Interaction of Cars and Bicycles on a One-Way Road Intersection: A Network CA-Based Model

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Abstract Modelling of heterogeneous traffic including non-motorised modalities is a topic of increased interest, as 'greening' becomes an integral part of transportation science. The variation of form among these heterogeneous flows means that models developed to represent them are just as diverse. The particular case of interest here is that of lane-sharing between bicycles and motorised vehicles, with positional discipline. A cellular automata-based model is developed and applied for the study of this kind of mixed traffic.

1 Introduction

In the push towards 'greening' of urban transport, encouragement and facilitation of alternative modalities features prominently, owing to the associated benefits that span environmental, health and social domains. Heterogeneous traffic flows including non-motorised modes, especially bicycles, have attracted less extensive modelling efforts to date. Our work offers a contribution in this area by way of a model for the type of heterogeneity formed through lane sharing with 'positional discipline', which is characteristic of Dublin and other cities where dedicated bicycle infrastructure is scarce and streets relatively narrow.

The added complexity involved in modelling heterogeneous traffic, as compared to that of the mode-homogeneous case, has two components: one that stems from differences in vehicle properties and driver/rider behaviour among different mode types and another arising from unique interactions that occur between specific pairs of modalities. In terms of these, the inclusion of the bicycle in a traffic model requires a representation of cyclists' behaviour and the allowance for interactions between bicycles and motorised traffic.

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All bicycle-focused modelling work must, indeed, include some manner of the former. However, characteristics of bicycle-only flow and related road capacities, including the bicycle-only fundamental diagram and levels of service, have been the central topic of a number of publications. These are reviewed in detail in [1], where the authors also present a cellular automaton bicycle flow model of their own, representing 'two abreast' bicycle flows. Another bicycle-only flow model using cellular automata, where multiple bicycles can occupy a single cell and distinction is made between slow and fast cyclists, is presented in [2].

Interactions between bicycles and motorised vehicles are *implicit* in models of broadly heterogeneous traffic, found, e.g., in many Asian countries, where any type of vehicle can occupy any lateral position on the road. A number of models aimed at representing this form of heterogeneity, all based on space-continuous simulation, are reviewed in [3]. A lane-based scenario including bicycles is modelled using car-following rules in [4]. Cellular automaton (CA) models described in [5] and [6] represent similar scenarios and were validated using real data and existing simulation models. While applied to heterogeneous motorised-only traffic, these CA models allow for differently-sized vehicles, including motorcycles, through multiple-cell occupancy and could easily be applied to a pedal-bicycle inclusive case.

Separately identifiable interactions between bicycles and motorised vehicles can be classified into *lateral interference* and *cross-flow*. The former occurs where bicycles and motor vehicles are moving side-by-side and interfere with each other's motion, mostly causing deceleration of the other vehicle type. The latter are interactions arising from intersections of bicycle flows with motorised ones, often in circumstances created exclusively by the presence of bicycles in traffic. For example, if bicycles and cars are sharing a lane by *positional discipline*, which means that bicycles keep to the left[1] and motorised vehicles to the right of the shared lane, cars turning left are in conflict with the bicycle flow and the two types of vehicle affect each other's movements. In the cellular automaton model presented in [7], lateral interference between a car lane and the adjacent multi-lane bicycle stream is represented through a higher probability for cars to slow down in circumstances of 'friction' or 'blockage' caused by bicycles. In [8], the lateral interference type of interaction is introduced into an optimal velocity model as a friction component accounting for the effect of pedestrians on cyclists and cyclists on motorised vehicles, with the different types of vehicles moving in designated but spatially adjacent lanes. A slightly different question, of how the general network flows are affected by different vehicle types moving side-by-side on individual links in the network, is posed in [9], where interactions are accounted for in a combined forecasting model through link impedance functions. Here, higher bicycle flows increase the impedance of motorised flows and vice versa. Cross-flow interactions are the subject of work described in [10], wherein a logit model is proposed for

[1]Our model assumes left-hand side driving, that in effect in Ireland, UK etc., without loss of generality.

the relation between the flow of turning cars and the straight-moving bicycle arrival rate, based on bicycle flow properties derived from empirical data. In [11] the same scenario is modelled building on the cellular automaton (CA) flow representation from [2], where a single cell can be occupied simultaneously by multiple bicycles. Here, general CA rule application takes place synchronously, with an exception made in instances of conflict between car and bicycle flows. These conflicts are resolved through stochastic designation of update sequence among the flows in conflict, on a case-to-case basis. Finally, interactions between left turning bicycles and straight moving cars on a two-way street are studied in [12] using a two-dimensional optimal velocity model.

