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An extended car-following model with the consideration of the illegal pedestrian crossing

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ABSTRACT

Pedestrian illegal crossings at midblock are very unpredictable and pose a potential tragic conflict with vehicles besides generally disrupting the normal flow of traffic. The drivers need to not only anticipate but also respond to their actions accordingly to avoid potential conflicts. The objective of this paper was to describe the behavior of the drivers under illegal pedestrian crossing circumstances by proposing an extended car-following model, and then analyze the impacts of the illegal pedestrian crossing on the normal traffic flow at the midblock. In this study, three conditions have been considered, namely: no pedestrians, pedestrians present but waiting, and pedestrians crossing. The numerical results illustrate that the disruptive nature of the illegal pedestrian crossing could worsen when the number of pedestrian is large, the pedestrian platoon size is small, and the speed limitation is high.

1. Introduction

Walking is one of the important modes of traveling that is sensitive to the distance and time. In order to avoid detour and shorten the travel time, pedestrians may adopt mid-block crossing and jaywalking, especially in a route along roads with less pedestrian facilities [1]. Such behavior is quite common in the developing countries and usually random and largely depends on the wisdom of the pedestrians (in deciding when it is appropriate and safe to cross) and the goodwill of the drivers (to yield to the illegal crossing). Therefore, the micro driving behavior will be affected by the illegal pedestrian crossing [2].

To investigate the impacts of pedestrian crossing on traffic flow, the substantial literature on analyzing the properties of vehicular traffic flow and pedestrian have been developed. In a normal urban traffic situation, there will be an intermittent flow of cars. Drivers who are familiar with a road segment that has no provision for pedestrian crosswalks are likely to drive cautiously while being sensitive to the fact that any time a pedestrian may start crossing [3]. For the one who is not familiar, the behavior of pedestrians may surprise him and probably end up in a fatal conflict. The behavior of the car following will depend on the reaction and actions of the lead vehicle according to the dynamics of car-following models. If one of the pedestrian crosses alone when the oncoming vehicle is at a reasonable distance, the lead vehicle may only need to slow down to allow the person to cross but if they are in a platoon, then the lead vehicle may have to stop depending on how close it is to the point of the illegal crosswalk. In such a scenario, a shockwave will be generated by the cars following the lead vehicle and will last as long as it takes the pedestrians to cross. When the density of pedestrians is high, the crossing speed will be lower and they will take longer to complete the crossing process.

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From the driver's point of view, the character of a driver, such as aggressive driving behavior, is significant in this study. An aggressive driver may neither slow down at an illegal crosswalk nor stop for the pedestrians unless they find a worst-case scenario where there is a pedestrian platoon already crossing. However, drivers are more likely to yield when they are driving at lower speeds, have low deceleration rates and to more assertive pedestrians [4]. As vehicles approach the illegal crosswalks, out of caution, drivers may slow down in anticipation [3] of a pedestrian crosswalk operation, especially if there is a pedestrian platoon waiting by the roadside. This response to the roadside stimulus by slowing down [5] will effectively widen the gap between the lead vehicle and the car following if the car in front has already passed the pedestrian, thus encouraging the pedestrian to commence the crossing. If the available gap is 18.3 m and the vehicle speed is less than 4.47 m/s, then 75% of the pedestrians are likely to commence crossing [6]. However, an aggressive driver may accelerate to preempt the commencement of a crossing maneuver and avoid delay.

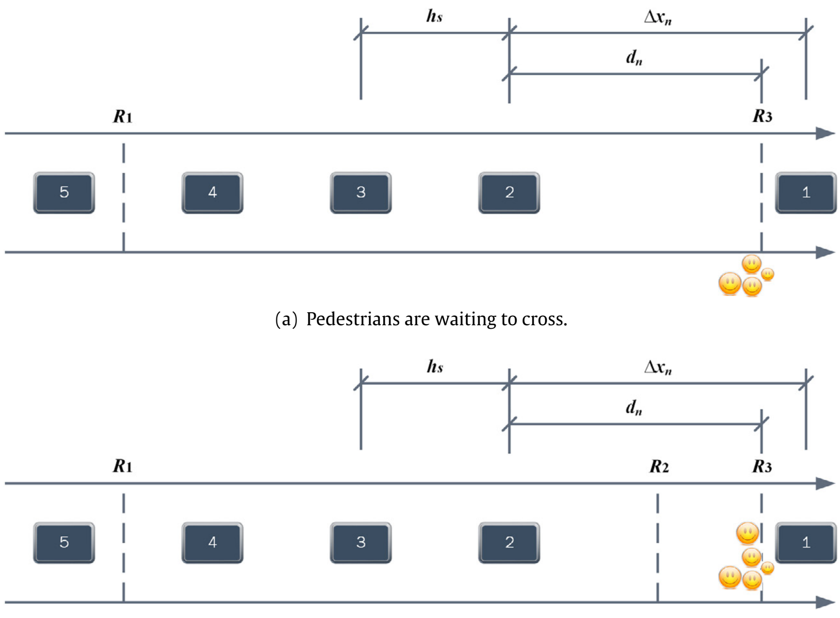
From the pedestrian's point of view, considering the fact that vehicles have right of way, crossing such road segments poses a safety challenge to pedestrians when they have to search for appropriate gaps between the vehicles before they can execute a safe crossing [7]. For pedestrians who value their safety and comfort, where there are alternative routes, the one along which a higher number of protected pedestrian crossings are available may be more preferable [8]. Many factors contribute to a pedestrian's decisions in order to execute a successful crossing maneuver at a midblock un-signalized and unmarked location. These include the number of lanes, the width of the road, the traffic density and speed, distance and speed of the oncoming vehicle, and the gap between the car in front and the one following behind it. A gap in traffic is generally defined as the space [9] or time [10] between vehicles in a traffic stream approaching a crossing. Temporal gap is the time passed after a pedestrian is ready to cross the road until the *n*th approaching vehicle reaches the point of conflict between the vehicle and pedestrian [10]. For vehicular traffic, it is the time difference between the leader and follower vehicle with respect to the pedestrian path [11]. The concept of Time to Arrival (TTA) investigates whether pedestrians use time or space gap in deciding whether it is safe to cross. Petzoldt [6] describes the TTA as the time a vehicle takes to travel the full length of the gap with its preceding vehicle. An acceptable gap (for crossing the road safely) may be determined by the pedestrian's gender, level of risk acceptance, the speed of the on-coming vehicle [6], how much the person trusts that the drivers will yield, and the person's perception of how long the gap is [1]. However, that perception may not be correct (the gap might be much longer or shorter than the person thinks it is).

