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Effect of Interactions between Vehicles and Mid-Block Crosswalks on Traffic Flow and CO₂ Emission

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Abstract: Unsignalized mid-block raised crosswalks have been adopted as inclusive transport strategies, providing humps to reduce vehicles' speed to promote drivers to yield to pedestrians. The interaction between vehicles and pedestrians can induce local jams that can merge to become a gridlock. The purpose of this paper is to investigate the interaction between vehicles and the mid-block raised crosswalk, analyzing its effects on traffic flow, instantaneous CO₂ emissions, and energy dissipation. A pedestrian–vehicle cellular automata model was developed, where a single-lane road with a mid-block raised crosswalk is considered. The lane boundaries were controlled with the injections rate (α) and extraction rate (β), while the pedestrians' entrance was controlled with the rate (α_p). The system's phase diagram was constructed, identifying four phases: maximum current, jamming, congestion, and gridlock. All observed phase transitions are of the second order. The transition from maximum current (or jamming) phase to gridlock phase is not noticed. Moreover, since the crosswalk is a bottleneck, the gridlock phase takes place when the pedestrians' influx exceeds a critical value ($\alpha_p > 0.8$). The study also revealed that the crosswalk is the main precursor of energy dissipation and CO₂ emissions, whose major effects are observed during the jamming phase.

Keywords: unsignalized mid-block raised crosswalks; cellular automata; pedestrians; phase diagram; CO₂ emissions; energy dissipation

Citation: Pérez Cruz, J.R.; Lakouari, N.; Pérez Sansalvador, J.C.; Zapotecatl López, J.L. Effect of Interactions between Vehicles and Mid-Block Crosswalks on Traffic Flow and CO₂ Emission. *Appl. Sci.* **2021**, *11*, 11794. <https://doi.org/10.3390/app112411794>

Academic Editor: Paola Pellegrini

Received: 22 October 2021

Accepted: 6 December 2021

Published: 11 December 2021

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1. Introduction

The accelerated increase in urbanization and motorization has carried multiple challenges for traffic management. Traffic calming devices, such as vertical/horizontal deflections, physical obstructions, and pavement markings, are deployed as an effort to reduce the negative effects of motor vehicles, altering driver behavior to improve the use conditions for non-motorized road users [1–4]. In this sense, unsignalized mid-block crosswalks have been widely adopted to constrain vehicles' speed while encouraging drivers to yield to pedestrians. These deployments cause a mixed traffic flow constituted by vehicles and crossing pedestrians.

Interaction between vehicles and crossing pedestrians have gained interest among researchers, and several studies have been developed. To study the relation between vehicle density and impact on traffic flow, Zaho et al. [5] proposed two cellular automata models, one to simulate a non-signalized crosswalk and the other to simulate an uncontrolled section where pedestrians cross the road anywhere, interacting with a dual-lane system. They found that less impact on traffic flow occurs when the pedestrians' entrance rate is moderate, becoming crowded and slow as the pedestrian entrance rate increases. Authors also deduced the density levels where pedestrians' influx has a less or more impact on traffic flow. Echab et al. [6] proposed a vehicle–pedestrian cellular automaton to investigate

the interactions between vehicles and crosswalks at a single-lane roundabout, focusing on the effects on traffic flow by constructing the system phase diagram [7]. Khallouk et al. [8] investigated the effects of the interference traffic flow promoted by crosswalks at unsignalized intersections, arguing that a crosswalk can be regarded as a dynamic impurity. Knoop and Daganzo [9] studied the spacing between crosswalks and its effect on road traffic capacity through Newell's simplified car-following model. They found that capacity increases as the distance between crosswalks is reduced, and that a spacing less than 25–50 m has no benefit.

