THROUGHPUT AND DELAY IN A DISCRETE SIMULATION MODEL FOR TRAFFIC INCLUDING BICYCLES ON URBAN NETWORKS

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Abstract
The 'greening' of transport is an ongoing concern in today's cities, with many struggling to reach carbon emission targets. One relevant area for effecting change is encouragement and facilitation of alternative, non-motorised transport modes, such as cycling and walking. Understanding the dynamics of non-motorised flows and their interaction with motorised traffic in an urban context is fundamental to exploring these alternatives and has been a recent focus of much technical (and social) research. In this paper, we describe the development of an agent-based simulation framework for mixed traffic on urban networks and its application to a basic network scenario, in which heterogeneity takes the form of lane-sharing by bicycles and cars. Performance is analysed in terms of throughput for different network and signalisation parameter values.

Introduction
The study of the physical properties of traffic is an integral part of transportation science, contributing information that forms the basis for transportation related management and policy decisions. Accordingly, he growing relevance of non-motorised modes of transport, which have beneficial characteristics with respect to the environment, health and society [1] [2], has created a need for the investigation of heterogeneous flow dynamics with focus on alternative modalities, such as walking and cycling. Of particular interest are the properties of motorised/non-motorised mixed urban traffic, as non-motorised modes are predominantly used in urban settings.

While non-motorised traffic and the motorised-non-motorised mix have, as topics, had their place in traffic flow science in the past, in recent years, with the mounting of environmental concerns in the world and, in parallel, with the fast motorisation of developing countries, they have gained increasing attention of the traffic science community.

Because of the many forms that non-motorised traffic integration with the overall road transportation system can take, the study of such traffic has been undertaken for a variety of specific conditions. For the purpose of dedicated bicycle facility design, there have been several studies, reviewed in [3], on track and lane capacity and level of service. Two recent bicycle-only flow models were developed using cellular automata [3][4]. Models for interactions between bicycles and motorised traffic in adjoining lanes have been modelled in [5][6] and [7], the focus in the former two being on conflicts at intersections and that of the latter on the inadvertent invasion of neighbouring, other modality lanes. The flow of fully mixed traffic, which occurs in the absence of lane discipline, was modelled in [8] and [9]. Traffic flow on networks, which is additionally impacted by topology, has also been modelled for the non-motorised and mixed cases. Reviews of a number of continuous-space simulation models, predominantly for traffic including bicycles without lane discipline, are given in [10], while [11] presents another complex model that includes bicycle flows and their various interactions on a network. In addition, some commercial offerings, such as VISSIM [12], simulate bicycle behaviour as part of their functionality.

In this paper, we describe a cellular automaton based network traffic simulation model and corresponding implementation framework that we have developed for the study of bicycle traffic within the wider context of heterogeneous vehicle flows in an urban setting. Our focus is on conditions similar to those prevailing in Dublin, where lanes are shared between motorised traffic and bicycles, lane sharing is based on 'positional discipline' (i.e. bicycles keep to the left and motorised vehicles to the right of the lane) and bicycle-dedicated controls are scarce. We apply the model to a small regular network and present the results of performed simulations in terms of overall flows and average trip times for bicycles and cars separately. This example, while simple, demonstrates the ultimate purpose of our model, which is to analyse general road traffic network properties, such as topology, geometry, rules of behaviour and signalisation, with respect to bicycles.

The following section, “Model”, briefly introduces the model and the implementation framework. Section “Network simulation” describes the simulated network and the results of a number of different simulation scenarios. The final section, “Conclusion”, summarises the conclusions drawn from the simulation results and introduces the questions that will be tackled by continuation of this research.

Model

Since first used by Nagel and Schreckenberg [13] for the simulation of a one-way flow of cars, cellular automata have been widely applied for the reproduction of traffic behaviour. Simulations based on cellular automata are fairly simple to implement and offer the advantage of computational efficiency. A cellular automata model is time and space-discrete. This means that time is represented by discrete moments called *time steps*, which occur at regular intervals, while space is represented by a grid of cells, which can either be occupied or unoccupied at any time step. Vehicles were initially represented as occupying one and one only cell, however, for reasons of modelling vehicles of different sizes and shapes (e.g. [9]), and model refinement (e.g. [14]), multiple cell occupancy by individual vehicles was introduced into models. Inversely, in [4] multiple bicycles can occupy a single cell.