Therefore, a pedestrian needs to compare the two microscopic parameters in order to decide whether it is safe to cross or not. The probability of a pedestrian accepting an available gap is inversely proportional to the speed of the approaching vehicle [10]. When pedestrians wait too long for the critical gap, they can form a pedestrian platoon wherefore they readily accept the available, albeit shorter and riskier, gaps [11]. Studies also indicate that younger male adult pedestrians are likely to accept a risky gap [11,12]. Depending on the size of the gap, number of lanes and the speed of the approaching vehicle, pedestrians cross the roadway in three different ways: single stage, two stages and rolling [1]. It is a challenge to find a single common gap or accurately estimate an acceptable gap in subsequent lanes in a multi-lane and multi-stream traffic flow so that a single-stage crossing can be executed. It is because of limited traffic visibility and the fact that vehicles are not stationary in those lanes. Studies have also been done to describe interactions between motor vehicles and pedestrians outside designated crossing facilities. They focus on pedestrian behavior during gap acceptance [10,13,14], crossing behavior at uncontrolled midblock locations in urban centers [15] in mixed traffic conditions [16], pedestrian jaywalking behavior (gap acceptance and speeds) and the corresponding driver reactions (yielding behavior) [17–19], changes in pedestrian road crossing behavior of an intersection under mixed traffic conditions [20] and human factors such as attitude, age, gender, and physiology that contribute to pedestrian behavior [17,21].

Since 1950s, many traffic flow models have been established to analyze various complex traffic phenomena [22–24]. The existing traffic flow models can be divided into two groups: microscopic models [25–46] and macroscopic models [47–60]. The former focus on exploring the micro properties of traffic flow, including car-following, lane-changing, overtaking, etc. Bando developed the Optimal Velocity model to describe the car-following behavior on a single-lane highway [61]. Helbing proposed Generalized Force Model to address the deficiency of the OV model [62]. Jiang extended the OV model by introducing positive relative velocity into the GF model and came up with the Full Velocity Difference (FVD) Model [63]. To-date, many car-following theory researchers have extended the FVD model to describe the behavior of drivers in different traffic circumstances. However, these studies and the inherent models do not describe the car-following traffic flow phenomena that is caused by the presence of illegal pedestrian crossing since they did not consider this factor. Therefore, this study focuses on the microscopic factors that influence normal traffic flow with respect to illegal pedestrian crossing. Building on previous car-following models, this study assumes that all the cars follow each other at a stable speed without tailgating or overtaking on a one-lane one-way roadway. It also considers the pedestrian crossing maneuver from the moment he chooses the appropriate time to cross up to the end excluding their behavior prior to the crossing. A model developed for urban traffic will be preferable.

2. Model

In actual traffic, drivers drive carefully considering potential traffic stimuli such as illegal pedestrians crossing, slow moving vehicles and those either joining or exiting the traffic stream. Consequently, some drivers may exhibit some cautious characteristics such as slowing down and response delay when approaching pedestrian crossing sites while the aggressive



(a) Pedestrians are waiting to cross.

(b) Pedestrians are crossing.

Fig. 1. Analyzing scenarios.

drivers would accelerate to attain anticipative optimal velocity [64]. To investigate the effect of illegal pedestrian crossing at midblock on behaviors of drivers.

2.1. Analyzing scenarios

The illegal pedestrian crossing site at midblock is considered as the research object, as illustrated in Fig. 1. From the pedestrians' point of view, ordinarily pedestrians would wait for an appropriate safe gap before they cross. They would consider vehicles within a sight distance range (R) depending on the speed of approaching vehicle for assessing the critical gap but at times when they wait too long, aggressive ones could dash across even when the gap is dangerously small.

From the drivers' point of view, in a normal traffic situation, a driver of the approaching vehicle may not be certain on the kind of pedestrian nor their possible actions of illegal crossing when the gap is not safe. To explore the effect of the pedestrians on the driving behaviors in a car-following model, we have identified three conditions that can affect smooth traffic flow, namely: no pedestrians, pedestrians present but waiting, and pedestrians crossing. These are summarized in three scenarios below.

Scenario 1: if the driver of the nth vehicle approaches the crossing site but if there are no waiting pedestrians, then the vehicle will proceed past the site.

Scenario 2: the nth vehicle enters the sight decision range R, and finds pedestrians waiting to cross but none is crossing, as shown in Fig. 1(a). It will proceed past the site according to the car-following model. If there is a cautious driver in the lead vehicle, the nth vehicle should slow down behind it and proceed according to the car-following model. However, if none of the pedestrians is crossing and there is no obstruction from a driver in the lead vehicle, the driver in the nth vehicle will adopt an aggressive driving strategy and accelerate to pass the crosswalk before any pedestrian can consider crossing.

Scenario 3: the nth vehicle finds that pedestrians have commenced crossing, as shown in Fig. 1(b), the driver should yield by adjusting the velocity to decelerate in advance and allow the pedestrian crossing maneuver to complete. However, if pedestrians crossing takes longer, vehicles have to stop and wait.

In order to describe the foregoing effects of the driver response on car-following behaviors of the arrival and traffic flow with the consideration of the illegal pedestrian crossing at the midblock, the existing car-following models should be extended. From the analysis above, the following is a description of the driving behavior of each vehicle.

2.2. Car-following behavior in scenario one

The motion behavior of the nth vehicle, according to the first scenario, shall not change. When the nth vehicle is out of the sight decision range, or the vehicle has passed the illegal crossing position, or the vehicle is not the head vehicle, or no waiting pedestrians, the Full Velocity Difference model given by Jiang [63] could be used to describe the car-following behaviors, as shown in Eq. (1).

$$\frac{dv_n(t)}{dt} = \kappa\left[V\left(\Delta x_n(t)\right) - v_n(t)\right] + \lambda \Delta v_n(t), \ (if\ x_n(n) < R_1\ or\ x_n(n) > R_3\ or\ \Delta x_n(t) < d_n(t)\ or\ N_p = 0) \tag{1}$$

where, t represents time, s; $v_n(t)$ is the velocity of the nth car at time t, m/s; $x_n(t)$ is the position of vehicle n at time t; $\Delta x_n(t) = x_{n+1}(t) - x_n(t)$ is the headway of two successive vehicles at time t, m; $\Delta v_n(t) = v_{n+1}(t) - v_n(t)$ is the velocity difference of two successive vehicles at time t, m/s; $d_n(t)$ is the distance between vehicle n and the site of the pedestrian crossing at time t, m; R_1 and R_3 are the position of the sight decision range and the illegal crossing, respectively, m; κ and λ are sensitivity parameters; and $V(.)$ is the optimal velocity function of the nth vehicle and can be selected as that proposed by Helbing and Tilch [62] below:

$$V\left(\Delta x_n(t)\right) = V_1 + V_2 \tanh[C_1(\Delta x_n - l_c) - C_2], \ (if\ x_n(t) < R_1; N_p = 0) \tag{2}$$

where, l_c is the average length of a car in the traffic stream, m; V_1, V_2, C_1, and C_2 are parameters; N_p is the number of pedestrians.

