CHAPTER 6 MODELING FOR THE TWO-DIMENSIONAL MOVING BEHAVIORS

This chapter tries to develop inhomogeneous particle-hopping models using CA approach to depict the two-dimensional moving behaviors for motorcycles. Based on the field survey, the cell and particle size and CA rules are defined in sections 6.1 and 6.2. Deterministic CA models are then used to simulate various scenarios in section 6.3. Section 6.4 conducts the validation through another set of field data. Furthermore, stochastic CA models are elaborated in section 6.5 and a brief discussion is presented in section 6.6.

6.1 Definition of Particles and Cells

To develop the inhomogeneous particles hopping models, we need to define the dimensions of particles and cells and the rules of particle moving to comply with the real situations. Based on above-mentioned field survey conducted on the southbound section of Tunhua South Road between Padeh Road and Civil Boulevard in Taipei City, it is found that the minimum gaps for a moving motorcycle and car are, respectively, 0.8 and 1.9 meters to the lead vehicle, 0.45 and 0.95 meters to the left neighboring vehicle, and 0.4 and 0.82 meters to the right neighboring vehicle. The majority of the vehicles' maximum speeds are less than 55 kph with acceleration (deceleration) less than 1.5 meter/sec^2 during these two observation periods. Previous cellular automaton traffic models (for instance, Nagel, 1998) define the cell unit as 7.5×7.5 meters and assume that each particle has identical size occupying one cell unit; namely, the space required for each vehicle is 7.5 meters both in length and in width. Because the definition of cell unit is too coarse, vehicles are modeled as particles with unrealistic speed jumps. This is obviously not the case what we have observed for the mixed traffic with motorcycles and cars.

In line with the vehicle dimensions and observed minimum gaps, we define a common cell unit with much finer square grid as 1.25×1.25 meters. Thus, based on our observation, a motorcycle in our CA models will always occupy 2×1 cells and a passenger car always takes away 6×2 cells while moving. The system is defined as follows:

- The traffic lanes are viewed as a two-dimensional space, in which x axis indicates the vehicle's moving distance and y axis denotes the vehicle's lateral position;

- Each cell is 1.25×1.25 meters;
- Time step is 1 second;
- Maximum speed $v_{\max}$ is 13 cell units per time step;
- Only two kinds of vehicles, motorcycle and car, are included;
- One motorcycle occupies 2 (2×1) cells, and one car occupies 12 (6×2) cells;
- Each cell can either be empty or occupied by one vehicle.

In addition, we consider both “car-following” and “lane-changing” behaviors for each particle that changes its positions over time and over a two-dimensional space, in which *X*-axis indicates the vehicle’s longitudinal movement distance and *Y*-axis denotes the vehicle’s lateral displacement distance. Each cell can be either empty or occupied at each time step. The time step in updating the related information for all particles is set as one second so that the magnitude of speed (meters per second) is exactly equal to the longitudinal position change (meters). According to the survey, the maximum speeds for motorcycle and car are nearly the same, thus we set both with identical maximum speed as 13 cells (about 58kph).

The gaps between the following particle (either motorcycle or car) and the front, right-front, left-front, right-behind and left-behind particles, respectively denoted by dX_f, dX_r, dX_l, dX_{rb}, and dX_{lb} are illustrated in Figure 6-1. In Figure 6-1(a), the i^{th} following particle is a motorcycle, which uses the 3^{rd} lateral cell lane with two motorcycles and two cars in both adjacent lanes. In Figure 6-1(b), the i^{th} following particle is a car, which occupies the 2^{nd} and 3^{rd} lateral cells with the same surrounding traffic situation. Note from Figure 6-1(a) and 6-1(b) that, even with exactly the same surrounding situation, the above-mentioned gaps are different because of the non-identical sizes of the following particles.

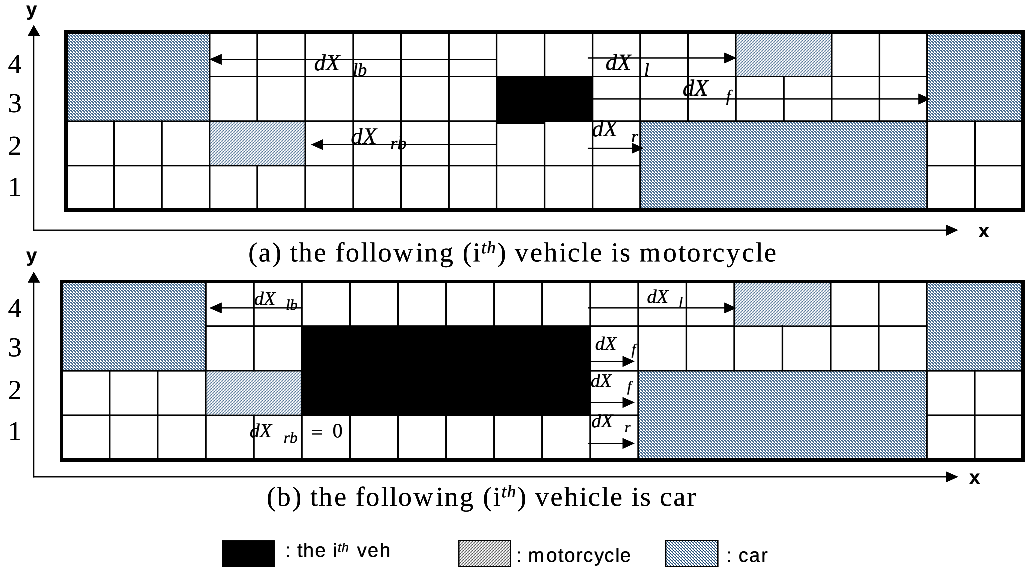

Figure 6-1 An illustration of inhomogeneous particles layout

6.2 Definition of CA Rules

Nagel and Schreckenberg (1992) first introduced a prototype CA traffic model (NaSch model, hereafter), which was to simulate the one-dimensional (single-lane) pure car motions with simple updating rules. In their model, the road is divided into identical square cells of length 7.5 meters and each cell can either be empty or occupied by one car. The states of all cars at time step $t+1$ can be obtained from those at time step t by applying the given rules at the same time. In this paper, we modify the NaSch model to simulate the two-dimensional mixed traffic motions with two different particles. We define the CA rules that govern the particles moving logics, including moving forward and lateral displacements from left to right or the reverse. Following the previous CA lane-changing models (Rickert, *et al.* 1996; Chowdhury, *et al.* 1997; Nagel, *et al.* 1998; Knospe, *et al.* 1999), we define a particle can change its "lane" (1.25-m cell in our definition) if both of the following two criteria are satisfied.

(1) The incentive criterion:

- The gap in front of i on the current lane is less than the current speed of i.
- The gap in front of i on the adjacent lane is larger than the current front gap of i.

(2) The security criterion:

- Lane changing should not collide or block other vehicles. Thus, lane changing is possible for vehicle i only if its adjacent lane is empty and the speed of the left or right behind vehicle is smaller than the gap between vehicle *i* and the behind. That is, the gap in front of i on the adjacent lane is larger than the current speed of i; and the gap in behind of i on the adjacent lane is larger than the current speed of behind vehicle.

The first one is the incentive criterion: the gap in front of particle *i* at the current lane should be smaller than the current speed of *i* and the gap in front of *i* in the adjacent lane(s) should be larger than the current front gap of *i*. The second one is the safety criterion: any lateral displacement should not collide or block other vehicles behind. Thus, "lane changing" is possible for vehicle *i* only when its adjacent lane(s) is empty and the speed of the left- or right-behind vehicle is smaller than the gap between vehicle *i* and the behind vehicle(s). Namely, the front gap of *i* in the adjacent lane(s) is larger than the current speed of *i;* and the behind gap of *i* in the adjacent lane(s) is larger than the current speed of behind vehicle. In fact, the above "lane changing" rules have included both symmetric and asymmetric situations. The particle using the intermediate cell(s) can make a symmetric lane change from both sides depending on which side provides larger gap. However, the particle using the edge (right-most or left-most) cell can only make an asymmetric lane change from one side in case that the adjacent gap is large enough.

Let dX_f^t, dX_l^t, dX_r^t, dX_b^t, dX_{lb}^t, and dX_{rb}^t respectively denote the gaps between vehicle *i* and the front, left-front, right-front, behind, left-behind and right-behind vehicles at time step *t*; $\mathbf{P}_i^t=(x_i^t,y_i^t)$, $\mathbf{P}_f^t=(x_f^t,y_f^t)$, $\mathbf{P}_l^t=(x_l^t,y_l^t)$, $\mathbf{P}_r^t=(x_r^t,y_r^t)$, $\mathbf{P}_b^t=(x_b^t,y_b^t)$, $\mathbf{P}_{lb}^t=(x_{lb}^t,y_{lb}^t)$ and $\mathbf{P}_{rb}^t=(x_{rb}^t,y_{rb}^t)$ respectively denote the positions of vehicle *i*, front, left-front, right-front, behind, left-behind and right-behind vehicles at time step *t*. A random generator is used to determine the vehicles' initial positions. Let $\mathbf{V}_i^t=(v_i^t,0)$, $\mathbf{V}_l^t=(v_l^t,0)$, $\mathbf{V}_r^t=(v_r^t,0)$, $\mathbf{V}_b^t=(v_b^t,0)$, $\mathbf{V}_{lb}^t=(v_{lb}^t,0)$ and $\mathbf{V}_{rb}^t=(v_{rb}^t,0)$ respectively denote the speed vectors of vehicle *i*, left-front, right-front, behind, left-behind and right-behind vehicles at time step *t*; L_i, L_f^t, L_l^t, and L_r^t denote the lengths of vehicle *i*, front, left-front and right-front vehicles at time step *t*; $\mathbf{PC}$ denote the vector of lateral position changed, in which $\mathbf{PC}=(0,-1)$ represents vehicle *i* changing to the right and $\mathbf{PC}=(0,1)$ changing to the left. Starting from an arbitrary initial condition with speed $\mathbf{V}_i^0=(v_i^0,0)$ and position $\mathbf{P}_i^0=(x_i^0,y_i^0)$, the states of the particles in our CA models are updated according to the following rules, as detailed in Figure 6-2:

(1) Estimate $V_{desired}$, dX_f^t, dX_l^t, dX_r^t, dX_b^t, dX_{lb}^t, dX_{rb}^t (the effective gaps);

(2) Check both incentive and safety criteria;

(3) Select the largest gap;

(4) Update the speeds;

Particle i updates its speed under the following logics:

If $dX_f^t > v_i^t$,

then $\mathbf{V}_i^{t+1} = Min\left[\mathbf{V}_i^t + (1,0), (v_{\max}, 0)\right]$;

Else, if $dX_l^t > v_i^t$ and $dX_{lb}^t > v_{lb}^t$ or $dX_r^t > v_i^t$ and $dX_{rb}^t > v_{rb}^t$

then change to larger-gap lane, $\mathbf{V}_i^{t+1} = \mathbf{V}_i^t + \mathbf{PC}$;

Else, cannot change lateral position

$v_i^{t+1} = dX_f^t$, $\mathbf{V}_i^{t+1} = (v_i^{t+1},\ 0)$.