Ours is a general cellular automata (CA) simulation model, primarily suited to representing lane-based traffic with positional discipline in case of lane sharing, is applicable to any vehicle type mix and accommodates both lateral interference and cross-flow types of interaction. The application here is to traffic including bicycles and cars on the intersection of two one-way streets. The scenario is used singly and as the building block of a 16-node network, in both cases under periodic boundary conditions, for a study of the relationship between traffic densities and flows. The model, which has been presented in some detail in [13], is summarised in Sect. 2, while the simulation scenario and results are presented in Sect. 3.

2 Model

The **spatial aspect** of the model uses the one-dimensional cellular automata (CA) space, or a *track*, as a building block. A track consists of cells of equal size, each occupied by a single vehicle or empty. Vehicle positions in the track are updated iteratively according to some rules with the aim of reproducing traffic flow dynamics. The iterations represent changes in the system during successive fixed time intervals or *time steps*. Any route that may be taken in the simulation scenario by any type of vehicle, as it navigates the model space, is represented as a track, resulting in a space consisting of tracks, each with cells of a size appropriate for the type of vehicle it accommodates and intersecting with other tracks, as dictated by the simulation scenario. Tracks may connect so as to form longer tracks, intersect, diverge, converge (the two latter cases corresponding to pairs of tracks that are identical up to, or starting with, a certain cell) or be adjacent to each other, forming spatial features that must be handled by the update rules, in addition to basic movement along a track.

The spatial elements of the simulated scenarios, each built from a number of tracks, are shown in Fig. 1. This figure is also intended to serve as an illustration of the general spatial modelling method, in which the model is 'extracted' from a sketch of the modelled space, hence the hand-drawn pictures. Figure 1a, b show the tracks modelling an intersection of two one-way streets and a one-way road stretch, respectively. In Fig. 1a the bicycle cells are marked in some detail. The car track

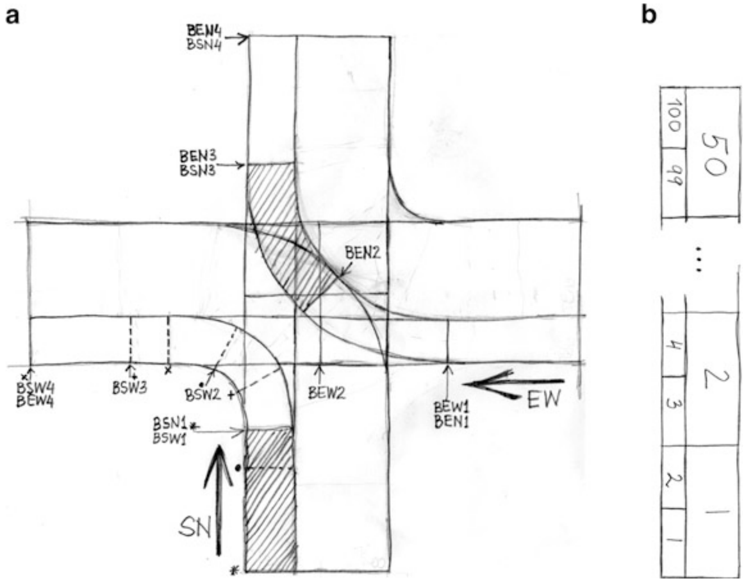

Fig. 1 Sketch for model of an intersection of two one-way streets (**a**) and for a straight road stretch (**b**), with mixed car and bicycle traffic sharing a road with positional discipline (bicycles stay to the *left* and cars to the *right*, with reference to the direction of movement). The four movement directions in the intersection (south-north [SN], south-west [SW], east-west [EW] and east-north [EN]) and the road stretch are each represented by two tracks – one for cars and one for bicycles, positioned side by side. The bicycle cell front lines are marked in (**a**) using the cell names, BSN1 for the first cell in the bicycle SN CA space, etc. A matching pair of symbols, such as * or + are used to mark the beginning and end lines of cells in the BSW CA space, indicating overlap between cells, which is used to model the slowing of vehicles caused by the turn. The shaded areas are examples of bicycle cells. The *arrows* indicate the travel direction. The car and bicycle tracks constituting the straight road stretch in (**b**) consist of 50 and 100 cells, respectively

cells are not shown to avoid cluttering the picture, however, they consist of: track CSN 2 cells, CSW 4 overlapping cells, CEW 2 cells and CEN 4 overlapping cells.