2.3. Car-following behavior in scenario two

In the second scenario, there are three possibilities. First, the nth vehicle is in the sight decision range, and pedestrians are waiting to cross. Therefore, the motion behavior of nth vehicle can be described by the FVD model.

$$\frac{dv_n(t)}{dt} = \kappa\left[V\left(\Delta x_n(t)\right) - v_n(t)\right] + \lambda \Delta v_n(t), \left(if\ \Delta x_n(t) \ge d_n(t); R_1 \le x_n(t) \le R_3; \frac{d_n(t)}{v_n(t)} \ge T_{ct}\right) \tag{3}$$

where, $\frac{d_n(t)}{v_n(t)}$ is the time gap between vehicle n at time t and the pedestrian crossing site, s; and T_{ct} is the total crossing time of the pedestrians, s, which can be computed by Eq. (6) according to the Highway Capacity Manual [65].

Secondly, the vehicle in front is driven by a cautious driver. Therefore, the nth vehicle will decelerate softly and then maintain motion in a low speed for drivers. Naturally, when the headway $\Delta x_n(t)$ is very small, the pedestrians may not attempt to cross, while the nth vehicle will maintain its current velocity, $v_n(t)$, which is relative to the car in front. Its motion behavior can be described by the following expression.

$$\frac{dv_n(t)}{dt} = min\left\{\kappa\left[v_{min}^c - v_n(t)\right], a_{min}\right\}, \left(if\ b_n = 0; \Delta x_n(t) < d_n(t); R_1 \le x_n(t) \le R_3; \frac{d_n(t)}{v_n(t)} < T_{ct}\right) \tag{4}$$

where, a_{min} is the maximum value of the softly deceleration, m/s^2; v_{min}^c is the minimum speed for conservative drivers when find pedestrians are waiting, m/s; and b_n is the character of the driver, 0 for conservative and 1 for aggressive.

Thirdly, if the nth vehicle adopts an aggressive driving strategy, then it should accelerate to the maximum allowable velocity that could ensure the vehicle passes the pedestrian crossing before the pedestrians start to cross if there is no other vehicle in front of it. Therefore, its motion behavior can be formulated as follows:

$$\frac{dv_n(t)}{dt} = \kappa\left[v_{max} - v_n(t)\right], \left(if\ b_n = 1; \Delta x_n(t) < d_n(t); R_1 \le x_n(t) \le R_3; \frac{d_n(t)}{v_n(t)} < T_{ct}\right) \tag{5}$$

where, v_{max} is the maximum speed limitation, m/s.

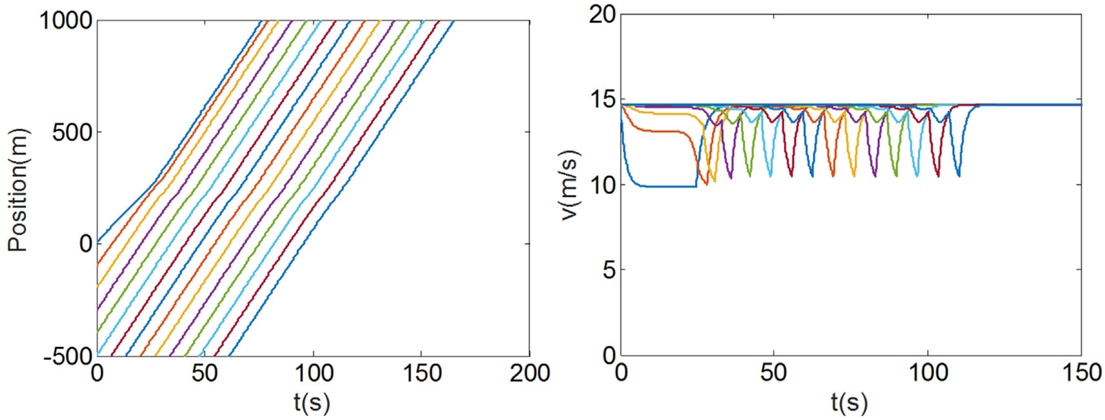
$$T_{ct} = \begin{cases} t_s + \dfrac{L_w}{S_p} + p_1\dfrac{N_p}{W_c}, & (if\ W_c > 3) \\ t_s + \dfrac{L_w}{S_p} + p_2 N_p, & (if\ W_c \le 3) \end{cases} \tag{6}$$

where, t_s is the pedestrians' start-up time, s; L_w is the crosswalk length, m, S_p is walking speed of the pedestrians, m/s; N_p is the number of pedestrians crossing during an interval; W_c is the crosswalk width, m; and p_1 and p_2 are two calibration parameters.

2.4. Car-following behavior in scenario three

This is a scenario where the driver is within the sight decision distance R, and the pedestrians are crossing. The driver's response to observed pedestrian action is to maintain the traditional car-following behavior if the distance between the vehicle and the crosswalk is large; otherwise, to avoid the sudden stop, driver will decelerate to the speed that can ensure the time gap is larger than the crossing time or decelerate to the minimum speed. The expression below describes the car-following behavior.

$$\frac{dv_n(t)}{dt} = \kappa\left[V\left(\Delta x_n(t)\right) - v_n(t)\right] + \lambda \Delta v_n(t), \left(if\ \Delta x_n(t) \ge d_n(t); x_n(t) > R_1; \frac{d_n(t)}{v_n(t)} \ge T_{ct}\right) \tag{7}$$



(a) Vehicles' running trail. (b) Vehicles' velocity.

Fig. 2. Vehicular flow in scenario two (pedestrians waiting).

$$\frac{dv_n(t)}{dt} = \kappa \left[max \left(\frac{d_n\left(t'\right)}{T_{ct}}, v_{min} \right) - v_n\left(t\right) \right], (if\ \Delta x_n\left(t\right) < d_n\left(t\right); R_1 \leq x_n\left(t\right) \leq R_2) \tag{8}$$

where, t' is the time the driver first finds that the pedestrian has begun to cross; R_2 is the position that vehicle is close to the illegal crossing, m.