In our model, which was introduced in [15], we use separate but overlapping cellular systems to solve both the problem of differently sized vehicles and that of intersection conflicts in the model. Each type of vehicle moves on a lattice of cells that allow it to occupy one and exactly one whole cell at any one time, i.e. a lattice of cells that are of that vehicle type's size. Intersections are represented as a collection of routes that can be taken by a vehicle through that intersection and each one modelled as a one-dimensional cellular automata space. These routes cross each other as the traverse the intersection, which, in addition to the superimposed cellular spaces of different granularity, is the other cause of overlap between cells.

The overlap between cells and the accompanying concept of *impingement*, which is the indicator of whether a cell is available for occupation by a moving vehicle, is one of the two main differences between our model and previous cellular automata models of traffic flow. While these previous models (cf. [13]) would inspect cells for whether they are occupied or not when determining how to move, in our model vehicles check cells for impingement. The other important difference between previous models and ours is the spatial aspect of conflict expression, which in our model follows naturally from the spatial representation of an intersection: a conflict is described in terms of which sections (i.e. which cells) of overlapping routes constitute it. This way of representing conflicts allows for the re-use of conflict resolution rules, since a conflict is always expressed in the form of two cell ranges: the cells of one route and the cells of the conflicting route that are within the 'conflict zone'.

We use the Nagel-Schreckenberg [13] rules as a base for the behaviour of vehicles. These are:

1) Acceleration: if $v_i < v_{\mathrm{MAX}}$ and $v_i < d_i$, $v_i \rightarrow v_i + 1$,

2) Slowing (due to cars ahead): if $d_i < v_i$, $v_i \rightarrow d_i$,

3) Randomisation: with probability p_{R} , $v_i \rightarrow v_i - 1$,

4) Vehicle motion: each vehicle is advanced v_i cells, where v_i is the velocity (in cells per time step) of the vehicle at the i^{th} time step, v_{MAX} is the maximal velocity for the vehicle, d_i is the number of free cells between this vehicle and the vehicle ahead, p_R is a probability, called the randomisation parameter, which introduces stochasticity into the model and the □symbol represents the change of velocity between the i^{th} and the $i+1^{th}$ time step. Rule number 4 is different from the others in that rules 1-3 prescribe how the velocity is to be updated at a time-step, while rule 4 says how the vehicle is to change position, i.e. by moving forward by v_i cells. The updates are *parallel*, which means that first the velocities of all the vehicles in the system are updated, after which the positions of all the vehicles are changed.

The modifications our model makes to the above are:
a) As already mentioned, in rule 2 d_i represents the number of un-impinged cells ahead of the vehicle, rather than the number of free cells ahead of it.
b) When approaching an intersection or an unresolved conflict, vehicles have an additional velocity limit, as show in Table 1.

Distance from intersection/conflict/bicycle	6	5	4	3	2	1	0
Velocity limit for car turning at intersection	-	2	2	2	1	1	-
Velocity limit for bicyle turning at intersection	-	-	-	-	1	1	-
Velocity limit for car approaching an unresolved conflict	2	2	2	1	1	0	-
Velocity limit for bicycle approaching an unresolved conflict	-	-	-	1	1	0	-
Velocity limit for car approaching bicycle in adjacent track	-	2	2	2	1	1	1

Table 1 *– Model velocity limits for vehicles in different situations. The first row shows a list of distances from the limiting feature of the environment. Each of the other rows specifies the velocity limits imposed by a certain feature of the environment, at different distances. A dash indicates that for the particular distance the feature does not impose a velocity limit on the approaching vehicle.*

c) The approach to an intersection that allows multiple routes to a vehicle demands a decision as to choice of route. A vehicle will turn with probability p_T (this is a sufficient manner of making a choice in the simulation example, since all decisions are between two routes).
d) At a conflict, vehicles that must give way apply a *soft yield* rule. This means that the minimal condition for entering the conflict zone is that crashes must be avoided. The vehicles are not concerned with whether they will hold up vehicles on conflicting routes. This, while not the most realistic scenario for interactions between motorised vehicles, may be a good model of mutual treatment between drivers and cyclists.