(5) Update the positions;

Particle i moves from P_i^t to P_i^{t+1} based on the updated speed; namely, $\mathbf{P}_i^{t+1} = \mathbf{P}_i^t + \mathbf{V}_i^{t+1}$.

Given the initial conditions and rules for updating particles' speeds and positions, we can simulate the particles' moving trajectories over time.

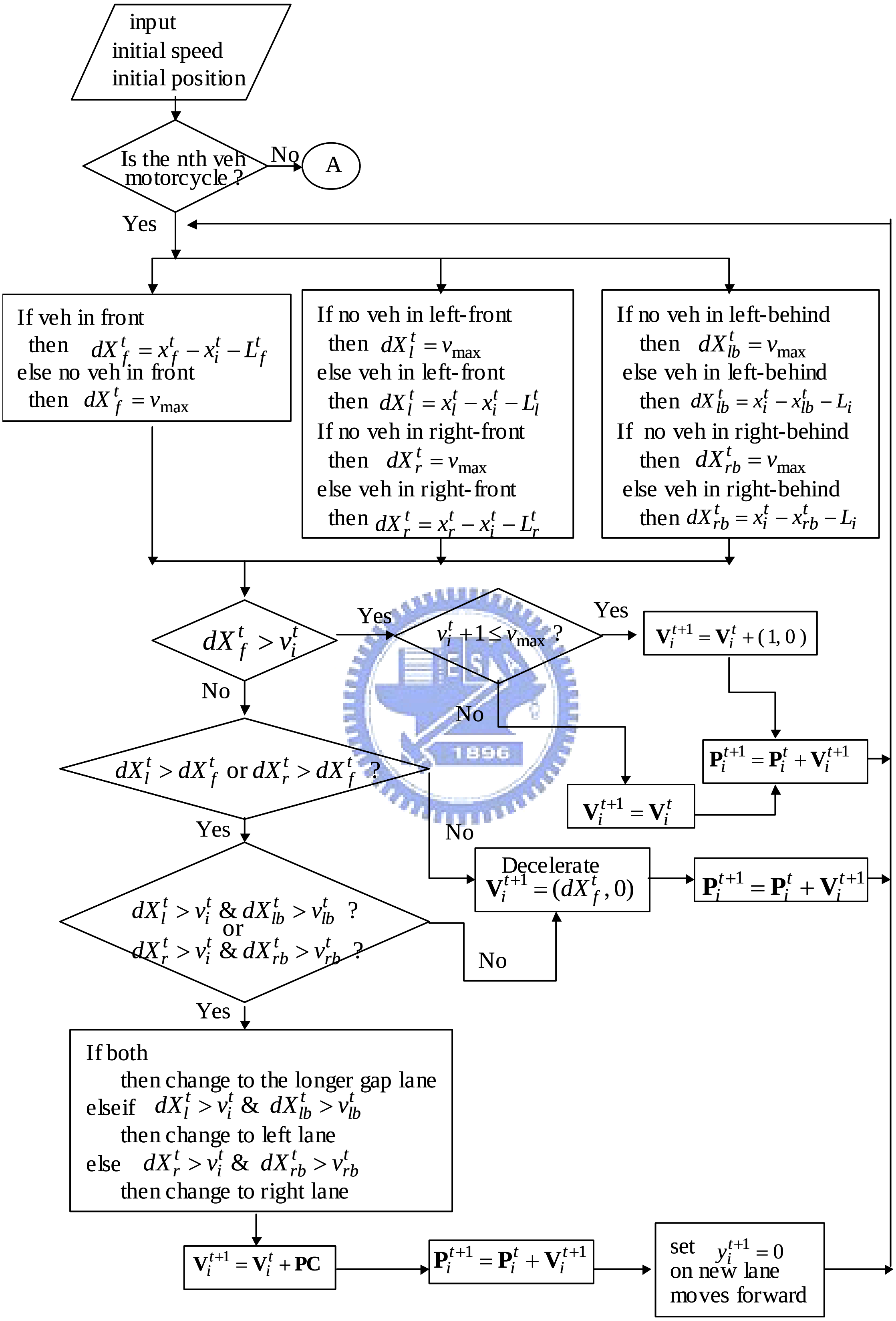

Figure 6-2 Rules for updating the particles' states

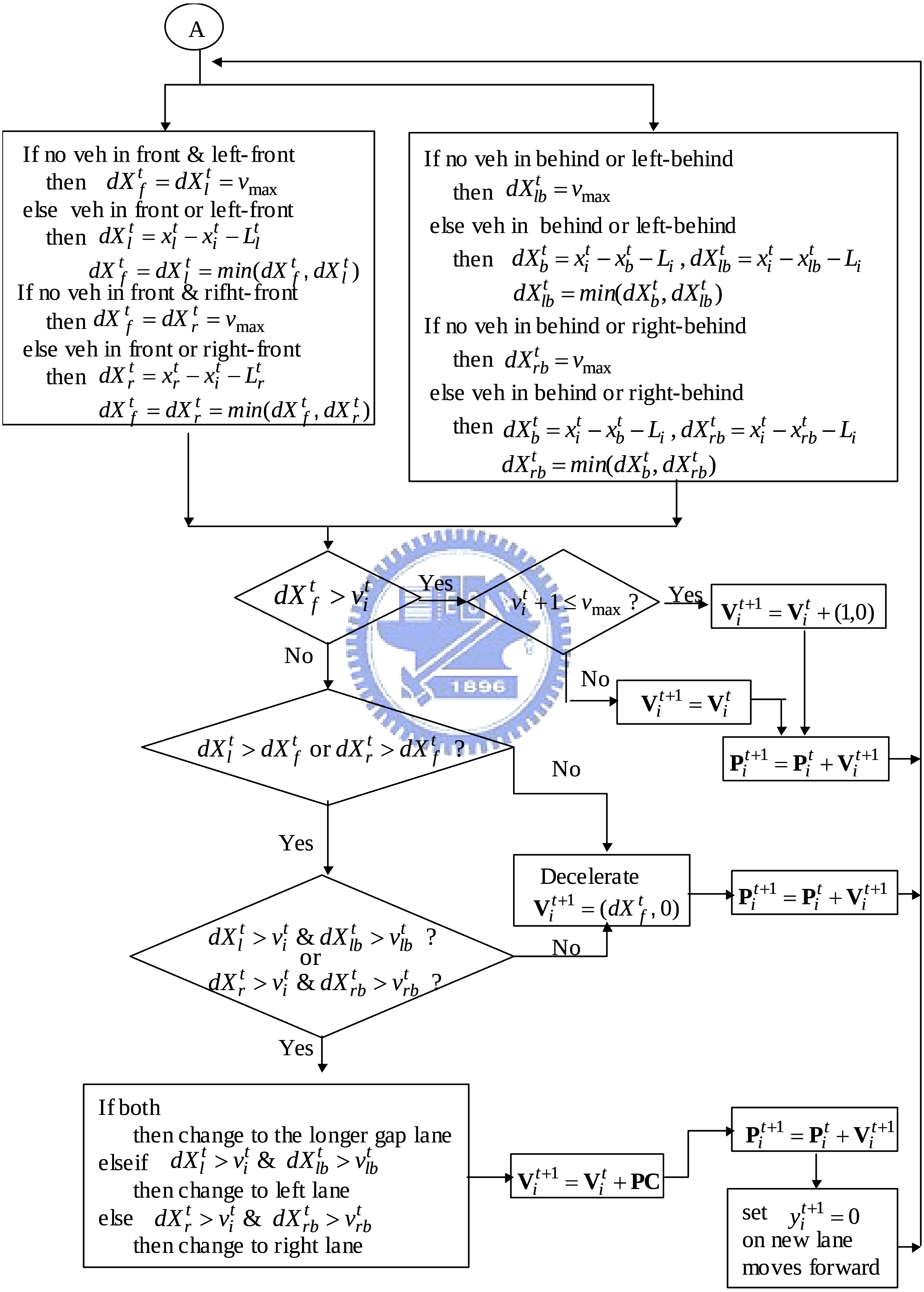

Figure 6-2 Rules for updating the particles' states (continued)

6.3 Simulations

The initial conditions in the following simulations are set as follows. A total of 150 inhomogeneous particles (cars and motorcycles) are generated according to given car mixtures from 0% to 100%. In the longitudinal direction, particles are equally spaced with distance headway (gap plus length of front particle) of 10 cells; however, in the lateral direction, particles are randomly scattered. Each particle moves at identical speed of 1 cell per second.

The aforementioned CA rules for updating the particle speeds and positions are used to simulate the particles' movements in the road section without interruptions by curb parking, pedestrian crossing, traffic light, etc. This study attempts five cases with "lane" width of 2 cell units (2.5m), 3 cell units (3.75m), 4 cell units (5m), 5 cell units (6.25m) and 6 cell units (7.5m). In both cases I (2.5m) and II (3.5m), it is impossible for any car to move in parallel along with the other car, thus the car has no chance to overtake another car. In other three cases, the car may have chances to overtake another car provided that the empty cells in the adjacent space are good enough. By contrast, a motorcycle is always possible to move in parallel along with the lateral motorcycle(s). Except for the case I, the motorcycle can also overtake the front car or move in parallel along with the car.