However, if pedestrians crossing takes longer, vehicles have to stop and wait. The following expression describes the applicable car following motion.

$$\frac{dv_n(t)}{dt} = \kappa \left[V\left(d_n\left(t\right)\right) - v_n\left(t\right)\right] - \lambda v_n\left(t\right), (if\ \Delta x_n\left(t\right) < d_n\left(t\right); R_2 \leq x_n\left(t\right) \leq R_3) \tag{9}$$

3. Simulations and analyses

The following is an analysis of the process that we used to explore how the illegal pedestrian crossing affect the traffic flow at midblock. The crosswalk is located at 300 m from the start of the test road segment. In the simulation, the pedestrians regardless of their demographics, will arrive at random either singly or in a group of two or more. In a real traffic situation, the decisions made and action taken by both pedestrians and drivers are independent because neither knows what the other will do. However, the pedestrians' decision to cross depends entirely on their perception of their approaching vehicle speed and judgment on how safe it is at every instant.

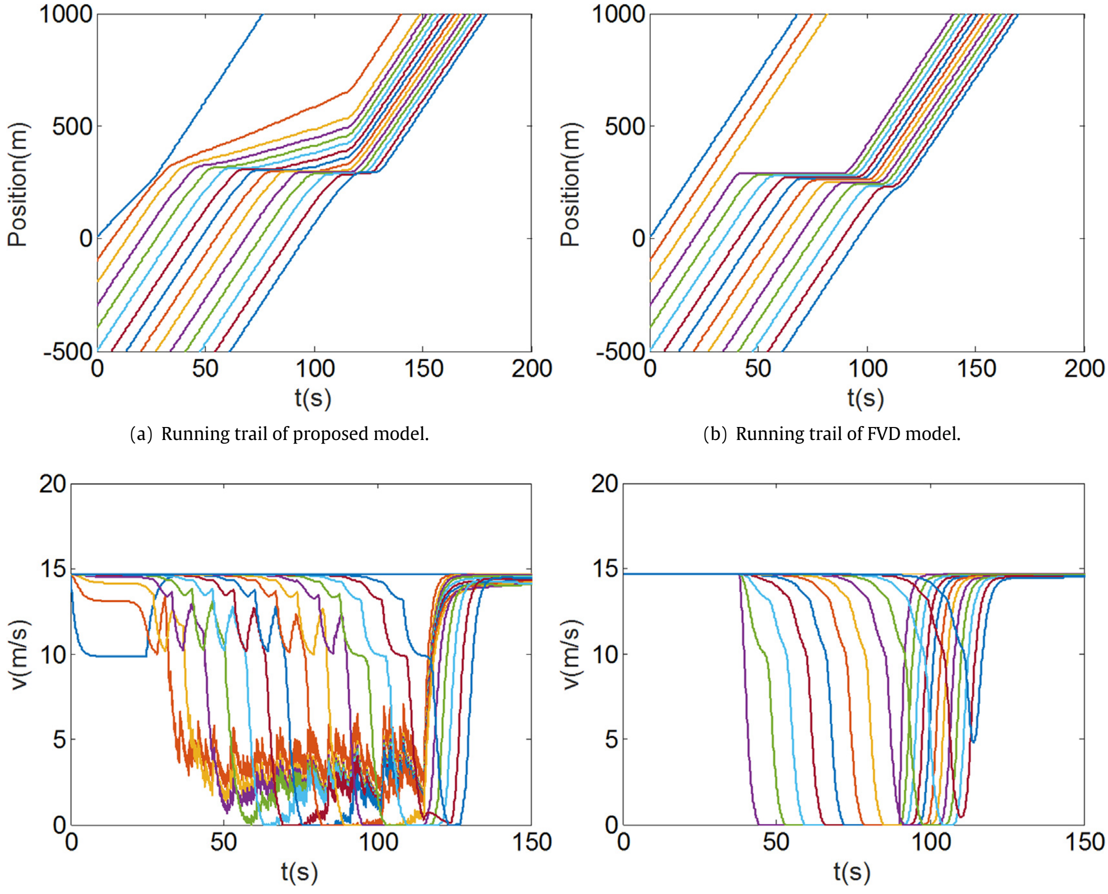
The initial optimal velocity parameters are defined as follows: time step Δt = 0.1 s, sensitivity $\kappa = 0.41\ s^{-1}$, $\lambda = 0.2\ s^{-1}$, vehicle length $l_c = 9$ m, $V_1 = 6.75$ m/s, $V_2 = 7.91$ m/s, $C_1 = 0.13\ m^{-1}$, $C_2 = 1.57\ m^{-1}$, $V_{max} = 16.66$ m/s, $V_{min} = 6$ m/s, The sight distance of the vehicle R is 50 m, pedestrians' start-up time $t_s = 1.0$ s, walking speed of the pedestrians $0.9 < S_p < 1.38$ m/s, $p_1 = 0.81$, $p_2 = 0.27$.

3.1. Model validation

Using the extended model, the effects of pedestrians on traffic flow can be observed from the illustration in the following figures. The effect of illegal pedestrian crossing on the traffic flow under scenario 2 (pedestrians are waiting but none attempts to cross) is firstly analyzed. Fig. 2, shows the vehicle transition.

However, when the approaching vehicle finds pedestrians are crossing (scenario 3), the vehicle should slow down to yield the pedestrian, as illustrated in Fig. 3(a), which is in contrast to a controlled stop shown in Fig. 3(b). The presence of illegal pedestrians and their unpredictable actions is disruptive to what would otherwise be smooth flow of traffic. Because it is not possible to accurately predict the future action of pedestrians, drivers have to be cautious to avoid fatal conflicts. This leads to frequent cases of accelerate–decelerate as shown in Fig. 3(c). In Fig. 3(c), the lead vehicle slows down ready to yield out of caution when approaching the site of the illegal crossing, then accelerates soon after passing the site. The following vehicles velocity transitions exhibit extreme fluctuations, but most of them need not stop. However, the FVD model in Fig. 3(d) shows a smooth slowing down-stop-start motion for approaching a controlled stop.

A further simulation was done to examine the effects of a higher population of pedestrians on the traffic flow. The results are show in Fig. 4. In this simulation illustrated in Fig. 4(b), the first hard yield occurs at the 50th second with a sustained low average velocity while in Fig. 3(a) it occurs at the 60th second with a higher average velocity.