Network simulation
The simulation is of a regular network of 4 x 4 nodes, arranged in a mesh such as the one shown in Figure 1.

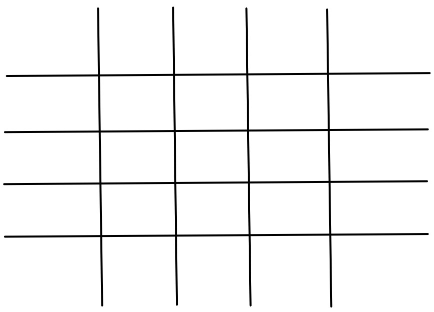


Figure 1 – *A schematic representation of the simulated network. All streets are one-way and the directions of movement are south-north and east-west.*

The intersections (nodes of the network) and roads (edges of the network) are modelled using the cellular spaces shown in Figure 2. From that figure, a so far unmentioned property of our model can be seen, namely the overlap of cells within a route in an intersection. This is used to express the slowing caused by a turn, but also to make the alignment of cells in the entire model easier. The overlap is not an imposition of the behaviour model, since overlap is already handled by the vehicle behaviour rules.

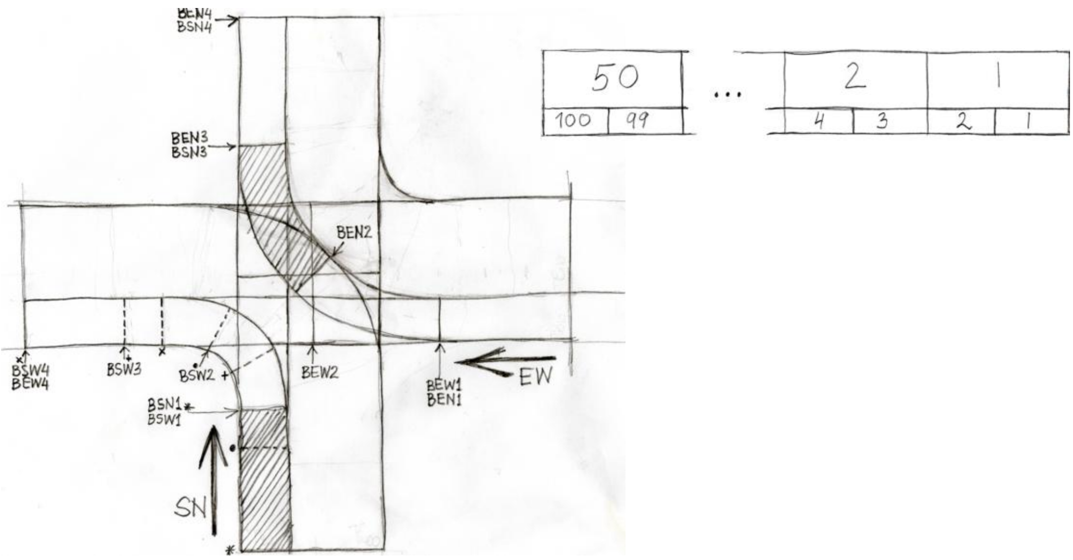


Figure 2 *– Spatial model components: intersection of two one-way roads (left) and a one-way stretch of road (right). The components include movement spaces for cars (larger cells) and for bicycles (smaller cells). The straight road stretch model does not include any overlaps between cells, since it represents a case with positional discipline. The example shown is of length 50 for cars and 100 for bicycles. The intersection model has overlapping routes. The markers starting with the letters BS show the fronts of bicycle cells, while those starting with BE show the back edges of bicycle cells. The shaded cells are examples of bicycles cells.*

All vehicles move either south-north or east-west. New vehicles are placed at each time step with probability $p_{IC}(p_{IB})$ for cars(bicycles) at the eight edge ends on the south and east, with velocity 2(1). The vehicles are placed at the farthest possible position based on cell occupancy and velocity, and if the first cell of the road is impinged at a particular time step, no vehicle is inserted at that time step. Vehicles leave the network at the 8 free edge ends at north and west.