In this study, the cell occupancy, a proxy of density (ρ), is defined as:

$$\rho = \frac{N_0}{N} \tag{6.1}$$

where, N is the number of total cells; N_o is the number of occupied cells.

6.3.1 Results

Figure 6-3 demonstrates the simulated time-space trajectories of two cars and eight motorcycles moving in the 2-cell lane environment (Case I). Of them, #3 and #10 are cars occupying both lateral cells all the time; #2, #5, #7 and #9 are motorcycles moving in the first lateral cell; #1, #4, #6 and #8 are also motorcycles moving in the second lateral cell. The slopes of the trajectories represent vehicle speeds (For instance, at *t*=45 vehicles are all stopped; at *t*=54, the most front two motorcycles #1 and #2 start to move, at *t*=55, the following car #3 starts to move, etc.). The distance between any two vehicles at the same time step represents the distance headway (gap plus front vehicle length). Since the length of a car is 6 cell units and of a motorcycle is 2 cell units, the distance headway for any two vehicles lead by a car is larger than that lead by a motorcycle. For instance, the distance headway between #3 and #4 (or between #3 and #5) is larger than the one between #4 and #6. Figure 6-3 has demonstrated this important property. The other four cases also demonstrate reasonable simulation outcomes, suggesting that our CA particles hopping models can satisfactorily depict the time-space interrelationship between motorcycles and cars..

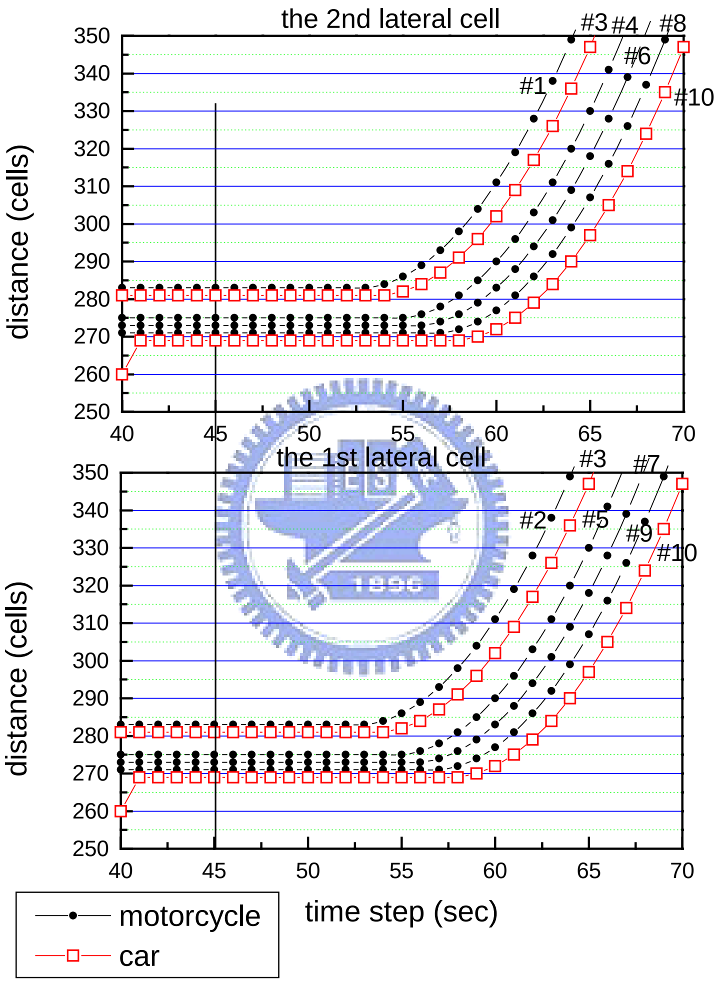

Figure 6-3 Simulated trajectories of ten particles in 2-cell lane (Case I)

6.3.2 Effects of lane widths and car percentages

The flow (q)-occupancy (ρ) and speed (v)-occupancy (ρ) diagrams of pure car and motorcycle flow under various lane widths, from 2 cell to 6cell, are presented in Figure 6-4 and Figure 6-5, respectively. Both Figure 6-4 and 6-5 reveal the maximum flow rates for pure motorcycle and car at the occupancy ranging from 0.13 to 0.18, 0.22 to 0.32. The ranges of occupancy at maximum flow rates for pure car concur with the findings by Nagel (1998) on one-dimensional model. Under pure motorcycle condition, the maximum flow rates for case I to V are 6,000 to 18,000 vph. Both Figure 6-4 and Figure 6-5 also indicate that jammed densities (occupancies) for pure car conditions under various cases range from 0.67 to 1.00, but only that of case I can reach 1.00. In the other cases, the jammed densities for pure car conditions are around 0.70. These phenomena reflect the fact that as the lane widths increase (e.g. case II ~ case V), the cells utilization efficiency for cars is not better.

Table 6.1 shows the maximum flow rates corresponding to various car mixes for these five cases. Similarly, the maximum flow rates are influenced by the width of lane and percentages of car. For example, under pure motorcycle condition, the maximum flow rate in case II and case V are 200% and 50% higher than that in case I; while in the condition of 100% car mixes, the maximum flow rates are the same for case I and case II, and that in case V is 120% higher than in case I. This result also explains that the following car cannot overtake the front car in both cases. Figure 6-6 presents the relationship between maximum flow rates and car mixes under various lane widths. Note that the maximum flow rates have a sharp decline from zero to 50 percentages of cars and a mild decline from 50 to 100 percentages.

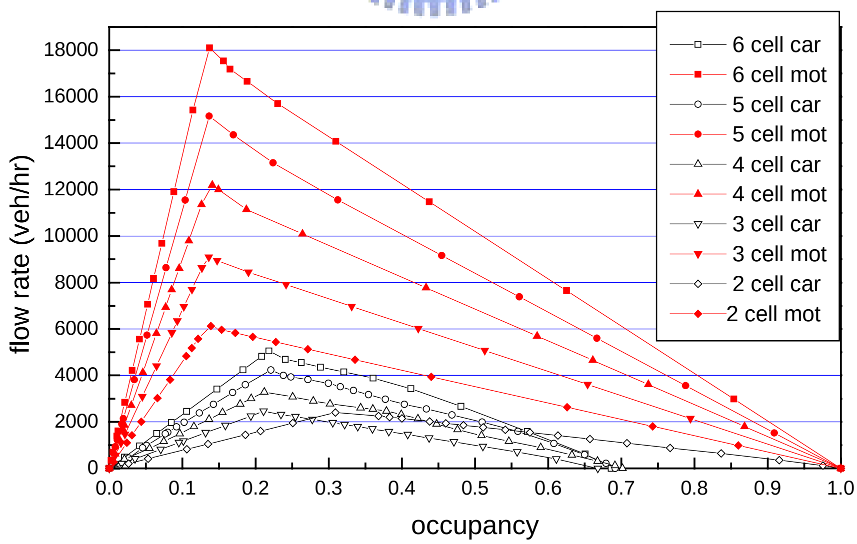

Figure 6-4 Flow-occupancy diagrams for pure motorcycles and pure cars

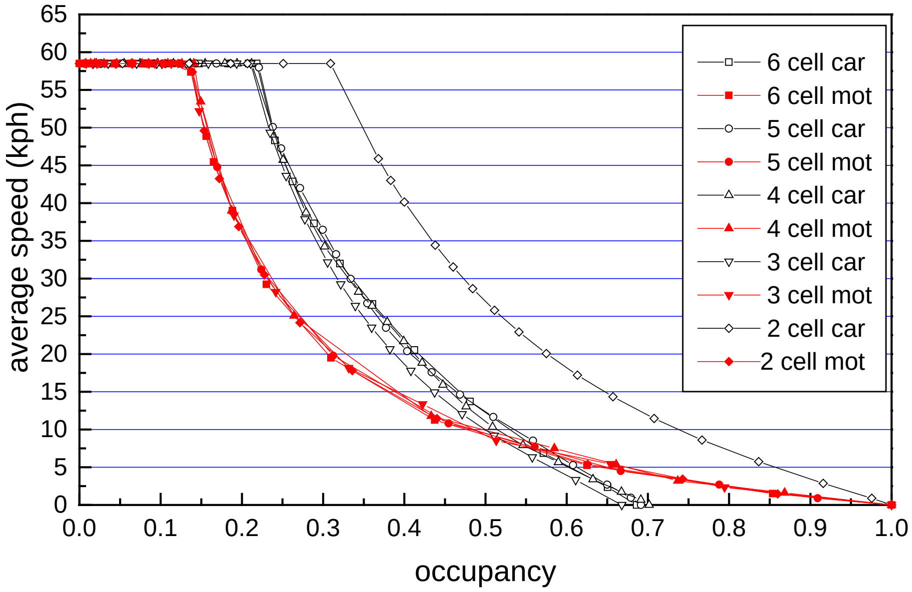

Figure 6-5 Speed-occupancy diagrams for pure motorcycles and pure cars

Table 6.1 Maximum flow rates under various traffic mixtures and lane widths

(unit:vph)

Percentages of cars	Case I 2 cells (2.5m)	Case II 3 cells (3.75m)	Case III 4 cells (5m)	Case IV 5 cells (6.25m)	Case V 6 cells (7.5m)
0%	6,000	9,000	12,000	15,000	18,000
10%	5,300	8,000	10,700	13,500	16,300
20%	4,550	6,950	9,450	12,000	14,500
30%	3,900	5,950	8,200	10,500	12,700
40%	3,400	5,200	7,100	8,950	11,000
50%	2,875	4,350	5,900	7,500	9,150
60%	2,750	3,750	5,150	6,650	8,200
70%	2,600	3,250	4,500	5,900	7,350
80%	2,500	2,900	4,000	5,300	6,600
90%	2,400	2,600	3,550	4,600	5,900
100%	2,300	2,300	3,250	4,150	5,200