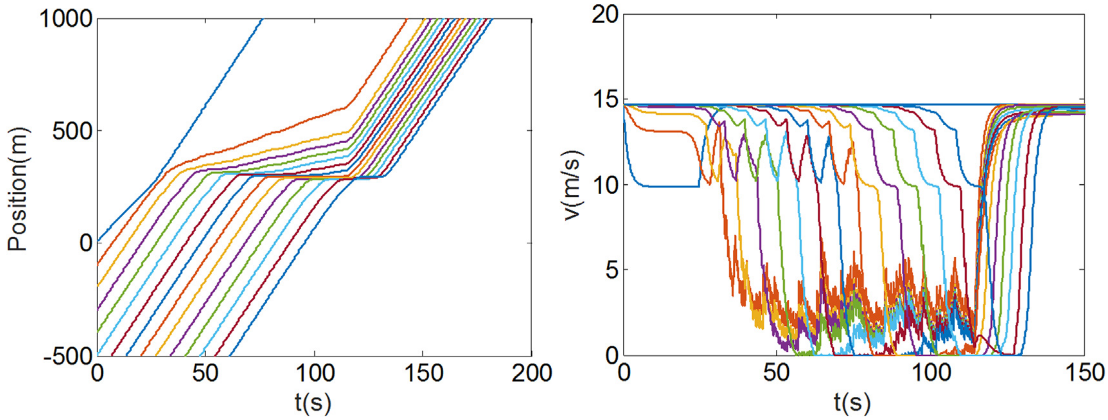
(a) Running trail of proposed model.

(b) Running trail of FVD model.

(c) Velocity of proposed model.

(d) Velocity of FVD model.

Fig. 3. Vehicular flow in scenario three under low pedestrian volume.



(a) Vehicles' running trail.

(b) Vehicles' velocity.

Fig. 4. Vehicular flow in scenario three under high pedestrian volume.

3.2. Sensitivity analysis

The illegal pedestrian crossing may cause the vehicle traffic stream to slow down due to their unpredictable behavior and, if they are already crossing, the vehicles may eventually have to stop to allow more pedestrians to complete crossing. In the

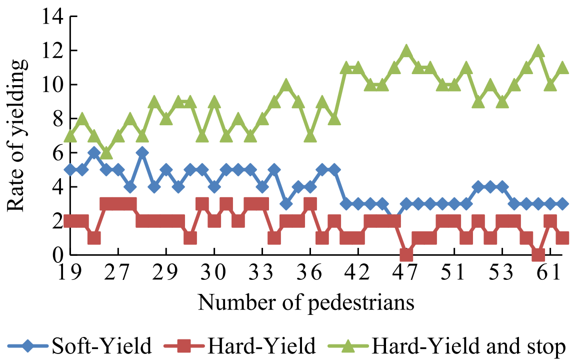


Fig. 5. Effect of the number of pedestrians on yielding behavior.

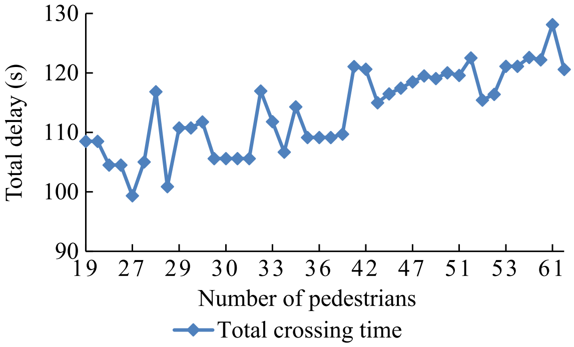


Fig. 6. Effect of the number of pedestrians on total delay.

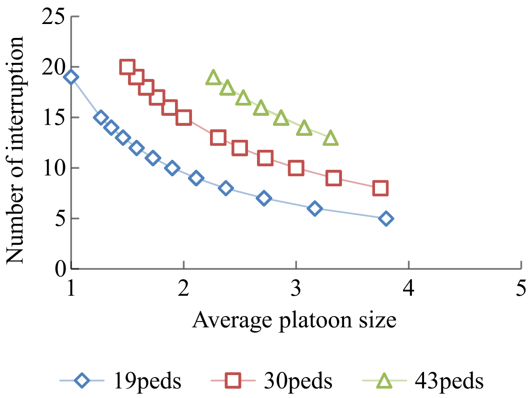
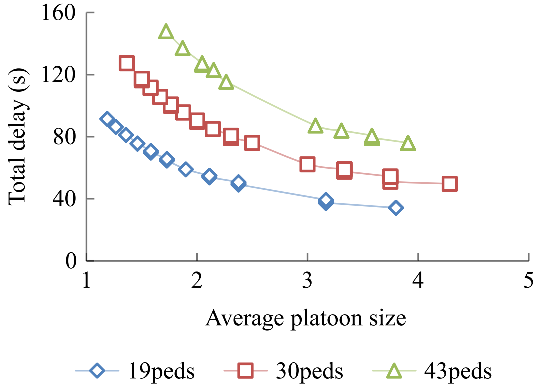


Fig. 7. Effect of pedestrian platoon size on traffic interruptions.

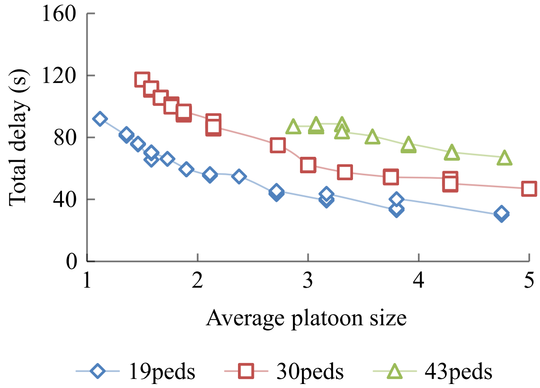
following analysis, the sensitivity analysis was produced with the consideration of some key factors of the proposed model, which includes the number of pedestrian, the pedestrian platoon size, and the speed limitation of vehicles. Two indicators are selected for the analysis, namely delay and yielding rate. Delay indicates the operational efficiency from the vehicle point of view, while yielding rate indicates the running safety from the pedestrian point of view. Note: soft-yield is that condition where a driver observes or anticipates pedestrian action and slows down in advance; hard-yield is the condition that the vehicle is too close to the crosswalk during a crossing activity and has to stop momentarily to let pedestrians complete crossing; hard-yield and stop is the condition that the vehicle not only slows down but eventually stops for an extended duration before restarting motion.

3.2.1. *Effect of the number of pedestrian*

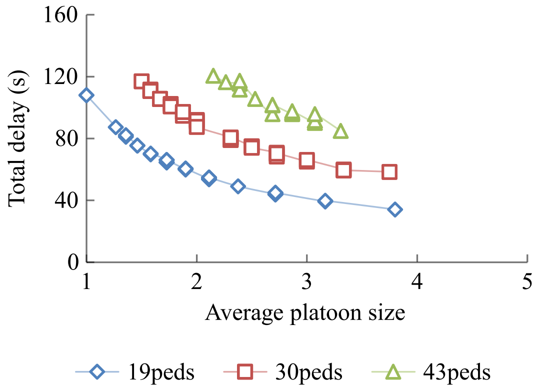
The effect of the number of pedestrian on the yielding rate and vehicular delay are shown in Figs. 5 and 6, respectively.