The actual spatial model used by the update rules is based on information extracted from sketches such as those in Fig. 1. This information consists of the item types described in Table 1 together with actual information for the elemental models in Fig. 1.

The space in which the update rules operate must be completed with a conflict resolution method, which can be considered a **control component** of the model. To use the elemental model in Fig. 1a as an unsignalised intersection, priority is assigned to either the south-north or the east-west direction, resulting in the left-hand-side (LHS) and the right-hand-side (RHS) rule, respectively. In the case of cross-flows on the same road, the straight moving flow always has priority, i.e., track BSN has priority over CSW and track CEW over BEN.

Table 1 Spatial model information item types and information item values extracted from the pictures in Fig. 1

Information item type	Value for inter-section model in Fig. 1a	Value for road stretch model in Fig. 1b
Description of tracks in terms of cell size, cell count, direction of cell numbering (corresponding to that of vehicle movement) and cells at which a turn (left or right) starts in the track	Car cells correspond to real lengths of 7.5 m, while bicycle cells correspond to half that length, i.e., 3.75 m; tracks BSW, CSW, BEN and CEN each have a turn, starting at cell 1	
Track connections (where one track extends another one so that the first cell of the extending track follows the last cell of the extended one)	The first cell of any track in the intersection and road stretch models may follow the last cell of another track and vice versa, if the followed and following cell are the same size	
Cell overlap instances	Shown in Table 2	None
Conflicts and divergences	Shown in Table 3	None
Indication as to whether any two tracks are geometrically positioned so as to cause inter-track interaction (other than that at conflicts) between vehicles and if yes, what kind of interaction	All adjacent car-bicycle track pairs imply interaction between bicycles and cars on those two tracks, by virtue of the tracks' proximity; cars decelerate in the presence of bicycles	

The **update rules** are based on those defined for traffic on a single-lane road by Nagel and Schreckenberg in [14]. These rules can be formulated using a *combined limit* value as follows:

0. Determine the combined limit value: $v_{\mathrm{CLi}} = \min(v_{\mathrm{MAX}}, d_i)$
1. Acceleration: if $v_i < v_{\mathrm{CL}}$, $v_i \to v_i + 1$
2. Slowing: if $v_{\mathrm{CLi}} < v_i$, $v_i \to d_i$
3. Randomisation: with probability p_{R}, $v_i \to v_i - 1$
4. Vehicle motion: each vehicle is advanced v_i cells

where v_{CLi} is the combined limit value for the ith vehicle, v_{MAX} is the maximal velocity for the vehicle type, d_i is the number of free cells to the nearest other vehicle ahead of vehicle i and v_i is the velocity of vehicle i. The variables are dimensionless: distance is measured in cells and velocity in cells per time step.

The update rules used herein modify the Nagel-Schreckenberg rules by (i) substituting d_i with $d_{\mathrm{U}i}$, which is the number of *unimpinged* cells ahead of the ith vehicle (a cell is impinged if an overlapping cell, including itself, is occupied) and (ii) including another three limiting factors in the combined limit value:

$$v_{\mathrm{CL}} = \min(v_{\mathrm{MAX}}, d_{\mathrm{U}i}, v_{\mathrm{LT}}(d_{\mathrm{T}i}), v_{\mathrm{LC}}(d_{\mathrm{C}i}), v_{\mathrm{LB}}(d_{\mathrm{B}i})) \tag{1}$$

where $v_{\mathrm{LT}}(d_{\mathrm{T}i})$ is the velocity limit imposed by the proximity of a turn, as a function of the distance to the turn, $d_{\mathrm{T}i}$, and $v_{\mathrm{LC}}(d_{\mathrm{C}i})$ and $v_{\mathrm{LB}}(d_{\mathrm{B}i})$ are analogous values relating to unresolved conflicts ahead of vehicles and bicycles ahead of cars on

Table 2 Cell overlap table for the two one-way street intersection spatial model in Fig. 1a. Each table entry indicates whether the cell associated with its row and the cell associated with its column overlap (1) or not (0). The matrix corresponding to the table is, as expected, symmetrical