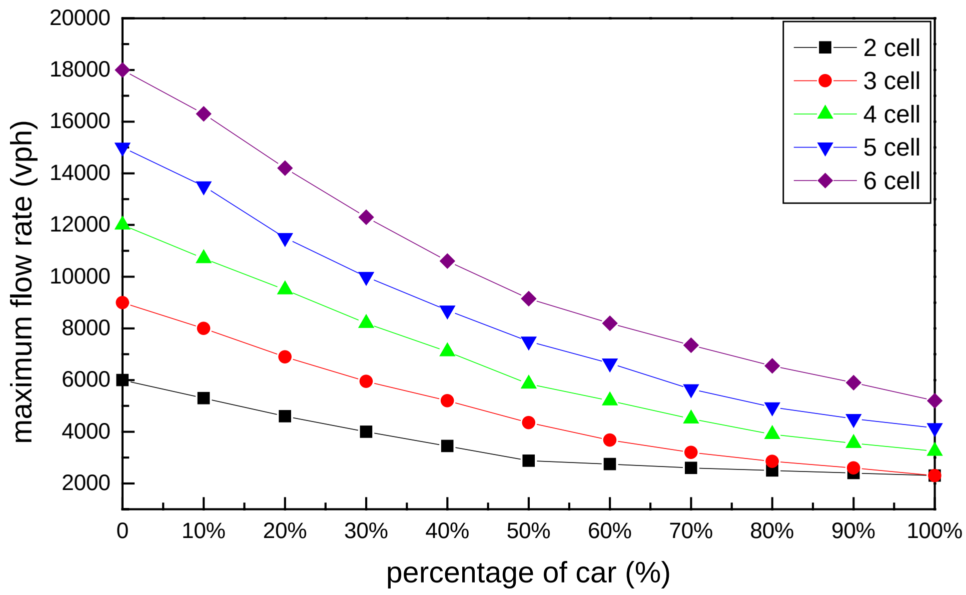

Figure 6-6 Maximum flow rates for various traffic mixtures

6.3.3 The motorcycle equivalent (me)

Similar to the concept of passenger car equivalents (pce), we define motorcycle equivalents (me) as a car equal to how many motorcycles in different car mixes under the prevailing conditions. The value of me under the same speed, for instance, is expressed as follows:

$$me = \frac{q_1(1-P_1) - q_2(1-P_2)}{q_2 P_2 - q_1 P_1} \tag{6.2}$$

where P_1 , P_2 are the car percentages; q_1 , q_2 are the flow rates corresponding to P_1 and P_2. The relationship of pce and me is:

$$pce = \frac{1}{me} \tag{6.3}$$

Table 6.2 summarizes the *me* and *pce* values under different traffic mixtures and lane widths. In case I, for example, the *me* values can range from 2.32 to 2.61 (at speed 55kph) and from 3.97 to 4.00 (at speed 5kph) with respect to 10% to 100% of cars. For pure cars with speed 55kph, the *me* values are from 2.61 to 3.46 as the lane width increases from two to six cells.

Table 6.2 The *me* and *pce* values under various traffic mixtures and lane widths

Speed	Percentages of cars	Case I 2 cells		Case II 3 cells		Case III 4 cells		Case IV 5 cells		Case V 6 cells	
(kph)	(%)	*me*	*pce*	*me*	*pce*	*me*	*pce*	*me*	*pce*	*me*	*pce*
	10	2.32	0.43	2.25	0.44	2.21	0.45	2.11	0.47	2.04	0.49
	20	2.52	0.40	2.47	0.40	2.32	0.43	2.25	0.44	2.21	0.45
	30	2.79	0.36	2.71	0.37	2.54	0.39	2.43	0.41	2.39	0.42
	40	2.91	0.34	2.83	0.35	2.73	0.37	2.71	0.37	2.67	0.38
55	50	3.17	0.32	3.14	0.32	3.10	0.32	3.00	0.33	2.93	0.34
	60	2.97	0.34	3.41	0.29	3.18	0.31	3.09	0.32	2.99	0.33
	70	2.87	0.35	3.59	0.28	3.38	0.30	3.30	0.30	3.07	0.33
	80	2.75	0.36	3.70	0.27	3.60	0.28	3.54	0.28	3.19	0.31
	90	2.67	0.38	3.74	0.27	3.64	0.27	3.59	0.28	3.28	0.30
	100	2.61	0.38	3.91	0.26	3.69	0.27	3.61	0.28	3.46	0.29
	10	2.52	0.40	2.44	0.41	2.33	0.43	2.25	0.44	2.17	0.46
	20	2.80	0.36	2.69	0.37	2.61	0.38	2.55	0.39	2.40	0.42
	30	2.94	0.34	2.83	0.35	2.71	0.37	2.59	0.39	2.51	0.40
	40	3.07	0.33	2.96	0.34	2.84	0.35	2.79	0.36	2.70	0.37
45	50	3.25	0.31	3.22	0.31	3.11	0.32	3.03	0.33	2.94	0.34
	60	3.01	0.33	3.50	0.29	3.29	0.30	3.20	0.31	3.02	0.33
	70	2.91	0.34	3.54	0.28	3.48	0.29	3.40	0.29	3.15	0.32
	80	2.80	0.36	3.68	0.27	3.61	0.28	3.50	0.29	3.21	0.31
	90	2.71	0.37	3.82	0.26	3.70	0.27	3.57	0.28	3.39	0.30
	100	2.66	0.38	3.98	0.25	3.77	0.27	3.69	0.27	3.57	0.28
	10	2.91	0.34	2.79	0.36	2.68	0.37	2.60	0.38	2.40	0.42
	20	2.75	0.36	2.82	0.35	2.79	0.36	2.77	0.36	2.74	0.37
	30	3.00	0.33	2.90	0.34	2.88	0.35	2.92	0.34	2.91	0.34
	40	3.09	0.32	3.03	0.33	2.93	0.34	2.94	0.34	2.94	0.34
35	50	3.57	0.28	3.49	0.29	3.32	0.30	3.16	0.32	3.16	0.32
	60	3.30	0.30	3.70	0.27	3.33	0.30	3.29	0.30	3.26	0.31
	70	3.13	0.32	3.71	0.27	3.69	0.27	3.64	0.27	3.33	0.30
	80	2.93	0.34	3.79	0.26	3.78	0.26	3.65	0.27	3.33	0.30
	90	2.85	0.35	3.96	0.25	3.82	0.26	3.71	0.27	3.46	0.29
	100	2.87	0.35	4.23	0.24	3.93	0.25	3.77	0.26	3.66	0.27
	10	3.30	0.30	3.16	0.32	3.04	0.33	2.83	0.35	2.60	0.38
	20	3.64	0.27	3.22	0.31	3.18	0.31	3.15	0.32	2.97	0.34
	30	3.82	0.26	3.30	0.30	3.25	0.31	3.21	0.31	3.19	0.31
	40	3.45	0.29	3.37	0.30	3.33	0.30	3.30	0.30	3.21	0.31
25	50	3.86	0.26	3.54	0.28	3.52	0.28	3.39	0.29	3.23	0.31
	60	3.58	0.28	3.86	0.26	3.57	0.28	3.43	0.29	3.33	0.30
	70	3.39	0.29	3.91	0.26	3.86	0.26	3.71	0.27	3.34	0.30
	80	3.36	0.30	3.97	0.25	3.94	0.25	3.74	0.27	3.53	0.28
	90	3.10	0.32	4.11	0.24	4.10	0.24	3.97	0.25	3.68	0.27
	100	3.06	0.33	4.34	0.23	4.19	0.24	4.03	0.25	3.82	0.26
	10	3.50	0.29	3.43	0.29	3.23	0.28	3.09	0.32	2.79	0.36
	20	3.81	0.26	3.80	0.26	3.59	0.28	3.32	0.30	3.27	0.31
	30	4.01	0.25	3.94	0.25	3.70	0.27	3.35	0.30	3.30	0.30
	40	4.26	0.23	3.41	0.29	3.81	0.26	3.36	0.30	3.31	0.30
15	50	4.30	0.23	4.21	0.24	4.15	0.24	3.62	0.28	3.46	0.29
	60	3.89	0.26	4.29	0.23	4.22	0.24	3.96	0.25	3.72	0.27
	70	3.74	0.27	4.80	0.21	4.43	0.23	4.07	0.25	3.93	0.25
	80	3.66	0.27	4.91	0.20	4.49	0.22	4.23	0.24	4.03	0.25
	90	3.49	0.29	4.97	0.20	4.61	0.22	4.25	0.24	4.10	0.24
	100	3.37	0.30	5.12	0.20	4.72	0.21	4.43	0.23	4.24	0.24
	10	3.97	0.25	3.86	0.26	3.63	0.28	3.42	0.29	3.18	0.31
	20	4.28	0.23	4.00	0.25	3.74	0.27	3.41	0.29	3.26	0.31
	30	4.33	0.23	4.15	0.24	4.07	0.25	3.52	0.28	3.45	0.29
	40	4.50	0.22	4.31	0.23	4.21	0.24	3.89	0.26	3.74	0.27
5	50	4.65	0.22	4.54	0.22	4.33	0.23	4.13	0.24	3.87	0.26
	60	4.67	0.21	5.05	0.20	4.49	0.22	4.21	0.24	4.17	0.24
	70	4.47	0.22	5.42	0.18	4.85	0.21	4.74	0.21	4.47	0.22
	80	4.37	0.23	5.52	0.18	5.11	0.20	4.88	0.21	4.72	0.21
	90	4.19	0.24	5.60	0.18	5.50	0.18	5.36	0.19	4.97	0.20
	100	4.00	0.25	5.81	0.17	5.65	0.18	5.59	0.18	5.39	0.19

Figure 6-7 demonstrates the *me* values with respect to various speeds for pure cars. Note that the *me* values decrease with the increase of speed in all cases. Lower *me* values represent higher efficiency of the cells utilization. Generally, the *me* values decrease as the lane width increases; indicating that the wilder roads provide higher degrees of freedom for particles' moving and overtaking than the narrower ones do.