(a) $V_{max} = 8.66$ m/s.



(b) $V_{max} = 10.66$ m/s.



(c) $V_{max} = 14.66$ m/s.

Fig. 8. Effect of pedestrian platoon size on delay.

From Fig. 5, one can find that more vehicles will soft-yield (with a high of 7 soft-yields) compared to when the number is high (with a low soft-yield of 2 vehicles) when the total number of pedestrians is low. Similarly, the number of those that yielded and stopped is higher (with a high of 12) when number of pedestrians increase. Consequently, when fewer lead vehicles soft-yield, the overall vehicle waiting time is longer and cumulative delay rises. When more lead vehicles soft-yields, traffic flow will be smoother but slower and there will be fewer pedestrians who will cross compared to when there are fewer soft-yields. Hard-yield action effectively breaks the flow of traffic such that when the lead vehicle in this instance finally starts to move forward, some of the following vehicles would have also stopped. At this point the newly arrived pedestrians take advantage of the stationary state of the traffic flow to cross by walking in between the stationary vehicles.

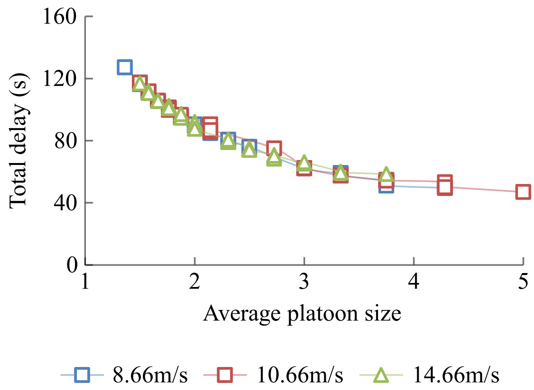


Fig. 9. Effect of speed limitation on delay.

As shown in Fig. 7, there was a progressive rise in delay as the number of pedestrians in each simulation is rising. It is due to the fact that the reduced number of vehicles soft-yielding at the head of the traffic stream has a cumulative effect of the vehicles behind which are made to wait for the J-walking pedestrians who take advantage of the stopped vehicles.

3.2.2. Effect of pedestrian platoon size

The size of the pedestrian platoons is another influencing factor related with pedestrians. The relationship between the average pedestrian platoon size and the number of traffic interruptions is shown in Fig. 7. There were more traffic interruptions from smaller platoons compared to bigger ones. In real life situations, each pedestrian decides when it is appropriate to cross. When this happens repetitively, the result is intermittent traffic interruptions for drivers who avoid potentially fatal conflict and ultimately delays and inconvenience. Fig. 8 further reveals that the cumulative delay is inversely proportional to the platoon size regardless of the vehicle approaching speed. Smaller platoons have a higher delay compared to bigger ones due to the frequency of crossing and traffic interruption than when a big platoon crosses at once. This scenario tends to justify the need for controlled crosswalks where for traffic flow efficiency to be achieved, pedestrians wait for an appropriate signal to cross together as a group.

3.2.3. Effect of speed limitation of vehicles

The speed limitation of the approaching vehicle also plays a significant role in vehicle–pedestrians traffic interactions. Fig. 9 explains the relationship between vehicular delay and the speed limitation. It can be noted that the effect of the speed limitation on total delay appears similar.

However, from the pedestrian point of view, the speed of the vehicle is critical in determining the TTA which is also a primary factor for the pedestrian to decide whether to cross or not. To establish its effect on the rate of yielding, simulation was carried out with maximum velocity set as 8.66 m/s, 10.66 m/s and 14.66 m/s as shown below.

From Fig. 10(a), there were very few instances of hard-yielding with an extended stop. However, when V_{max} is 14.66, and shown in Fig. 10(c), there are extended stoppages throughout the simulations. It implies that at lower vehicular speed, pedestrians are able to cross the road without necessarily making motorists stop. When vehicular speed is higher, congestion builds up quickly as more vehicles arrive and join the queue. The highest number of soft-yielding is consistently recorded when V_{max} is set at 10.66 m/s. This means that vehicles were able to yield for the pedestrians to cross but still continued accelerating past the crosswalk without having to stop.

4. Conclusions

In this study we investigated the car-following model and how the illegal pedestrian crossing affect the traffic flow. From the analysis, the results show that the illegal pedestrians have a negative effect on the traffic flow majorly because of being unpredictable, causing jams, and unprogrammed disruption of the flow. Though the overall delay was marginal, the disruption of the vehicle runs was visible by the fluctuation of velocity near the crossing site. The unpredictable nature can cause fatal conflicts when either party misjudges the other's actions. Therefore, we recommend that either additional provision for pedestrian crossing be made or deterrent measures put in place to prevent this behavior.

Acknowledgment

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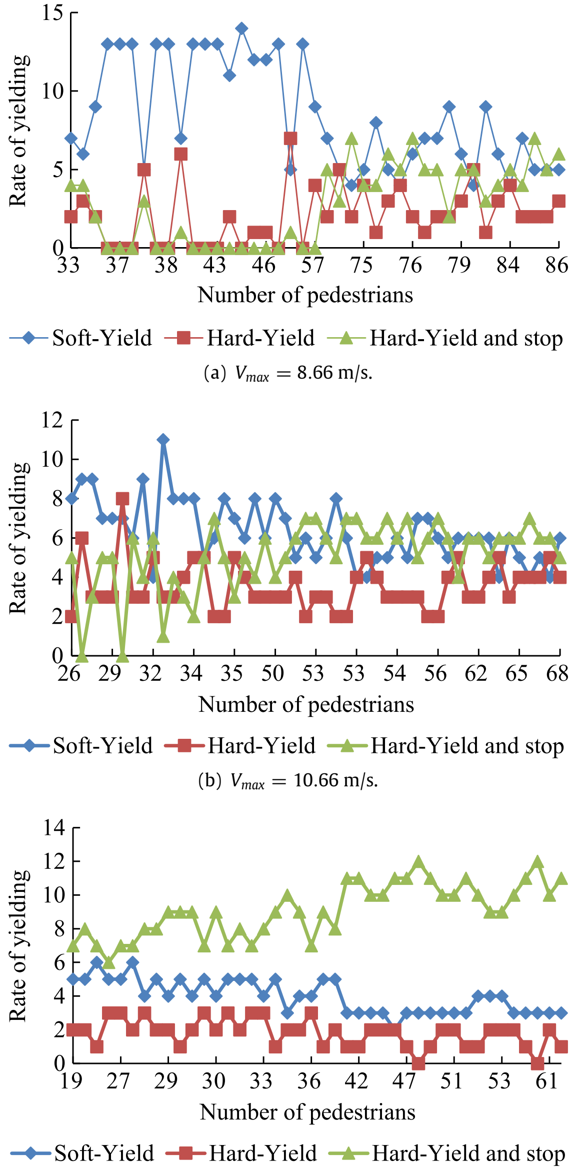

(a) $V_{max} = 8.66$ m/s.