	CEN4	CEN3	CEN2	CEN1	BEN4	BEN3	BEN2	BEN1	CEW2	CEW1	BEW4	BEW3	BEW2	BEW1	CSW4	CSW3	CSW2	CSW1	BSW4	BSW3	BSW2	BSW1	CSN2	CSN1	BSN4	BSN3	BSN2	BSN1
CEN4	1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
CEN3	1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
CEN2	1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
CEN1	1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
BEN4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
BEN3	0	0	0	0	0	1	0	0	1	1	0	0	0	0	1	1	1	0	0	0	0	0	1	0	0	1	0	0
BEN2	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0
BEN1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CEW2	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	1	0
CEW1	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0	1	1	0	0	0	0
BEW4	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
BEW3	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	0	1	1	0	0	1	0	0	1	0
BEW2	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	1	0	0	0	0	0	1	0	0	0	0
BEW1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CSW4	0	0	0	0	0	1	0	0	1	0	0	1	1	0	1	1	1	0	0	0	0	0	1	0	0	1	1	0
CSW3	0	0	0	0	0	1	1	0	1	1	0	1	1	0	1	1	1	1	0	0	0	0	1	1	0	1	1	0
CSW2	0	0	0	0	0	1	1	0	1	1	0	1	1	0	1	1	1	1	0	0	0	0	1	1	0	1	1	0
CSW1	0	0	0	0	0	0	1	0	0	1	0	1	1	0	0	1	1	1	0	0	0	0	0	1	0	0	1	0
BSW4	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
BSW3	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1	0
BSW2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	1	1
BSW1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1
CSN2	1	1	1	1	0	1	0	0	1	1	0	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0
CSN1	1	1	1	1	0	0	1	0	1	1	0	1	1	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0
BSN4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
BSN3	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1	0	0
BSN2	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	1	1	0	1	1	0	0	0	0	0	1	0
BSN1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1

Table 3 Conflicts and divergences for model in Fig. 1a. A conflict is defined with the first cell in conflict of each the left and the right involved track. For example, a conflict between tracks BSN and CSW starts at cell 2 of the former and cell 1 of the latter. A divergence is, similarly, defined with the first divergent cell of each the left and the right involved track

Conflict or divergence id, prefixed C or D, respectively	First cell of conflict/divergence in left track	First cell of conflict/divergence in right track
D1	BSW1	BSN1
D2	CSW1	CSN1
D3	BEW1	BEN1
D4	CEW1	CEN1
C1	BSN2	CSW1
C2	BSN2	BEW3
C3	BSN2	CEW2
C4	BSN3	BEN3
C5	CSN1	BEW2
C6	CSN1	CEW1
C7	CSN1	BEN2
C8	CSN1	CEN1
C9	BSW2	BEW3
C10	CSW1	BEW2
C11	CSW1	CEW1
C12	CSW1	BEN2
C13	BEN2	CEW1

adjacent tracks, respectively. The three velocity limit functions have been chosen so as to allow vehicles to reach a turn, conflict or bicycle at velocity 1, 0 and 1, respectively (only in the case of an unresolved conflict does a vehicle actually have to stop), while decelerating by, at most, 1 at any time step. The update is performed in parallel, which means that in each time-step the velocity update rules (1–3) are applied to all vehicles in the simulation, then the position update rule (4) is applied to all the vehicles. The rules are identical for bicycles and cars but the value of v_{MAX} is decided separately for the two types of vehicle.

Navigation of the multi-track space is handled using two system-wide parameters: probability of turning right, p_{TR}, and probability of turning left, p_{TL}.

3 Simulation Results

The two scenario spaces, shown in Fig. 2, were built using the elemental models from Fig. 1. The following parameters and initial conditions apply to both: maximal velocity, v_{MAX}, is 3 for cars and 2 for bicycles; the randomisation parameter is

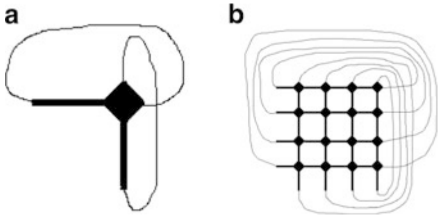

Fig. 2 Schematic representation of simulation scenario space for intersection of two one-way streets (**a**) and a 4×4 node network (**b**), both with closed boundary conditions. The *diamond shapes* each represent the intersection from Fig. 1a, while the *straight lines* between nodes represent the element in Fig. 1b. The pair of points at the ends of each free-form line are directly connected in the model, to form closed boundaries

$p_R = 0.1$; simulation length is 10^5 timesteps, each corresponding to 1s; the turning probabilities, p_{TL} and p_{TR} and vehicle densities are varied; initial vehicle spatial distribution is homogeneous among and within tracks, initial velocity for all vehicles 0. Flows are measured at the cells preceding all the southern- and east-most intersection entry points.