Figure 6-8 illustrates the *me* values with respect to different percentages of cars at speed 45 kph. We notice that case I has special *me* values with respect to various car mixtures. It has the highest *me* values, the worst cells utilization efficiency, as the car percentages are lower than 50%. Nevertheless, it turns out to be the lowest *me* values, the best cells utilization efficiency, as the car percentages are over about 60%. This interesting result reflects the fact that if motorcycles are the majority, once the cars appear, the following motorcycles would have no chance at all to overtake the cars in case I but the overtaking chance becomes higher as the lane width gets larger. By contrast, if cars become the majority in case I, the motorcycles will be grouped into several blocks by any two cars, thus makes the cell utilization better than the other cases.

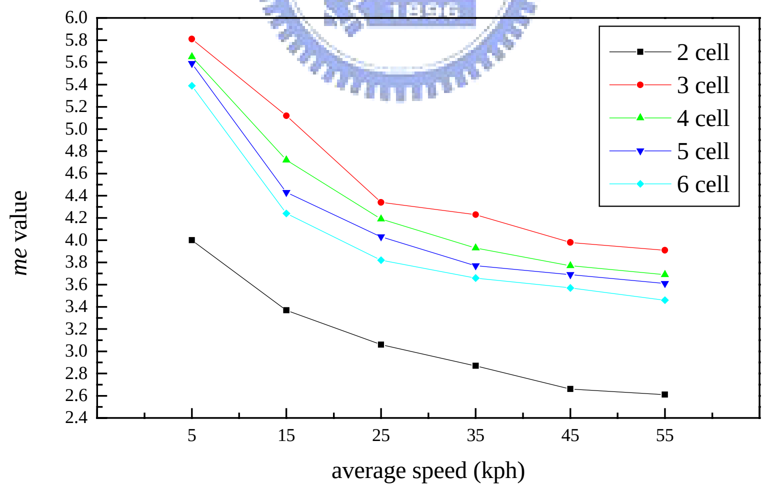

Figure 6-7 The *me* values at various speeds under pure cars

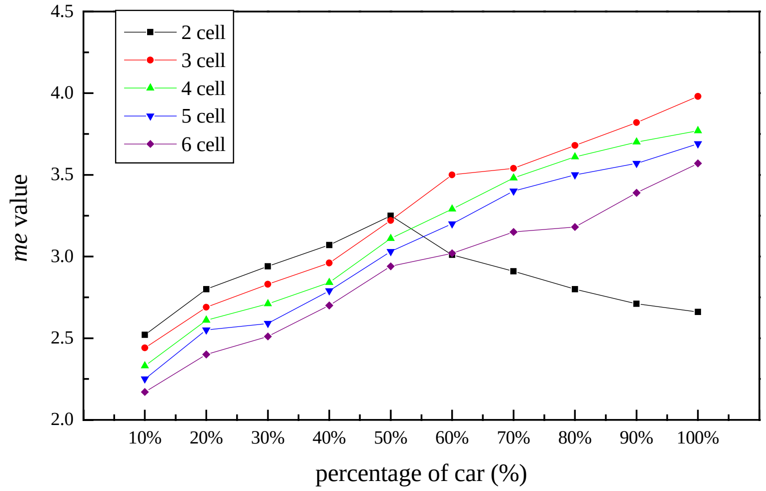

Figure 6-8. The *me* values for various traffic mixtures at speed 45 kph

6.4 Validation

In order to validate the proposed inhomogeneous particles hopping models, we conduct a two-hour survey (16:30 to 18:30pm) in the T-2 Provincial Highway at Chuwei of Taipei County. The southbound mixed traffic flows in the outer lane of 3.5-meter width are recorded by a video camera and a total of 4,882 vehicles are observed (motorcycles are prohibited in the inner lanes). This survey has obtained 120 one-minute flow rates with corresponding speeds and densities. Figure 6-9 displays the speed-flow relationship for these 120 samples. Figure 6-10 further shows the speed distributions for individual motorcycles and cars, which approximately follow normal distributions with mean 55 kph and standard deviation 11.8 kph.

Note from Figure 6-10 that the speeds for motorcycles in the T-2 Highway are slightly higher than the cars. Thus, we further undertake a statistical test and the result ($\chi^2 = 81.71 > \chi^2_{(0.05,10)} = 18.3$) has rejected the null hypothesis that speed is independent of the vehicle type. Therefore, we modify the aforementioned CA parameters by assigning the car with maximum speeds of 12 cell units (54 kph) and the motorcycle with 13 cell units (58.5 kph). The field observed data in T-2 Highway and the simulated data are presented in Figure 6-11 and Table 6.3. Note that most of the discrepancies between the observed and simulated data are less than ± 5%, suggesting that our CA rules have been validated by another field observation.

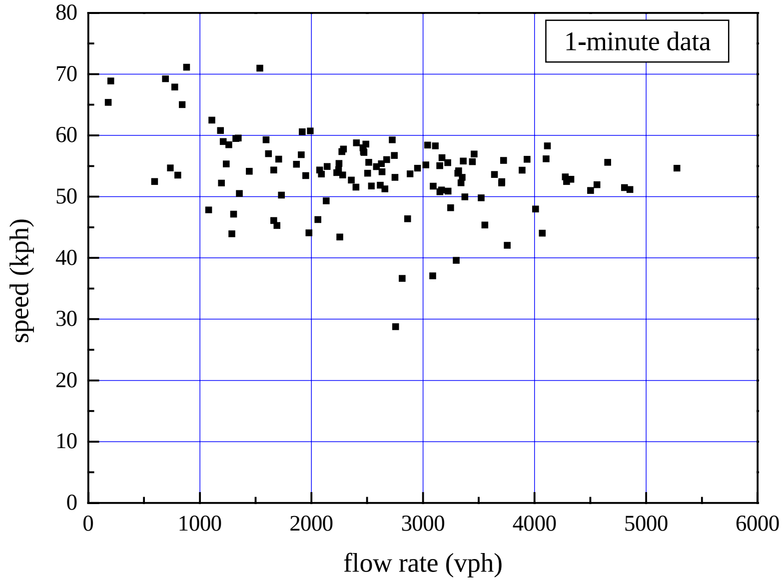

Figure 6-9. Observed speeds versus flow rates in T-2 Highway

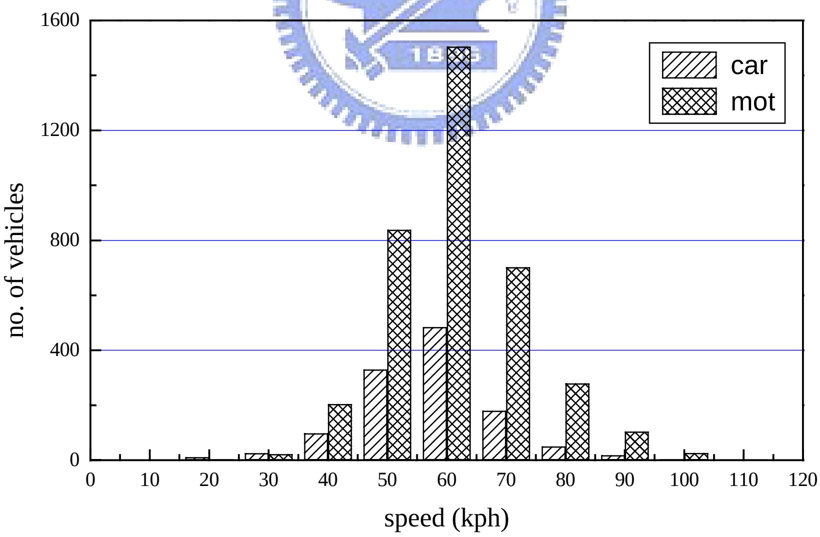

Figure 6-10. Observed speed distributions in T-2 Highway

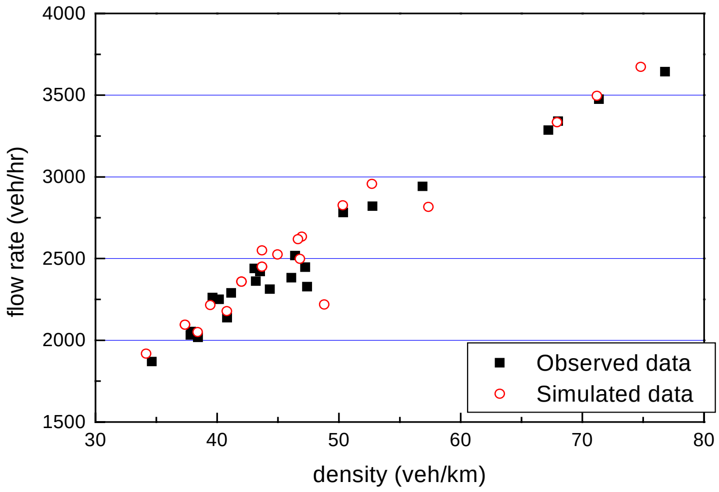

Figure 6-11. Observed and simulated flow-density in T-2 Highway

Table 6.3 A comparison between observed and simulated data in T-2 Highway

Percentages of motorcycles	Observed data			Simulated data			△Flow rate (%)
	Speed (kph)	Flow rate (vph)	Density (vpk)	Speed (kph)	Flow rate (vph)	Density (vpk)	
61%	52.54	2,018	38.42	53.38	2,050	38.40	1.56%
61%	52.38	2,138	40.82	53.38	2,178	40.80	1.87%
78%	54.00	1,870	34.63	56.16	1,918	34.16	2.59%
66%	51.82	2,447	47.23	56.09	2,634	46.96	7.63%
63%	51.69	2,383	46.10	53.38	2,498	46.80	4.83%
71%	54.69	2,362	43.18	56.09	2,450	43.68	3.73%
70%	53.73	2,032	37.81	56.09	2,095	37.36	3.12%
67%	48.89	3,286	67.21	49.10	3,335	67.92	1.49%
81%	47.45	3,644	76.80	49.10	3,673	74.80	0.77%
77%	49.12	3,341	68.01	49.10	3,335	67.92	-0.18%
72%	48.68	3,475	71.37	49.10	3,496	71.20	0.61%
71%	53.48	2,821	52.76	56.09	2,957	52.72	4.80%
81%	55.25	2,782	50.35	56.16	2,826	50.32	1.59%
72%	51.73	2,942	56.87	49.10	2,816	57.36	-4.27%
83%	52.19	2,313	44.32	56.16	2,525	44.96	9.15%
73%	56.66	2,440	43.06	56.09	2,450	43.68	0.42%
79%	55.65	2,290	41.15	56.16	2,359	42.00	3.00%
76%	54.27	2,518	46.40	56.16	2,619	46.64	4.00%
78%	56.08	2,251	40.14	56.16	2,359	42.00	4.78%
91%	55.63	2,421	43.53	58.39	2,550	43.68	5.33%
80%	57.07	2,261	39.62	56.16	2,215	39.44	-2.05%
72%	54.20	2,053	37.87	56.09	2,095	37.36	2.08%
74%	49.13	2,328	47.39	45.48	2,219	48.80	-4.68%
58%	301.27	181.74	52.59	2115	40.22	2253	54.12