(b) $V_{max} = 10.66$ m/s.

(c) $V_{max} = 14.66$ m/s.

Fig. 10. Effect of speed limitation on yielding rate.

References

[1] S. Chandra, R. Rastogi, V.R. Das, Descriptive and parametric analysis of pedestrian gap acceptance in mixed traffic conditions, KSCE J. Civil Eng. 18 (1) (2014) 284–293.
[2] S. Jin, X. Qu, C. Xu, D.-H. Wang, Dynamic characteristics of traffic flow with consideration of pedestrians' road-crossing behavior, Physica A 392 (18) (2013) 3881–3890.
[3] K. Yi-Rong, S. Di-Hua, Y. Shu-Hong, A new car-following model considering driver's individual anticipation behavior, Nonlinear Dynam. 82 (2015) 1293–1302.
[4] B. Schroeder, N. Rouphail, Event-based modeling of driver yielding behavior at unsignalized crosswalks, Transp. Eng. 137 (2010) 455–465.
[5] T.Q. Tang, Y.H. Wu, L. Caccetta, H.J. Huang, A new car-following model with consideration of roadside memorial, Phys. Lett. A 375 (2011) 3845–3850.
[6] T. Petzoldt, On the relationship between pedestrian gap acceptance and time to arrival estimates, Accid. Anal. Prev. 72 (2014) 127–133.
[7] M. Paul, P. Rajbonshi, A comprehensive review on pedestrian gap acceptance at unsignalized road, Int. J. Eng. Res. Technol. (IJERT) 3 (11) (2014) 325–328.
[8] E. Papadimitriou, G. Yannis, J. Golias, A critical assessment of pedestrian behaviour models, Transp. Res. F 12 (2009) 242–255.
[9] S.N.M. Nor, B.D. Daniel, R. Hamidun, W.A.A. Bargi, M.M. Rohani, J. Prasetijo, M.Y. Aman, K. Ambak, Analysis of pedestrian gap acceptance and crossing decision in Kuala Lumpur, in: MATEC Web of Conferences, 2017.