Unsignalized zebra mid-block crosswalks (UZMC) were designed to protect crossing pedestrians by only using longitudinal stripes on the road. The characteristics of these facilities have been attractive for many researchers due to their broad adoption and multiple effects. Pedestrian safety, waiting time, and suitable locations for UZMC have been widely investigated by analyzing the drivers yielding rate, the crossing behavior, the number of lanes, and vehicles gaps [10–13]. Lu et al. [14] proposed a pedestrian–vehicle cellular automaton to investigate the interaction behaviors at UZMC, focusing on the analysis of pedestrians and vehicles delays as a function of the drivers yielding rate. Zhao et al. [15] also investigated the interaction between vehicle yielding and UZMC, extending the full velocity difference car-following model and found that the number of lanes affects the pedestrians' waiting time, whilst vehicles' delay increases more rapidly with the growth of vehicles and pedestrians volumes. Li et al. [16] proposed a fuzzy cellular automaton, intended to model the decision-making process of individual drivers, to analyze both the safety and efficiency of UZMC. In that study, the authors also provide an estimation for the pedestrian flow with which a crosswalk installation is justified according to the Chinese normative. Overall, studies have been focused on traffic flow effects in terms of delays and safety factors, leaving aside other implications.

A raised crosswalk differs from a zebra crosswalk in that is settled on a hump to induce speed reduction, even without pedestrians trying to cross the road. Raised crosswalks have gained popularity due to their inclusive approach since they also are intended to reduce obstacles for people with mobility restrictions, such as wheelchair users [17–20].

In terms of pollutant emissions, traffic lights, speed humps, and crosswalks have important effects because all the aforementioned traffic-calming devices can induce significant speed changes. Pérez-Sansalvador et al. [21] analyzed the effects on CO₂, NO_x, VOC, and PM pollutants of many speed humps on a single lane. Lav et al. [22], Kiran [23], and Obregón-Biosca [24] even analyzed the effects of speed humps' geometrical shape. Speed reduction, induced by a speed hump, combined with the obstruction caused by pedestrians' influx can induce major effects on traffic emissions as well as on energy dissipation.

This paper is focused on investigating the interference between vehicles and a mid-block raised crosswalk, analyzing its effects on traffic flow, instantaneous CO₂ emissions, and energy dissipation, through cellular automaton simulations. The effects on traffic flow were analyzed through the system's phase diagram determining that the system reaches four phases: maximum current, jamming, congestion, and gridlock, with second-order transitions among them. Simulation results also revealed that major energy dissipation and CO₂ emissions occur during the jamming phase. The ulterior objective of the study is to provide a novel reference framework to understand the traffic physics involved with raised crosswalks by isolating the longitudinal vehicle–pedestrian interactions from other dependencies. In this way, results can motivate the development of microscopic simulation tools, able to provide resources for decision making and forecasting. The provided analysis also can be helpful for the definition of urban planning guidelines such as nomograms.

The remainder of the document is organized as follows: Section 2 presents the models for traffic flow, crosswalk, pedestrian movement, instantaneous traffic emissions, and energy dissipation. In Section 3, the simulation results are presented and discussed. Finally, the main conclusions are stated in Section 4.

2. Modeling and Methods

2.1. System Model

The system is formed by a unidirectional lane containing a raised crosswalk at the middle. The lane is modeled as an arrangement of L cells, each representing 7.5 m length and 3.6 m width. The crosswalk is located at the position $L/2$ and is modeled as a cell's sub-grid, of length 3.6 m; pedestrians move along the crosswalk to cross the street (see Figure 1a). To simplify the system's dynamics analysis, a unidirectional pedestrian flow is considered.

Figure 1. Scheme of the lane and the crosswalk; (a) crosswalk within the lane, (b) crosswalk deployment.

2.2. Modeling the Crosswalk

The specification of raised crosswalks varies according to the city normative; however, several documents agree on a trapezoidal shape design with a height between 0.07 and 0.15 m, with a ramp on both sides with length of 1.07–3 m and a plateau of 1.8–5.2 m width enabled to pedestrians' transit [17,25–27].

The crosswalk plateau (hereinafter referred to as crosswalk) is modeled as a matrix of $L_c \times W_c$ cells as depicted in Figure 1b. Each cell represents an area of 0.6×0.6 m, which according to the Highway Capacity Manual (HCM) is sufficient to bound a single moving pedestrian [28]. The bottom row of the crosswalk is used as a waiting zone, representing an area outside the lane where the pedestrians enter the system with a probability α_p . A pedestrian located within the waiting zone decides to start crossing or not the lane, depending on whether the next cells are empty and there is an adequate distance to the nearest vehicle.