6.5 Stochastic CA Models

6.5.1 Deviations of maximum speeds

One of our deterministic CA rules has set the maximum speeds for individual vehicles of the same type with a fixed value. Of course, this assumption is too strict and does not fully fit the real world situations. Therefore, we further allow the deviations of maximum speeds for individual particles by modifying the CA rules with stochastic maximum speed distributions. Take an example that the maximum speeds are normally distributed with mean 13 cells and standard deviation 1 cell, denoted by *N*(13,1). The flow-occupancy and speed-occupancy diagrams for pure cars and pure motorcycles with stochastic maximum speeds *N*(13,1) are shown in Figures 6-12 and 6-13. Compared with Figures 6-4 and 6-5 obtained from deterministic maximum speeds V_{max}=13, we find that both maximum flow rates and optimal speeds by the stochastic CA models have decreased. It is due to the "slow-vehicle" effects.

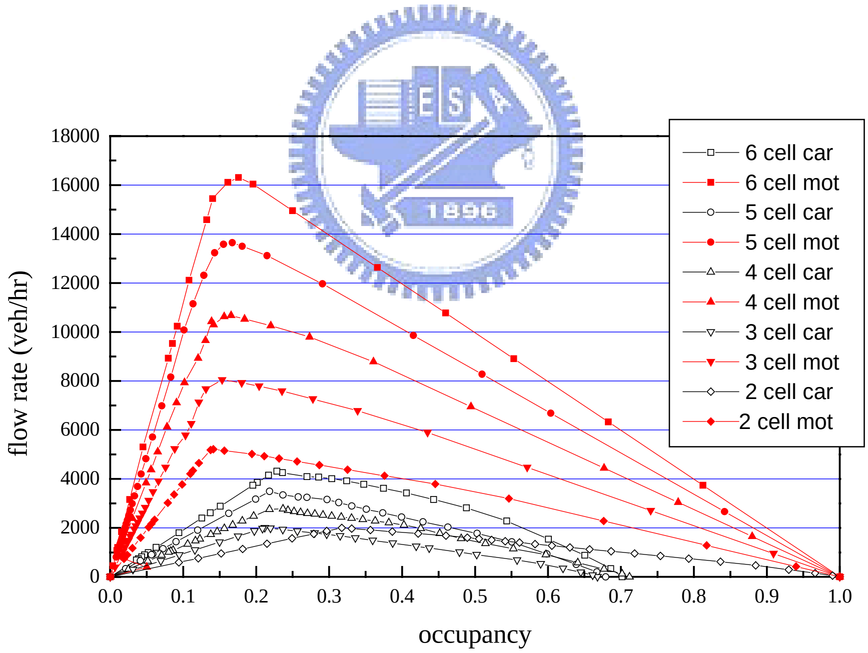

Figure 6-12 Flow-occupancy diagrams for pure motorcycles and pure cars (Stochastic CA models with maximum speeds ~ *N* (13,1))

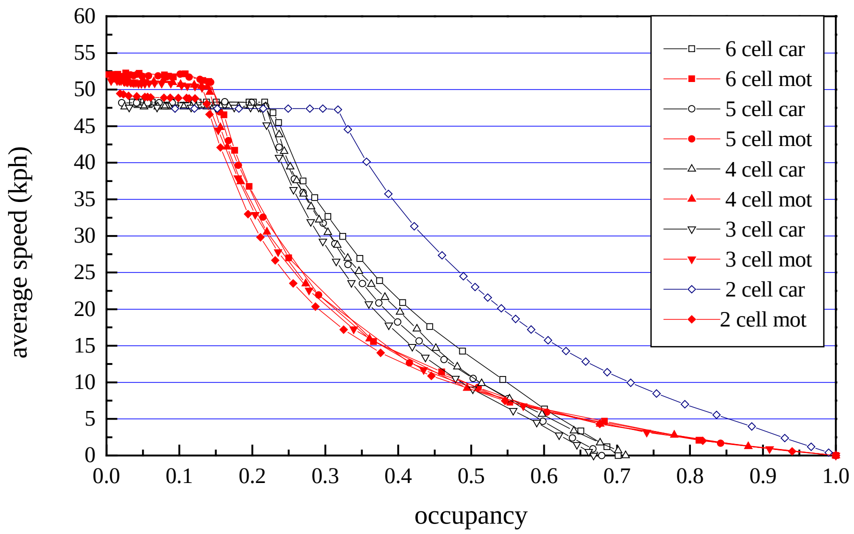

Figure 6-13 Speed-occupancy diagrams for pure motorcycles and pure cars (Stochastic CA models with maximum speeds ~ *N* (13,1))

In this *N*(13,1) example, Figure 6-14 further presents the maximum flow rates with respect to various traffic mixtures. Figure 6-15 displays the *me* values for various speeds under pure car condition. Figure 6-16 shows the *me* values with respect to various traffic mixtures at speed 45 kph. Compared with Figures 6-6, 6-7 and 6-8 obtained from deterministic maximum speeds $V_{max}=13$, we find that the corresponding *me* values for the stochastic CA models are apparently higher. It explains that with the deviation of maximum speeds, some slow vehicles have reduced the overall particles moving freedom.

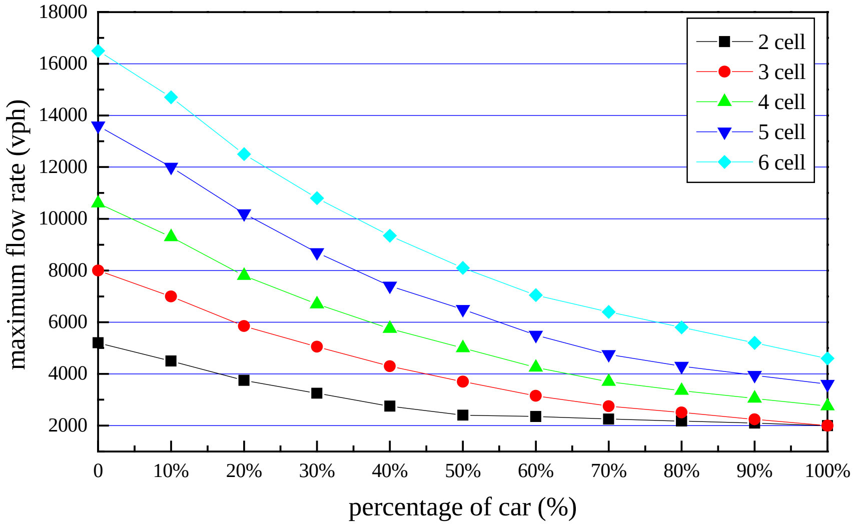

Figure 6-14 Maximum flow rates for various traffic mixtures
(Stochastic CA models with maximum speeds ~ *N* (13,1))

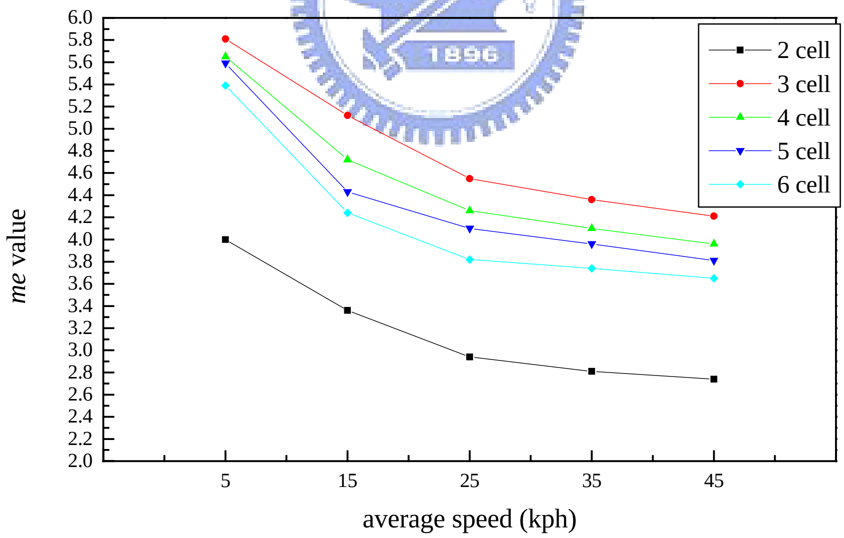

Figure 6-15. The *me* values at various speeds under pure car condition
(Stochastic CA models with maximum speeds ~ *N* (13,1))

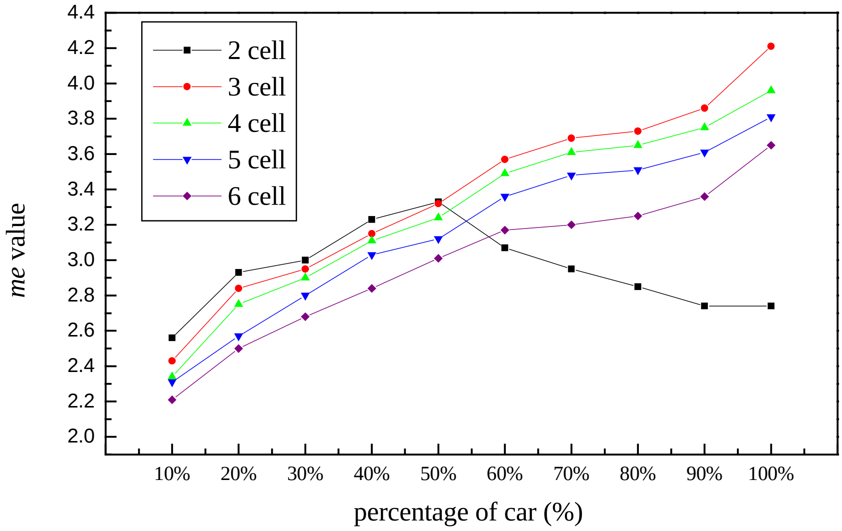

Figure 6-16. The *me* values for various traffic mixtures at speed 45 kph (Stochastic CA models with maximum speeds ~ *N* (13,1))

Figures 6-17 and 6-18 further compare the simulation results for pure motorcycles and pure cars among different maximum speed deviations: $V_{\max}=13$, *N* (13,1) and *N* (13,2). We find that as the maximum speed deviations get larger, the optimal speeds and maximum flow rates have significantly declined. Tables 4 and 5 present the details of maximum flow rates and optimal speeds among different maximum speed deviations. We conclude that the maximum flow rates and optimal speeds are negatively influenced by the deviation of maximum speeds; but the influence is less significant as the lane width gets larger.