[10] D.S. Pawar, G.R. Patil, Pedestrian temporal and spatial gap acceptance at mid-block street crossing in developing world, J. Saf. Res. 52 (2015) 39–46.
[11] B.R. Kadali, D.P. Vedagiri, Effect of vehicular lanes on pedestrian gap acceptance behaviour, in: 2nd Conference of Transportation Research Group of India (2nd CTRG), Procedia - Social and Behavioral Sciences, vol. 104, 2013, pp. 678–687.
[12] B. Antic', D. Pešic', N. Milutinovic, M. Maslac, Pedestrian behaviours: Validation of the Serbian version of the pedestrian behaviour scale, Transp. Res. F 41 (2016) 170–178.
[13] H.J. Amin, R.N. Desai, P.S. Patel, Modelling the crossing behavior of pedestrian at uncontrolled intersection in case of mixed traffic using adaptive neuro fuzzy inference system, J. Traffic Logist. Eng. 2/4 (2014) 263–270.
[14] D.S. Pawar, G.R. Patil, Critical gap estimation for pedestrians at uncontrolled mid-block crossings on high-speed arterials, Saf. Sci. 86 (2016) 295–303.
[15] B.R. Kadali, P. Vedagiri, Modelling pedestrian road crossing behaviour under mixed traffic condition, Eur. Transp.\Trasporti Europei (2013) (ISSN 1825-3997), Paper no. 3.
[16] M.S. Serag, Modelling pedestrian road crossing at uncontrolled mid-block locations in developing countries, Int. J. Civil Struct. Eng. 4 (2014) 274–285.
[17] E. Duim, M.L. Lebrão, J.L.F. Antunes, Walking speed of older people and pedestrian crossing time, J. Transp. Health 5 (2017) 70–76.
[18] B.H. Goh, K. Subramaniam, Y.T. Wai, A.A. Mohamed, Pedestrian crossing speed: The case of Malaysia, Int. J. Traffic Transp. Eng. 2 (4) (2012) 323–332.
[19] Y. Zheng, T. Chase, L. Elefteriadou, B. Schroeder, V.P. Sisiopiku, Modeling vehicle–pedestrian interactions outside of crosswalks, Simul. Model. Pract. Theory 59 (2015) 89–101.
[20] G. Asaithambi, M.O. Kuttan, S. Chandra, Pedestrian road crossing behavior under mixed traffic conditions: A comparative study of an intersection before and after implementing control measures, Transp. Dev. Econ. 2 (14) (2016).
[21] V. Perumal Marisamynathan, Study on pedestrian crossing behavior at signalized intersections, J. Traffic Transp. Eng. (Engl. Edn) 1 (2) (2014) 103–110.
[22] S.W. Yu, Z.K. Shi, Analysis of car-following behaviors considering the green signal countdown device, Nonlinear Dynam. 82 (2015) 731–740.
[23] T.Q. Tang, L. Chen, S.C. Yang, H.Y. Shang, An extended car-following model with consideration of the electric vehicle's driving range, Physica A 430 (2015) 148–155.
[24] T.Q. Tang, Y.H. Wu, L. Caccetta, H.J. Huang, A new car-following model with consideration of roadside memorial, Phys. Lett. A 375 (2011) 3845–3850.
[25] Y.F. Li, D.H. Sun, W.N. Liu, M. Zhang, M. Zhao, X.Y. Liao, L. Tang, Modeling and simulation for microscopic traffic flow based on multiple headway, velocity and acceleration difference, Nonlinear Dynam. 66 (2011) 15–28.
[26] G.H. Peng, R.J. Cheng, A new car-following model with the consideration of anticipation optimal velocity, Physica A 392 (2013) 3563–3569.
[27] T.Q. Tang, H.J. Huang, W.X. Wu, Y.H. Wu, Analyzing trip cost with no late arrival under car-following model, Measurement 64 (2015) 123–129.
[28] T.Q. Tang, W.F. Shi, H.Y. Shang, Y.P. Wang, An extended car-following model with consideration of the reliability of inter-vehicle communication, Measurement 58 (2014) 286–293.
[29] T.Q. Tang, K.W. Xu, S.C. Yang, H.Y. Shang, Influences of battery exchange on the vehicle's driving behavior and running time under car-following model, Measurement 59 (2015) 30–37.
[30] T.Q. Tang, Q. Yu, S.C. Yang, C. Ding, Impacts of the vehicle's fuel consumption and exhaust emissions on the trip cost allowing late arrival under car-following model, Physica A 431 (2015) 52–62.
[31] Y. Naito, T. Nagatani, Effect of headway and velocity on safety-collision transition induced by lane changing in traffic flow, Physica A 391 (2012) 1626–1635.
[32] T. Nagatani, K. Tobita, Vehicular motion in counter traffic flow through a series of signals controlled by a phase shift, Physica A 391 (2012) 4976–4985.
[33] K. Tobita, T. Nagatani, Effect of signals on two-route traffic system with real-time information, Physica A 391 (2012) 6137–6145.
[34] N. Sugiyama, T. Nagatani, Multiple-vehicle collision in traffic flow by a sudden slowdown, Physica A 392 (2013) 1848–1857.
[35] M. Treiber, A. Kesting, D. Helbing, Delays inaccuracies and anticipation in microscopic traffic models, Physica A 360 (2006) 71–88.
[36] M. Herrmann, B.S. Kerner, Local cluster effect in different traffic flow models, Physica A 255 (1998) 163–188.
[37] T. Nagatani, Stabilization and enhancement of traffic flow by the next-nearest-neighbor interaction, Phys. Rev. E 60 (1999) 6395–6401.
[38] X. Zhao, Z. Gao, A new car-following model: Full velocity and acceleration difference model, Eur. Phys. J. B 47 (2005) 145–150.
[39] S.W. Yu, Z.K. Shi, An extended car-following model considering vehicular gap fluctuation, Measurement 70 (2015) 137–147.
[40] S.W. Yu, Z.K. Shi, An improved car-following model considering relative velocity fluctuation, Commun. Nonlinear Sci. Numer. Simul. 36 (2016) 319–326.
[41] S.W. Yu, J.J. Tang, Q. Xin, Relative velocity difference model for the car-following theory, Nonlinear Dynam. 91 (2018) 1415–1428.
[42] S.W. Yu, X.M. Zhao, Z.G. Xu, Z.K. Shi, An improved car-following model considering the immediately ahead car's velocity difference, Physica A 461 (2016) 446–455.
[43] W.X. Zhu, L. Jia, L. Zhao, Modeling and simulation of traffic flow in work zone on highway, in: 2010 8th World Congress on Intelligent Control and Automation, IEEE, 2010, pp. 471–476.
[44] Q. Xin, N. Yang, R. Fu, S.W. Yu, Z.K. Shi, Impacts analysis of car following models considering variable vehicular gap policies, Physica A 501 (2018) 338–355.
[45] T.Q. Tang, Y.X. Shao, L. Chen, Modeling pedestrian movement at the hall of high-speed railway station during the check-in process, Physica A 467 (2017) 157–166.
[46] L. Chen, T.Q. Tang, H.J. Huang, J.J. Wu, Z.Q. Song, Modeling pedestrian flow accounting for collision avoidance during evacuation, Simul. Model. Pract. Theory 82 (2018) 1–11.
[47] A.K. Gupta, V.K. Katiyar, Analyses of shock waves and jams in traffic flow, J. Phys. A 38 (2005) 4069–4083.
[48] A.K. Gupta, V.K. Katiyar, A new anisotropic continuum model for traffic flow, Physica A 368 (2006) 551–559.
[49] A.K. Gupta, V.K. Katiyar, Phase transition of traffic states with on-ramp, Physica A 371 (2006) 674–682.
[50] A.K. Gupta, P. Redhu, Analyses of the driver's anticipation effect in a new lattice hydrodynamic traffic flow model with passing, Nonlinear Dynam. 76 (2014) 1001–1011.
[51] A.K. Gupta, S. Sharma, Nonlinear analysis of traffic jams in an anisotropic continuum model, Chin. Phys. B 19 (2010).
[52] R. Jiang, Q.S. Wu, Z.J. Zhu, A new continuum model for traffic flow and numerical tests, Transp. Res. B 36 (2002) 405–419.
[53] N. Bellomo, M. Delitala, V. Coscia, On the mathematical theory of vehicular traffic flow - I. Fluid dynamic and kinetic modelling, Math. Models Methods Appl. Sci. 12 (2002) 1801–1843.
[54] M. Delitala, A. Tosin, Mathematical modeling of vehicular traffic: A discrete kinetic theory approach, Math. Models Methods Appl. Sci. 17 (2007) 901–932.
[55] D. Ngoduy, Multiclass first-order modelling of traffic networks using discontinuous flow-density relationships, Transportmetrica 6 (2010) 121–141.
[56] D. Ngoduy, Multiclass first-order traffic model using stochastic fundamental diagrams, Transportmetrica 7 (2011) 111–125.
[57] D. Ngoduy, Effect of driver behaviours on the formation and dissipation of traffic flow instabilities, Nonlinear Dynam. 69 (2012) 969–975.
[58] D. Ngoduy, M.J. Maher, Calibration of second order traffic models using continuous cross entropy method, Transp. Res. C 24 (2012) 102–121.
[59] D. Ngoduy, Analytical studies on the instabilities of heterogeneous intelligent traffic flow, Commun. Nonlinear Sci. Numer. Simul. 18 (2013) 2699–2706.
[60] G.H. Peng, A new lattice model of the traffic flow with the consideration of the driver anticipation effect in a two-lane system, Nonlinear Dynam. 73 (2013) 1035–1043.

[61] M. Bando, K. Hasebe, K. Nakanishi, A. Nakayama, A. Shibata, Y. Sugiyama, Phenomenological study of dynamical model of traffic flow, J. Phys. I 5 (1995) 1389–1399.
[62] D. Helbing, B. Tilch, Generalized force model of traffic dynamics, Phys. Rev. E 58 (1998) 133–138.
[63] R. Jiang, Q.S. Wu, Z.J. Zhu, Full velocity difference model for a car-following theory, Phys. Rev. E 64 (2001).
[64] G. Peng, H. He, W.-Z. Lu, A new car-following model with the consideration of incorporating timid and aggressive driving behaviors, Physica A 442 (2016) 197–202.
[65] Highway Capacity Manual 2010, Transportation Research Board, Washington, 2010.