2.3. Pedestrians' Motion Rules

The pedestrian crossing event is governed by the pedestrian's prudence and speed as well as the available space in the crosswalk. Once a pedestrian enters the waiting zone, she/he decides to remain at such a site or to start crossing by considering a critical gap g_c between the crosswalk and the nearest vehicle. Based on Reference [29], the critical gap for a pedestrian i is computed in terms of the lane width W_l , the desired pedestrian speed v_i^p , and a safety factor γ that reflects the pedestrians' prudence, as follows:

$$g_c = \frac{W_l}{v_i^p} + \gamma. \quad (1)$$

By considering the HCM and Reference [8,29], γ is randomly selected between 0 and 2.5 with probability $P_\gamma = \frac{1}{m'}$, for some $m' > 0$. If g_c is satisfied, the pedestrians proceed to cross the lane having the priority over vehicles, which means the nearest vehicle must stop until the pedestrians finish the maneuver.

A pedestrian's motion throughout the crosswalk is conducted according to v_i^p and the availability of space within the neighborhood, prioritizing the forward movement. A pedestrian's neighborhood N is a matrix with up to three columns and v_{max}^p rows, located in front of the current cell. However, since there may be other pedestrians within the neighborhood, each column j is trimmed according to the position of the nearest neighbor, which determines the available space gap g_j in such a column (see Figure 2).

Each of the remaining cells have an associated probability $P_{j,k} \in [0, 1]$, where j is the row index. As the first option, the pedestrian selects to remain on the same column (forward movement) as long as $g_k \neq 0$. Otherwise, if $g_k = 0$, the pedestrian must select as the next location, the column containing the cell with the highest probability. In the case that there are no empty cells within the neighborhood, the pedestrian remains at the same location until a space becomes available.

Figure 2. Pedestrian's neighborhood.

Once a pedestrian i has selected her/his next location, her/his movement is described through a cellular automata model defined by three rules:

1. Acceleration:

$$v_i^p = \begin{cases} \min(v_{rand}^p, g_k) & \text{if the pedestrian is in the waiting zone,} \\ g_k & \text{otherwise,} \end{cases} \quad (2)$$

2. Deceleration:

$$v_i^p = \min(v_i^p, g_k), \quad (3)$$

3. Movement:

$$N_{j,k}, \text{ such that } j = j + v_i^p, \quad (4)$$

where v_i^p is the current speed of the pedestrian i at location $N_{j,k}$. The maximum speed for a pedestrian is denoted as v_{max}^p ; therefore, v_{rand}^p is a random integer between 0 and v_{max}^p . According to References [28–30], the average speed for a pedestrian is 1.4 m/s, hence $v_{max}^p = \lceil \frac{1.4}{0.6} \rceil = 3$, denoting with $\lceil \cdot \rceil$ the ceiling function. Varying the pedestrians' speed among 1 and v_{max}^p allows the recreation of different pedestrian capacities, which in the real world are influenced by age group or people's physical conditions.

2.4. Vehicles' Movement

The motion of a vehicle is described through a modified NaSch model, based on the extensions proposed in References [8,21,31], that captures the deceleration effects of a vehicle approaching a raised crosswalk. Thereby, the motion of a vehicle is described by the following four rules:

1. Acceleration:

$$v_i = \min(v_i + 1, v_{max}) \quad (5)$$

2. Deceleration:

$$v_i = \begin{cases} \min(g_{cw}, g_i) & \text{if } g_{cw} < v_i, \\ \min(1, g_i) & \text{if } g_{cw} = 0 \text{ \& the crosswalk is empty,} \\ 0 & \text{if } g_{cw} = 0 \text{ \& the crosswalk is occupied,} \\ \min(g_i, v_i) & \text{otherwise,} \end{cases} \quad (6)$$

3. Randomization:

$$v_i = \max(v_i - 1, 0), \text{ with a breaking probability } P_b, \quad (7)$$

4. Movement:

$$x_i = x_i + v_i, \quad (8)$$

where v_i is the current speed of vehicle i at position x_i ; v_{max} is the vehicle maximum speed; g_i is the gap towards the next vehicle $i + 1$; and g_{cw} is the distance between vehicle i and the crosswalk.