The results of some of simulation instances are shown in Figs. 3 and 4. While the priority bicycle flows for the LHS rule take the form of a standard fundamental diagram (Fig. 3a), the car flows are reduced at high bicycle densities (b), because of the slowing effect built into the model for adjacent bicycle and car tracks. The non-priority flows are low, as expected (c, d). The same conditions on each of the nodes in the network scenario produce similar, but fairly ‘noisy’ priority-flow diagrams for the case with 50-cell edges (e, f) and ones almost identical to those for the isolated intersection in the case of 200-cell edges (g, h). The diagram in Fig. 4a shows a case of a scaled fundamental diagram, owing to increased densities on two perpendicular tracks. This is reproduced in the network case (b). Another effect that can be seen is that of gridlock causing sudden flow failure, due to increase of other vehicle type density cross-flows (c). The diagrams are rather random in the network case (d, e), but the effect is still visible, particularly for the scenario with 200-cell edges (e). A simulation case that exhibits both the scaled fundamental diagram and gridlock is shown in Fig. 4f. The last two diagrams (g, h) show a case where the priority east-west bicycle flow is ‘protected’ from diagram scaling, due to high densities in the adjacent car track, which do not allow bicycles turning from the south-north track easy entry into the east-west one.

The application of this method of modelling is envisaged as a useful and systematic approach for the investigation of networks that accommodate heterogeneous traffic of the type encountered in old city centres, such as Dublin’s, but also for other types of networks and other vehicle type mixes.