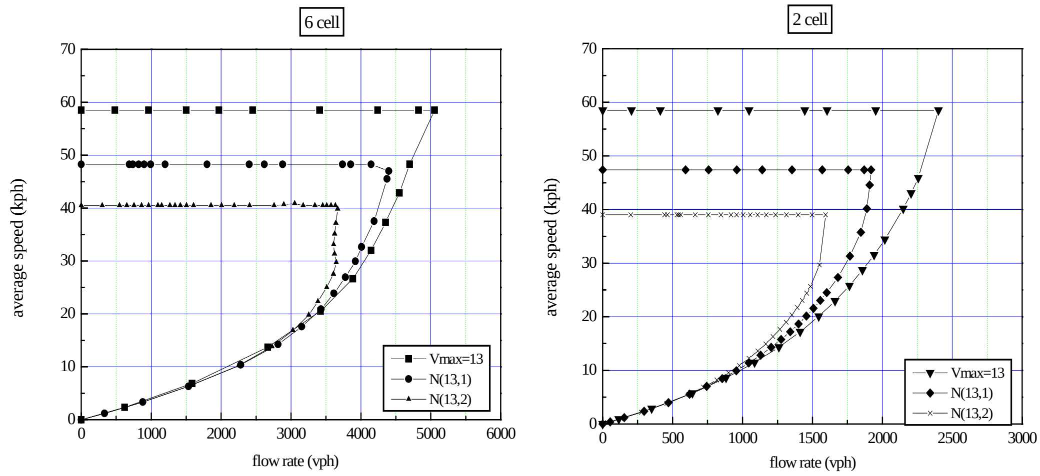

Figure 6-17. Speed-flow diagrams of CA models with various maximum speed deviations (pure motorcycles)

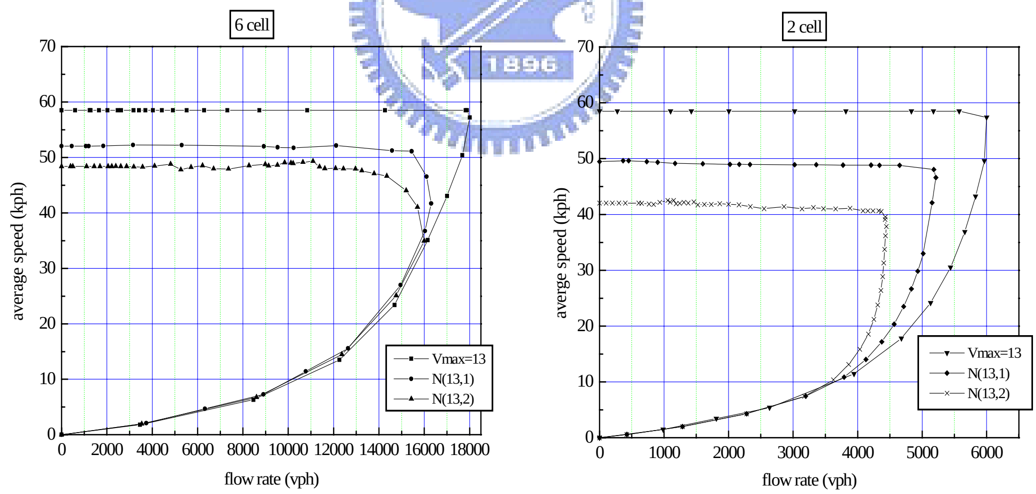

Figure 6-18. Speed-flow diagrams of CA models with various maximum speed deviations (pure cars)

Table 6.4 Maximum flow rates with various maximum speed deviations

Lane width	Pure motorcycles (vph)					Pure cars (vph)				
	V_{max}=13	N(13,1)		N(13,2)		V_{max}=13	N(13,1)		N(13,2)	
	a	b	(b-a)/a	c	(c-a)/a	d	e	(e-d)/d	f	(f-d)/d
2 cells (2.5 m)	6,000	5,200	-13.3%	4,450	-25.8%	2,300	1,900	-17.4%	1,550	-32.6%
3 cells (3.75 m)	9,000	8,000	-11.1%	7,200	-20.0%	2,300	1,900	-17.4%	1,550	-32.6%
4 cells (5 m)	12,000	10,680	-11.0%	9,800	-18.3%	3,250	2,700	-16.9%	2,250	-30.8%
5 cells (6.25 m)	15,000	13,400	-10.7%	12,800	-14.7%	4,150	3,520	-15.2%	2,900	-30.1%
6 cells (7.5 m)	18,000	16,250	-9.7%	15,950	-11.4%	5,200	4,450	-14.4%	3,650	-29.8%

Table 6.5 Optimal speeds with various maximum speed deviations

Lane width	Pure motorcycles (kph)			Pure cars (kph)		
	V_{max}=13	N(13,1)	N(13,2)	V_{max}=13	N(13,1)	N(13,2)
2 cells (2.5 m)	58.5	49.5	42.0	58.5	47.5	39.0
3 cells (3.75 m)	58.5	51.0	44.6	58.5	47.5	39.0
4 cells (5 m)	58.5	51.3	47.0	58.5	47.7	39.3
5 cells (6.25 m)	58.5	51.8	47.1	58.5	48.2	40.0
6 cells (7.5 m)	58.5	52.0	48.4	58.5	48.3	40.5

6.5.2 More applications

Our stochastic CA models are further applied to simulate two cases that previous researches have dealt with: one is the pure car condition in a 3-cell freeway inner lane and the other is the pure motorcycle condition in a 2-cell lane. In the first case, we select the inner lane (3.75m) of Taiwan National Freeway N-1, where the observed maximum speeds are normally distributed with mean 22 cells and standard deviation 2 cells, *N*(22, 2). The simulation results show that the maximum lane flow is 2,300~2,350 vph with corresponding optimal speed 75~80kph. The speed-flow relationship is displayed in Figure 6-19. The simulation results have agreed to the Taiwan Highway Capacity Manual (Institute of Transportation, 2002).

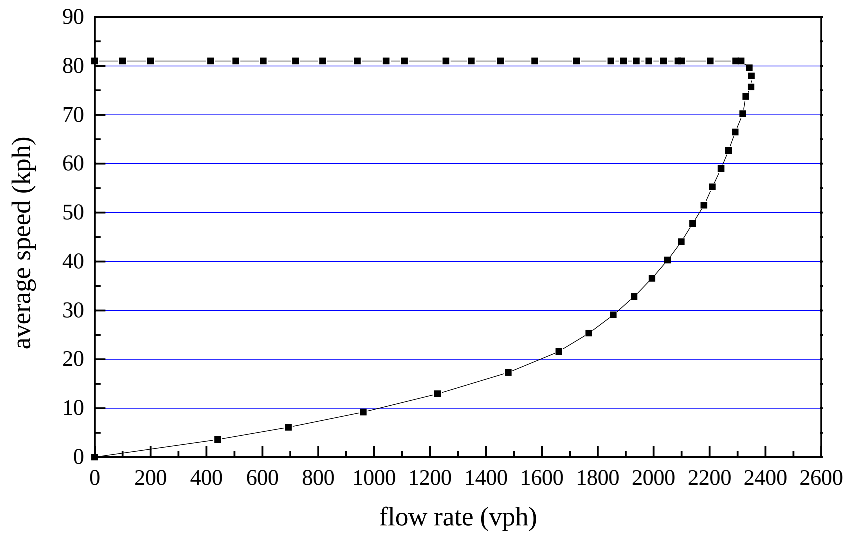

Figure 6-19. Speed-flow diagram of stochastic CA models for pure cars (3.75-meter freeway inner lane with maximum speeds ~ $N(22,2)$)

In the second case, we select a 2.5-meter motorcycle exclusive lane, where the observed maximum speeds are normally distributed with mean 13 cells and standard deviation 1 cell, $N(13,1)$. The simulated results conclude that the maximum flow rate is 5,200~5,300 vph with corresponding optimal speed 45~50kph. Figure 6-20 displays the speed-flow curve. The simulation results have also nearly complied with Tseng and Lin (2001), who found that the maximum flow rate is 5,400 vph on a 2.5-meter motorcycle exclusive lane.