For this work, the open-boundary condition strategy has been adopted. Each vehicle is inserted at the lane's first position with probability α if and only if such a position is empty. Vehicle i starts with speed $v_i = 0$ and accelerates as it moves through the lane. When the vehicle's new computed position exceeds the lane length, such a vehicle is deleted with probability β . This strategy is intended to reproduce the dynamic of vehicles when transiting across urban intersections.

2.5. Traffic Emission Model

The model proposed by Panis et al. [32] is used to outline the possible environmental impacts related to the implantation of mid-block raised crosswalks. The model allows estimating the instantaneous emissions of each vehicle per time step as a function of its speed and acceleration. In this work, it is considered that a time step is equivalent to one second. For a vehicle i with instantaneous speed v_i and acceleration a_i , the emission is computed as follows:

$$E_i = \max(E_0, f_1 + f_2 v_i + f_3 v_i^2 + f_4 a_i + f_5 a_i^2 + f_6 v_i a_i), \quad (9)$$

where E_0 is a lower-limit emission value for each vehicle and pollutant type, and f_1 to f_6 are emission constants, specifically determined for a vehicle's type and a certain pollutant. In this way, there are four sextuples of emission constants, each one related to a pollutant: CO_2 , NO_x , VOC, and PM.

This work evaluates the effect of an unsignalized mid-block crosswalk on CO_2 emission, which is considered to be the biggest cause of rapid climate change on Earth [33].

2.6. Energy Dissipation

The energy dissipation rate E_d per time step per vehicle [34] is evaluated to analyze the *stop and go* effects induced by the raised crosswalks. For a vehicle i moving with speed v_i , its kinetic energy is computed as $\frac{mv_i^2}{2}$, where m is the vehicle's mass. For simplification, all other dissipation factors such as rolling and air drag are neglected. In this sense, the dissipated energy $e_i(t)$ of vehicle i in the time slot $[t - 1, t]$ is defined as follows:

$$e_i(t) = \begin{cases} \frac{m}{2} (v_i^2(t-1) - v_i^2(t)) & \text{for } v_i(t) < v_i(t-1) \\ 0 & \text{otherwise.} \end{cases} \quad (10)$$

By considering the total number of vehicles in the system N , the average energy dissipation rate is determined by:

$$E_d = \frac{1}{T} \frac{1}{N} \sum_{t=t_0+1}^{t_0+T} \sum_{i=1}^N e_i(t), \quad (11)$$

denoting by T the stationary period, considered after t_0 time steps. The difference in the kinetic energy at each location of the lane also is analyzed to inquire about the focused

effects nearby the crosswalk. Thereby, the energy dissipation profile $SE_d(x)$ at each location (x) of the lane is determined whenever the position is occupied by a vehicle as follows:

$$SE_d(x) = \frac{1}{T} \sum_{t=t_0+1}^{t_0+T} e(x). \quad (12)$$

Here, the dissipation energy must be divided by the vehicles' mass, which is considered the same for all vehicles for simplification.

3. Results and Discussions

The effects of the mid-block raised crosswalks were determined by a computational study considering a lane with $L = 1000$ cells. The crosswalk was configured by considering the minimum specifications for the lane width ($W_l = 3.6$) and the space occupied by a pedestrian; therefore, a matrix of $W_c = \frac{1.8}{0.6} = 3$ columns and $L_c = \frac{3.6}{0.6} + 1 = 7$ rows is used.

The lane's boundaries are controlled by the rates α and β for the injection and extraction of vehicles, respectively. In this way, a road section between two intersections is modeled so that the injection rate (α) mimics the state at the first intersection, whilst the extraction rate (β) represents the state of the second intersection. Similarly, the entrance of pedestrians to the crosswalk is controlled by the rate α_p .