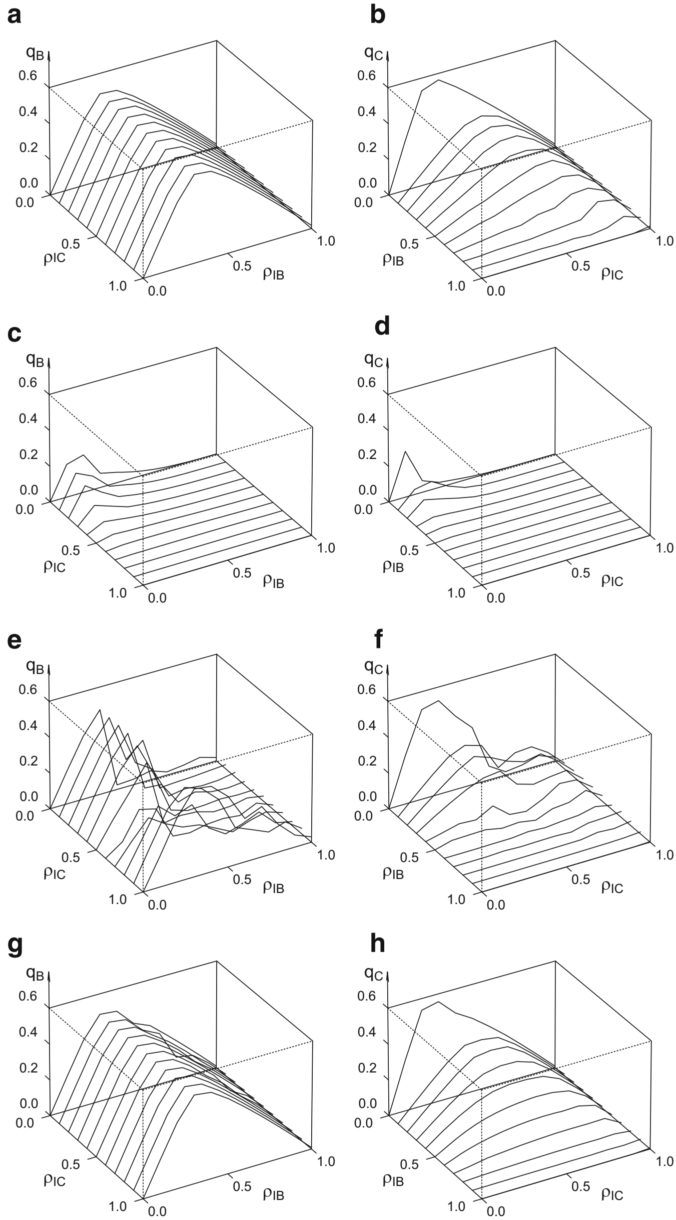

Fig. 3 Average flow for bicycles or cars, as a function of overall bicycle and car density. Each scenario instance is specified using (i) scenario name (intersection or network with length of edge in brackets), (ii) conflict resolution rule (LHS or RHS), (iii) vehicle type (B for bicycle or C for car) and (iv) direction of flow measurement (south-north or east-west). All turning probabilities are 0. (**a**) Intersection, LHS, B-SN. (**b**) Intersection, LHS, C-SN. (**c**) Intersection, LHS, B-EW. (**d**) Intersection, LHS, C-EW. (**e**) Network(50), LHS, B-SN. (**f**) Network(50), LHS, C-SN. (**g**) Network(200), LHS, B-SN. (**h**) Network(200), LHS, C-SN

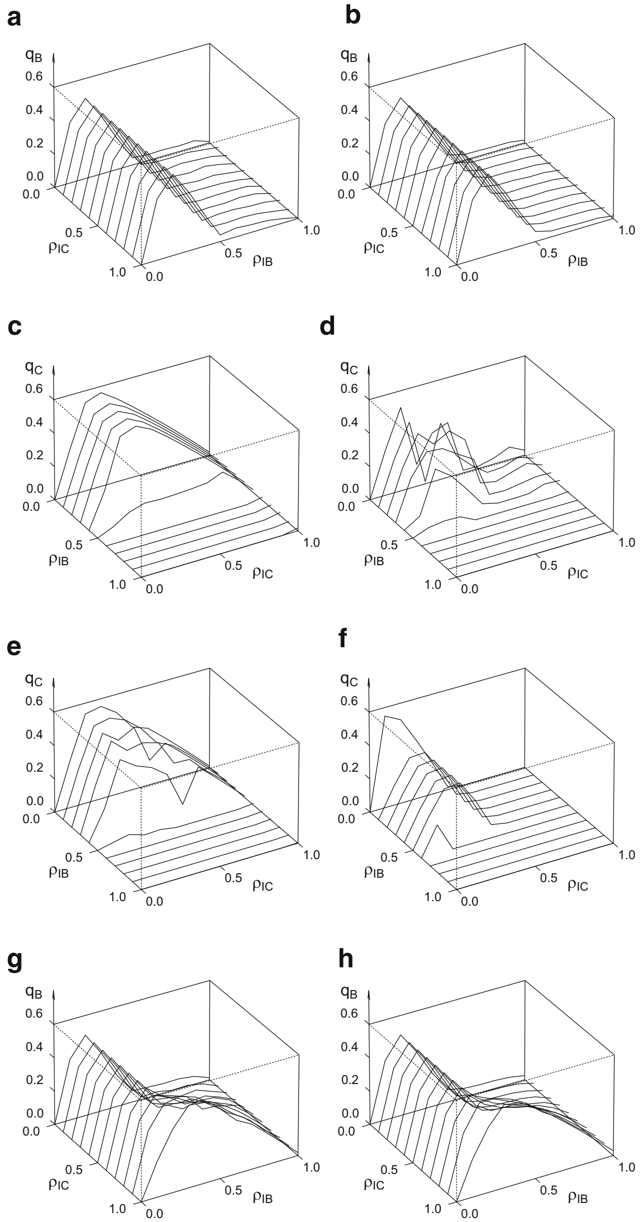

Fig. 4 Average flow for bicycles or cars, as a function of overall bicycle and car density, continued. Each scenario instance is specified using (i) scenario name (intersection or network with length of edge in brackets), (ii) conflict resolution rule (LHS or RHS), (iii) vehicle type (B for bicycle or C for car), (iv) direction of flow measurement (south-north or east-west) and (v) any turning probabilities that are not equal to 0. (**a**) Intersection, RHS, B-EW. (**b**) Network(50), RHS, B-EW. (**c**) Intersection, LHS, C-SN. (**d**) Network(50), LHS, C-SN. (**e**) Network(200), LHS, C-SN. (**f**) Intersection, LHS, C-EW. (**g**) Intersection, RHS, B-EW. (**h**) Network(50), RHS, B-EW

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