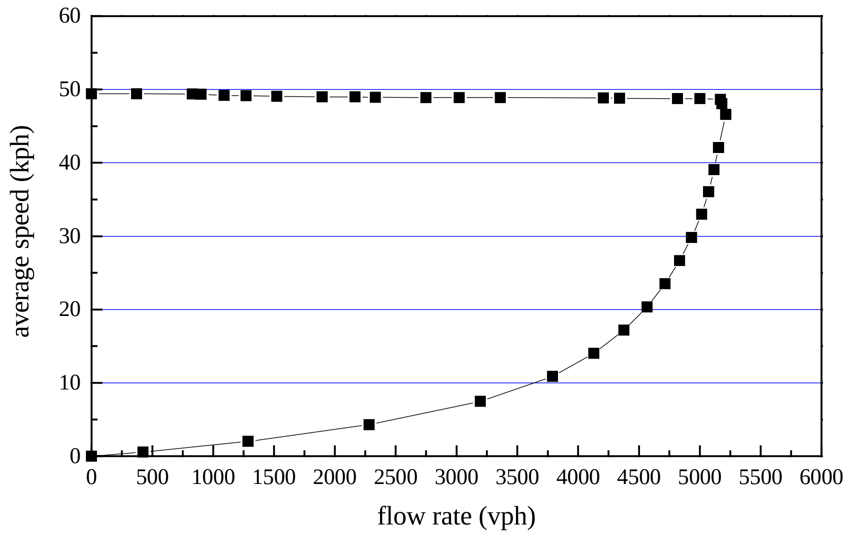

Figure 6-20. Speed-flow diagram of stochastic CA models for pure motorcycles (2.5-meter motorcycle exclusive lane with maximum speeds ~ $N(13,1)$)

6.6 Discussions

Based on the observation and dimensions of cars and motorcycles, we set the time step as 1 second and the cell unit as 1.25×1.25 meters. Therefore, a motorcycle in our CA model will occupy 2×1 cell units in length and width; a passenger car will take 6×2 units in length and width. The maximum speed of a motorcycle or car is set to be 13 cell units per time step. The preliminary simulation results show that this inhomogeneous particle-hopping model can reasonably simulate the moving trajectories of motorcycles and cars.

The simulation results reveal that the maximum flow rates correspond to cell occupancy (a proxy of density) of 0.13~0.32. Under pure motorcycle condition, the maximum flow rates for cases I to V are 6,000 to 18,500 vph. The jammed densities (occupancies) for pure car conditions under various cases range from 0.67 to 1.00, but only that of case I can reach 1.00. In the other case, the jammed densities for pure car conditions are around 0.70. These phenomena reflect the fact that as the lane widths increase (e.g. case II ~ case V), the cells utilization efficiency for vehicles is not better. We also find that case I has higher me values than other cases when the car percentages are less than 50%, implying that the particles on the lane width of (over) 3.75 meters are moving more freely than on the 2.5-meter lane. However, if the car percentages are greater than 50%, the me values in case I will decrease with the increase of car percentages, reflecting that case I performs better than other cases in terms of cells utilization efficiency. This finding is justified from the field observation since the probability for motorcycles overtaking the lead cars is lower when more cars exist in the 3.75-meter lane.

In order to validate this inhomogeneous particle-hopping model, we simulate three traffic flow situations. We modify the updating rules with different maximum speed of car and motorcycle based on the situations. It is found that most of the discrepancies between estimates and expected values are small. In other words, we can find that estimates are approximated to expected values. We also examine that influences of speed variation, and find that speed variations are larger, the average speeds and maximum flow rates are lower. However, while the lane widths are broader, the influences are slighter. Under pure motorcycle conditions, maximum flow rate for 7.5-meter lane in N (13,1) and N (13,2) states are 9.7% and 11.4% lower than preliminary simulation results; in 2.5-meter lane, those are 13.3% and 25.8%. Similarly, maximum flow rate for 7.5-meter lane in N (13,1) and N (13,2) states are 14.4% and 29.8% lower than those in VMAX=13 state under pure car conditions; in 2.5-meter lane, those are 17.4% and 32.6%.

Our simulation results are experimented under five scenarios of lane width, 2.5, 3.75, 5, 6.25 and 7.5 meters. More scenarios of lane or road width can also be experimented; however, more complicated CA parallel updating rules will be required. Moreover, the inhomogeneous particle-hopping model tested and validated in different cities or countries, where motorcyclists and drivers may act differently, deserves further explorations.

CHAPTER 7 CONCLUSIONS

This chapter summarizes the major findings of the current research. Some general conclusions are drawn based on the previous chapters and possible directions for further explorations are presented.

7.1 General Conclusions

1. Summary of literature review

- Both the aforementioned conventional traffic flow models and particle-hopping (CA) models are developed only for depicting the interactions between individual cars, and will not be used in this study.
- Because the differences between motorcycles' behaviors and cars' behaviors are very large, microscopic analysis is more suitable than macroscopic analysis for inhomogeneous vehicles.
- The particle-hopping models are microscopic models, we can modify the models to reflect the moving behaviors of non-identical vehicles.
- To capture the interaction between vehicles, the longitudinal moving and latitudinal displacement of motorcycles under various situations must be observed.

2. Characteristics of field data

- Of these total, only 422 motorcycles (13.8%) are found with following behaviors, the others (86.2%) are treated as "sneaking" or "lane-changes" because their moving paths are either in between two adjacent vehicles or with lateral displacements greater than 0.5 meters.
- More than 75% of the observed motorcycles have traveled along the curbside. They appear within 5.0-7.0 meter, measuring from the separated island, in the 10-meter width slow lane. 89% of them have lateral displacement less than 0.5 meters within the observation range of 30 meters. The average gaps between lead vehicle and the following motorcycle is about 6~7 meters; the average gaps between left-front (or right-front) and the following motorcycle are 3~3.9 (or 2~3.6) meters. 80% of the total observations have traveled at speed ranging from 25 to 55 km/h.

3. Motorcycle-following model

- The rather low values of R^2 (0.295 and 0.103) or high RMSE values (0.76 and 0.92) of GM based models for case (I) and case (II) conclude that GM based models fail to describe the motorcycle-following behaviors. In contrast, the rather low RMSE values (0.16 and 0.34) of fuzzy-based models for the two cases strongly suggest that fuzzy-based models have overwhelmingly outperformed in depicting the motorcycle-following behaviors.
- We attempt to use the fuzzy-based model to simulate motorcycle platoons in a motorcycle exclusive lane of two-meter width, where overtaking and parallel traveling are not possible (It is the case (I)). All scenarios have come up with stable space headway of 9.63 meters at speed of 40kph, which is equivalent to a flow rate of 4,150 motorcycles per hour. This result corresponds with 2001 Highway Capacity Manual of Taiwan (2001) proposes service volume for two-meter width motorcycle exclusive lane with level of service between B and C, ranging from 3,600 to 5,400 motorcycles per hour.

4. Simulation results

- The preliminary simulation results show that this inhomogeneous particle-hopping model can reasonably simulate the moving trajectories of motorcycles and cars. The results are as follows:
- Based on the observation and dimensions of cars and motorcycles, we set the time step as 1 second and the cell unit as 1.25×1.25 meters for proposed inhomogeneous particle-hopping model. Therefore, a motorcycle in our CA model will occupy 2×1 cell units in length and width; a passenger car will take 6×2 units in length and width. The maximum speed of a motorcycle or car is set to be 13 cell units per time step.
- The simulation results of case I (2.5 meters) ~ case V (7.5 meters) reveal that the maximum flow rates correspond to cell occupancy (a proxy of density) of 0.13~0.32. Under pure motorcycle condition, the maximum flow rates for cases I to V are 6,000 to 18,000 vph.
- The jammed densities (occupancies) for pure car conditions under various cases range from 0.67 to 1.00, but only that of case I can reach 1.00. In the other case, the jammed densities for pure car conditions are around 0.70. These phenomena reflect the fact that as the lane widths increase (e.g. case II ~ case V), the cells utilization efficiency for vehicles is not better.

- We also find that case I has higher me values than other cases when the car percentages are less than 50%, implying that the particles on the lane width of (over) 3.75 meters are moving more freely than on the 2.5-meter lane. However, if the car percentages are greater than 50%, the me values in case I will decrease with the increase of car percentages, reflecting that case I performs better than other cases in terms of cells utilization efficiency. This finding is justified from the field observation since the probability for motorcycles overtaking the lead cars is lower when more cars exist in the 3.75-meter lane.
- This study modifies the updating rules with different maximum speed of car and motorcycle based on the situations. It is found that most of the discrepancies between estimates and expected values are small. In other words, we can find that estimates are approximated to expected values.
- This study also examines that influences of speed variation, and find that speed variations are larger, the average speeds and maximum flow rates are lower. However, while the lane widths are broader, the influences are slighter. Under pure motorcycle conditions, maximum flow rate for 7.5-meter lane in N (13,1) and N (13,2) states are 9.7% and 11.4% lower than preliminary simulation results; in 2.5-meter lane, those are 13.3% and 25.8%. Similarly, maximum flow rate for 7.5-meter lane in N (13,1) and N (13,2) states are 14.4% and 29.8% lower than those in VMAX=13 state under pure car conditions; in 2.5-meter lane, those are 17.4% and 32.6%.

7.2 Further Explorations

1. Because the present-type detection systems cannot precisely trace the relative positions of all vehicles in mixed traffic, advanced technologies need to be developed to improve the efficiency of data collection.
2. Reaction times of drivers will determine the updated time step for CA rules. Hence, an experimental study on the reaction time of drivers is an important issue and requires further investigation.
3. Our inhomogeneous particles hopping models have been established and validated in northern Taiwan. Motorcyclists and car drivers may act differently in different cities or countries, thus it deserves further explorations. The simulation results have been experimented under the lane width from 2 to 6 cells (2.5 to 7.5 meters). Other scenarios of lane (road) widths can also be experimented.

4. This study deals only with the interacting movements of two vehicle types, motorcycle and car, on the surface roads where flows are not interrupted by curb parking, crossing vehicles or traffic signals. Future studies can explore with more vehicle types including bus and bicycle or with interference (such as bus stop) at roadway sections or with signalized interruptions at intersections. However, it requires introducing more complicated CA rules that can realistically manage the particles stopping, starting, moving and turning behaviors.

5. In any cases, special attentions must be paid to the control of particles acceleration or deceleration to avoid unrealistic speed jumps or drops. Since the motorcyclists and car drivers may act differently in other cities or countries, more empirical case studies from different environments also deserve further explorations.

6. If we could have marked the lanes so as to govern the vehicle movements in the longitudinal direction and thus revise our CA rules accordingly, we would anticipate a higher road capacity than the condition without lane marking. The effect of lane marking on road capacity deserves further investigation.