The system was simulated for 100,000 iterations, considering only the last 10,000 iterations to collect the results and ensure a steady-state of the system. In addition, the results were averaged through 100 independent executions to reduce the stochastic fluctuation. The maximum allowed speed for vehicles speed was $v_{max} = 2$ to mimic the maximum allowed speed in cities. For pedestrians, the maximum speed was $v_{max}^p = 3$. The system's braking probability was set to $P_b = 0$, which means the speed fluctuation is induced only by the effects of the boundaries and the pedestrian's influx, allowing us to focus on studying the interaction between vehicles and the crosswalk.

3.1. Effects on Traffic Flow

The flow variation is investigated for several values of α , as a function of the vehicles' extraction β and the pedestrian entrance α_p , to understand the effect of the crosswalk. As observed in Figure 3, the flow decreases quantitatively as α_p increases. However, the plateau region decreases qualitatively as α increases. These effects suggest the crosswalk induces a bottleneck.

The system's phase diagram (the construction of the phase diagram is explained in Appendix A) is constructed on the plane (α_p, β) , taking the vehicles' flow as an order parameter, to achieve a better understanding of the bottleneck effect on traffic flow. In Figure 4, it can be observed that the system reaches up to four phases: maximum current (MC), jamming (J), congestion (C), and gridlock (GL). These four phases depict all states in which traffic flow is present in the system. In this way, maximum current describes steady to limited-steady traffic, jamming phase describes high-density steady traffic to traffic at saturation, congestion describes the state with unstable speed, and gridlock describes the state when traffic is completely standstill. For each phase, more detailed descriptions are given below.

The maximum current phase is characterized by presenting free-flowing conditions, which means vehicles can move at their desired speed, except for the small platoons of standing vehicles that appear in the vicinity prior to the crosswalk and at the end of the lane (see Figure 5a). In addition, in this phase, it is common to observe gaps between vehicles, and these gaps are used by pedestrians to traverse the crosswalk without perturbing traffic flow. As depicted in Figure 4a, for $\alpha = 0.1$, the maximum current is the largest phase where the flow in the lane becomes decoupled from the pedestrian entrance and extraction rates, i.e., in this phase, the flow does not depend on α_p and β . When $\alpha = 0.4$, the maximum current phase is reached when $\beta > 0.5$ and $\alpha_p < 0.3$ and is observed as a planar surface in Figure 3b. The range of values for α_p and β of the maximum current phase decreases

according to the increase in α ; hence, for $\alpha = 0.7$ this phase is bounded by $\alpha_p < 0.1$ and $\beta > 0.7$ (see Figure 4c). As the queue prior to the crosswalk increases, the system transitions to the jamming phase or to the congestion phase, depending on the vehicles' extraction rates β .

Figure 3. Variation of traffic flow as a function of α_p and β for different values of α ; (a) $\alpha = 0.1$, (b) $\alpha = 0.4$, (c) $\alpha = 0.7$, and (d) $\alpha = 1$.

The jamming phase appears for pedestrian entrance rates $0 \leq \alpha_p < 0.72$, increasing its extension, with respect to β , as the injection rate α increases. Indeed, the extension of the jamming phase increases according to the decrease in the maximum current phase as depicted in Figure 4b–d. Here, the effects of the extraction and the bottleneck are combined, inducing a queue of stop-and-go vehicles all along the lane as depicted in Figure 5a. Due to this condition, the queue is observed to be dense enough with closely spaced vehicles along the lane. In this phase, vehicles still interact among them, while the pedestrians' influx does not completely inhibit the traffic flow. If the pedestrian entrance α_p increases, triggering the rapid growth of both the bottleneck and the queue prior to the crosswalk, then the system transitions to the congestion phase.

Figure 4. Phase diagram in the plane (α_p, β) : (a) $\alpha = 0.1$, (b) $\alpha = 0.4$, (c) $\alpha = 0.7$, and (d) $\alpha = 1$.

