) *Fundamental relationships for traffic flows at signalised intersections* Research Report ARR 340, ARRB Transport Research Ltd

Allinson, NM and Sales, MJ (1992) CART - A cellular automata research tool *Microprocessors and Microsystems, 16 (8)* 403-15

Bham, GH and Benekohal, RF (2004) A high fidelity traffic simulation model based on cellular automata and car-following concepts *Transportation Research C,* (12) 1-32

Bang, K and McLean, RM (1997) Transport modelling in Asian developing countries *Journal of the Eastern Asia Society for Transportation Studies 2* (3), 795-808

Batty, M and Xie, Y (1997) Possible urban automata. *Environment and Planning B: Planning and Design 24* (2), 175-92

Blue, VJ and Adler, JL (2001) Cellular automata microsimulation for modelling bi-directional pedestrian walkways *Transportation Research B 35*, 293-312

Brackstone, M and McDonald, M (2000a) Car-following: a historical review *Transportation Research F 2* (4), 181-96

Cecchini, A and Rinaldi, E (1999) Building urban models with multi-cellular automata *Proc Sixth Conference on Computers in Urban Planning and Urban Management* Venice, September (FrancoAngeli: Milan).

Clement, SJ and Taylor, MAP (2003) *Possibilities for using cellular automata to model mixed-user, chaotic, bi-directional road traffic systems* Working Paper TSC03-1, Transport Systems Centre, University of South Australia

Couclelis, H (1985) Cellular worlds: a framework for modelling micro – macro dynamics *Environment and Planning A 17*(4) 585-96

Cuesta, JA; Martinez, FC; Molera, JM and Sanchez, A (1993) Phase transitions in two-dimensional traffic-flow models *Physical Review E 48*(6): R4175-R4178

Dia, H (2002) An agent-based approach to modelling driver route choice behaviour under the influence of real-time information *Transportation Research C 5*(6), 331-49

Esser, J; Neubert, L; Wahle, J and Schreckenberg, M (1999) Microscopic online simulations for urban traffic pp 535-54 of Ceder, A (ed). *Transportation and Traffic Theory* (Pergamon-Elsevier: Oxford)

Gunay, B; Bell, MGH and Sung, K (1997) A simulation analogy for untidy multi-lane unidirectional traffic flows *Journal of the Eastern Asia Society for Transportation Studies 2* (3), 837-51

Gundaliya PJ; Mathew, TV and Dhingra, SL (2004) Heterogeneous traffic flow modelling using cellular automata *Proc 10th World conference in Transportation Research*, Istanbul

Helbing, D; Farkas, I J; Fasold, D; Treiber, M and Vicsek, T (2001) Critical discussion of ‘synchronized flow’, simulation of pedestrian evacuation and optimization of production processes *Presentation to the Traffic and Granular Flow ’01* Conference, 15-17 October 2001, Nagoya

Helbing, D (2001) Personal communication

Krauss, S; Wagner, P and Gawron, C (1996) Continuous limit of the Nagel-Schreckenberg model *Physical Review E, 54*(4) 3707-12.

Kwon, Y; Morichi, S and Yai, T (1997) Analysis of behaviours and interactions of pedestrians, bicycles and cars in narrow urban streets *Journal of the Eastern Asia Society for Transportation Studies 2* (3), 853-62

Lawarence, WL and Chang, C-W (2004) Inhomogeneous particle hopping models for mixed traffic with motorcycles and car *Proc International Conference on the Application of Information and Communication Technology in Transportation Systems in Developing Countries*, University of Maratuway, Srilanka

Molera, JM; Martínez, FC and Cuesta, JA (1995) Theoretical approach to two-dimensional traffic flow models *Physical Review E 51*(1) 175-87

Nagatini, T (1993) *Physical Review E vol 48*, 3290

Nagel, K and Schreckenberg, M (1992) A cellular automaton model for freeway traffic *Journal de Physique 1 France 2*, pp 2221-9

Nagel, K and Paczuski, M (1995) Emergent traffic jams *Physical Review E 51*(4), 2909-18

Nagel, K (1996) Particle hopping models and traffic flow theory *Physical Review E 53*(5), 4655-72

Nagel, K; Wolf, DE; Wagner, P and Simon, P (1998) Two-lane traffic rules for cellular automata: a systematic approach *Physical Review E, 58*(2), 1425-37

Rickert, M; Nagel, K; Schreckenberg, M and Latour, A (1996) Two-lane traffic simulations using cellular automata *Physica A* A231, 534

Rucker, R and Walker, J (1989) CelLab User Guide http://www.fourmilab.ch/cellab/manual/. Last accessed 010423

Schadschneider, A and Schreckenberg, M (1993) Cellular automaton models and traffic flow *Journal of Physics A: Mathematics and General 26*: L679-83

Schadschneider, A (2001a) Bionics-inspired cellular automaton model for pedestrian dynamics *Presentation to the Traffic and Granular Flow '01 Conference*, 15-17 October 2001, Nagoya

Schadschneider, A (2001b) Personal communication

Schelhorn, T; O'Sullivan D; Haklay, M and Thurstain-Goodwin, M (1999) STREETS: an agent-based pedestrian model *Proc Sixth Conference on Computers in Urban Planning and Urban Management,* Venice, (FrancoAngeli: Milan)

Schreckenberg, M; Schadschneider, A; Nagel, K and Ito, T (1995) Discrete stochastic models for traffic flow *Physical Review E 51*(4), 2939-49

Simon, PM and Gutowitz, HA (1998) Cellular automaton model for bidirectional traffic *Physical Review E vol 57*(2) 2441-4

Tadaki, S and Kikuchi, M (1994) Jam phases in a two-dimensional cellular-automaton model of traffic flow *Physical Review E 50*(6), 4564-70

Tobler, W (1979) Cellular geography pp 379-86 of Gale, S and Olsson, G (eds) *Philosophy in Geography* Reidel Dortrecht

Tyler, Tim (2002a) Hexagonal Engineering http://hex.org.uk/ Last accessed 021204

Tyler, Tim (2002b) Margolus Neighbourhood http://cell-auto.com/neighbourhood/margolus/ Last accessed 021204

Tyler, Tim (2002c) The Q*Bert Neighbourhood http://cell-auto.com/neighbourhood/qbert/index.html Last accessed 021204

Tyler, Tim (2002d) Star-of-David Neighbourhood http://cell-auto.com/neighbourhood/sod/index.html Last accessed 021204

Tyler, Tim (2002e) Necker Neighbourhood http://cell-auto.com/neighbourhood/necker/index.html Last accessed 021204

Wahle, J; Neubert, L; Esser, J and Schreckenberg, M (2001) A cellular automaton traffic flow model for online simulation of traffic *Parallel Computing 27,* 719-735

White, J; Garside, S and Whittaker, J (1999) A verification of a cell-type transmission model pp 241-254 of Meersman, H; Van De Voorde, E and Winkelmans, W (eds) *Proc World Conference of Transport Research, Volume 3: Transport Modelling/Assessment* (Pergamon-Elsevier: Oxford)