Simulations were performed for 10 parameter sets:

1) no turning occurs, there is no signalisation, east-west roads have priority
2) no turning occurs, there is no signalisation, south-north roads have priority
3) no turning occurs, all intersections are signalised: 1 min cycle, equal red-green split
4) no turning occurs, all intersections are signalised: 2 min cycle, equal red-green split
5) vehicles turn with probability p_T=0.5, no signalisation, east-west roads have priority
6) vehicles turn with probability p_T=0.5, no signalisation, south-north roads have priority
7) vehicles turn with probability p_T=0.5, signalisation with 1 min cycle as above
8) vehicles turn with probability p_T=0.5, signalisation with 2 min cycle as above
9) vehicles turn with probability p_T=0.5, signalisation: 2 min cycle with 4 green phases: cars S-N 15s; bicycles S-N 45s; cars E-W 15s; bicycles E-W 45s
10) vehicles turn with probability p_T=0.5, signalisation: 2 min cycle with 4 green phases: cars S-N 45s; bicycles S-N 15s; cars E-W 45s; bicycles E-W 15s

Figure 3 shows the average flow results for bicyles and Figure 4 the average flow results for cars. Figure 5 shows how the length of the roads between intersections affects the flows for cars and bicycles.

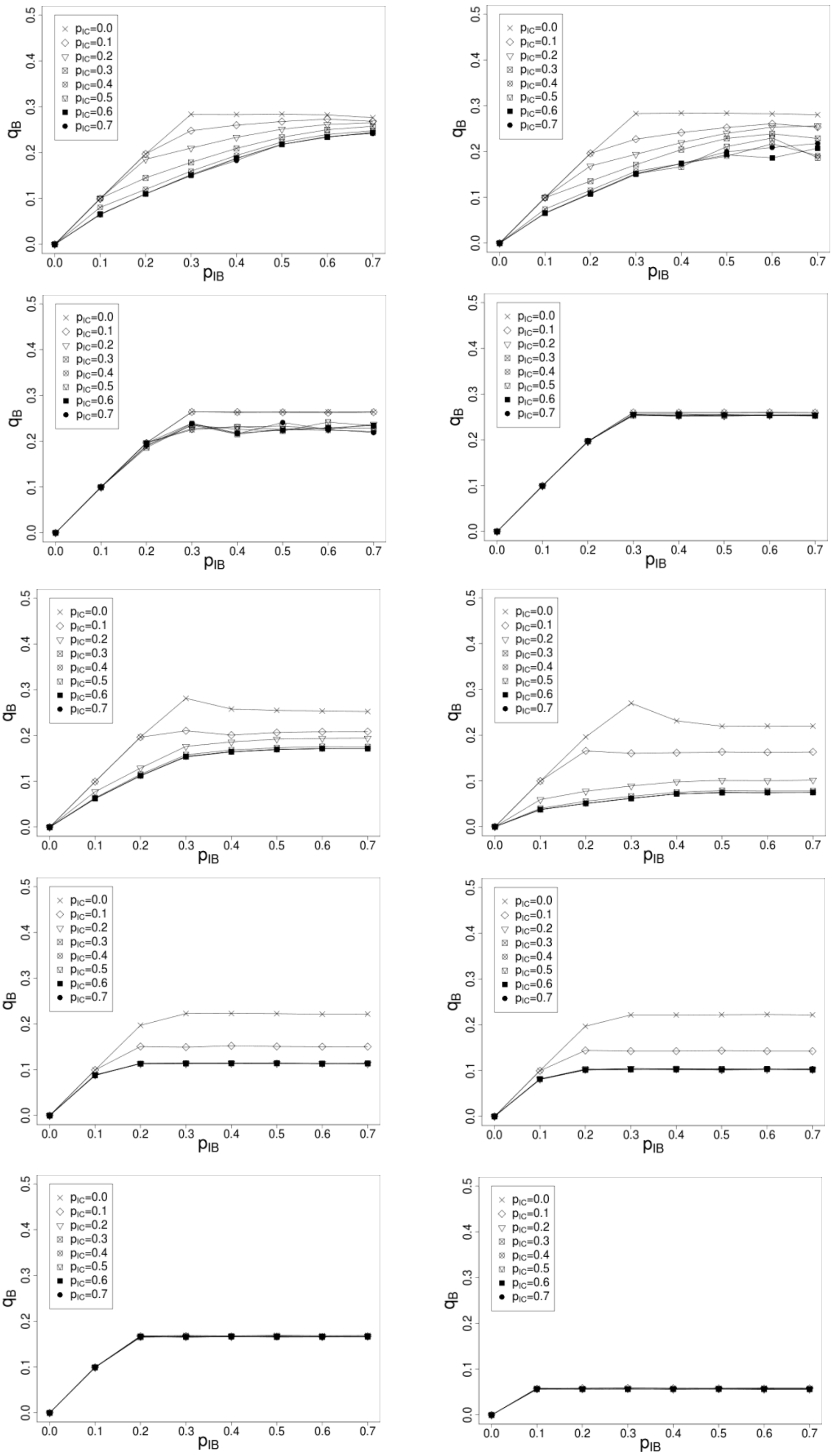


Figure 3 *– Bicycle flow as a function p_{IB} , for simulation parameter sets 1-10.*

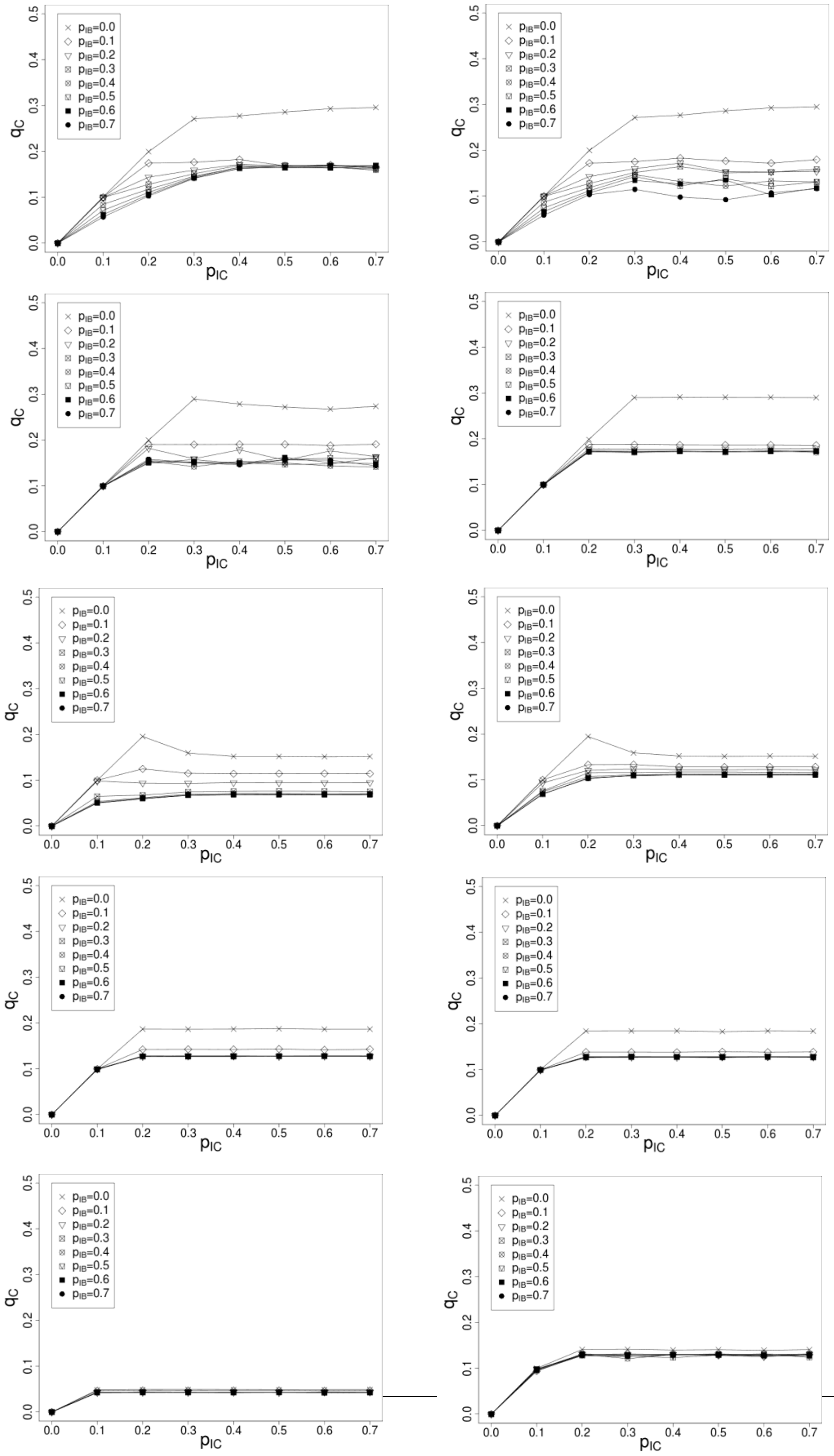
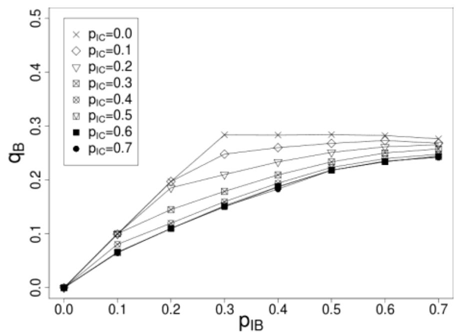
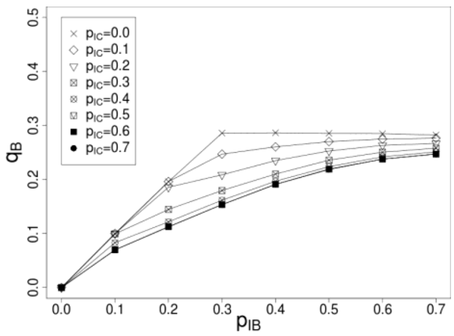


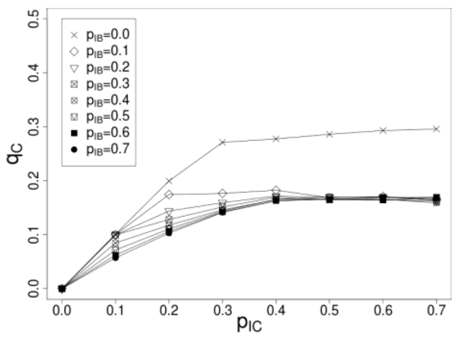
***Figure 4** – Car flow as a function p_{IC} , for simulation parameter sets 1-10.*



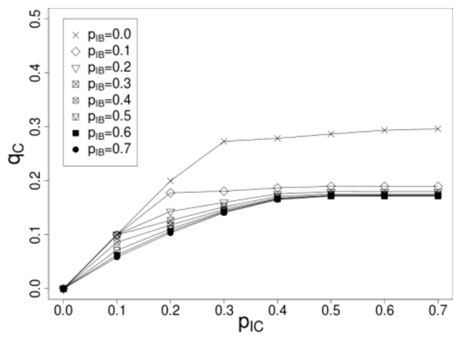
Bicycle flows, road length = 50(100)



Bicycle flows, road length = 200(400)



Car flows, road length = 50(100)



Car flows, road length = 200(400)

***Figure 5** – Effect of the road length (network edge length) on flows.*

From the figures it can be seen that the un-signalised network performs better in the case that priority is given to the east-west roads. Also, traffic lights produce an improvement on the throughput in both cases and for both vehicle types, with the longer cycle of 2 minutes being somewhat more beneficial than the cycle of 1 minute. Turning manoeuvres considerably reduce the capacity of the network for both vehicle types and the traffic lights somewhat increase the capacity, although the cycle length does not seem to make a difference in the case where vehicles perform turns. The signalisation with 4 phases simply reduces the capacity and does not seem to be a good idea. The length of roads between intersections has a small impact (see Figure 5): greater lengths result in better capacities. However, the effected differences at the lengths used are not large.

Conclusion

The paper presented a cellular automata model for network traffic with heterogeneous vehicles. The simulations performed on a simple network demonstrate how the model can be used to analyse network features and parameters. Planned further work will include the use of the model for the study of larger and more complex networks. To this end, real data comparisons and/or sensitivity analysis will be performed with the aim of calibrating the model, which, once rendered robust and explored in detail, will be used as an optimisation tool.

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