Congestion takes place when the bottleneck worsen the system's traffic flow. As depicted in Figure 5c, the crosswalk becomes a considerable obstruction strongly influenced by pedestrians occupying the crosswalk, generating long queues of non-moving vehicles. In this phase, the traffic flow decreases as α_p increases (see Figure 3), which means the congestion phase is expanded as the maximum current phase is contracted (see Figure 4). This phase differs from the jamming phase since bottleneck contributes to generating wide free spaces after the crosswalk, decreasing the effect of the extraction rate β . Due to the crosswalk occupancy, vehicles wait for long periods to pass. It can be argued that during this phase, the system is preparing to transition continuously to reach the order which corresponds to the gridlock phase, which means that the system exhibits a second-order phase transition.

When flow becomes null, the gridlock takes place. As depicted in Figure 5d, in the gridlock phase, the bottleneck completely prevents vehicles' movement, the free space is condensed after passing the crosswalk, while stopped vehicles are queued before engaging the crosswalk. Gridlock phase is reached when $\alpha_p \geq 0.8$, and it remains immutable for any combination of α and β values. This means that the crosswalk is the main cause for gridlock in the system, and the extraction rate can contribute to the gridlock formation only when $\beta = 0$.

It is important to note that the crosswalk produces a vehicle reservoir in the first half of the lane. Here, the probability of vehicles passing the crosswalk acts as an alternative injection rate for the second half of the lane, contributing to vehicles' delay even when the values of β are significantly higher than α ; therefore, the system depends on α_p .

Figure 5. Examples of space-time diagrams for the four phases: (a) Maximum Current ($\alpha = 0.4$, $\alpha_p = 0.2$, $\beta = 0.7$), (b) Jamming ($\alpha = 0.4$, $\alpha_p = 0.2$, $\beta = 0.3$), (c) Congestion ($\alpha = 0.4$, $\alpha_p = 0.6$, $\beta = 0.7$), and (d) Gridlock ($\alpha = 0.1$, $\alpha_p = 0.9$, $\beta = 0.5$).

3.2. Effects on CO₂ Emissions and Energy Dissipation

As was discussed in the previous section, the mid-block raised crosswalk induces a bottleneck with different repercussions on the traffic behavior depending on the pedestrians' entrance rate α_p . To inquire about other collateral effects, in this section, the carbon dioxide emissions (CO₂) and the energy dissipation (E_d) are investigated. For simplicity's sake, it is considered that all vehicles use petrol as fuel; hence, for the instantaneous CO₂ emission, the constants for Equation (9) were set as $E_0 = 0$, $f_1 = 5.53 \times 10^{-1}$, $f_2 = 1.61 \times 10^{-1}$, $f_3 = -2.89 \times 10^{-3}$, $f_4 = 2.66 \times 10^{-1}$, $f_5 = 5.11 \times 10^{-1}$, and $f_6 = 1.83 \times 10^{-1}$.

According to References [35–37], greater speed fluctuations give rise to higher CO₂ emissions and energy dissipation as a consequence of acceleration or deceleration, respectively. Figures 6 and 7 show 3D presentations of the variation of the CO₂ emissions and energy dissipation as a function of α_p and β , for several values of α .

Figure 6. Variation of CO_2 as a function of α_p and β for different values of α ; (a) $\alpha = 0.1$, (b) $\alpha = 0.4$, (c) $\alpha = 0.7$, and (d) $\alpha = 1$.

From the plotted surfaces of Figures 6 and 7, one can note that the most notorious variations of CO_2 emissions and energy dissipation match the phases determined for traffic flow (see Figure 4). To obtain an affordable explanation about these effects, let us focus on the two most contrasting phases, jamming and gridlock.

Firstly, let us analyze the jamming phase, where the highest levels of emission and energy dissipation are present. In this region, the averaged CO_2 emission value reaches up to 21.27 g/s, and the maximum level for averaged E_d/m is 0.193. The jamming phase is characterized by the queue of stop-and-go vehicles all along the lane, such that deceleration-acceleration events are recurrent due to a large number of interactions between vehicles. On the one hand, vehicles' acceleration contributes to the increase in CO_2 emission, and on the other hand, the topmost levels of energy are dissipated due to deceleration. To improve the understanding of this effect, the lane's energy dissipation profile is analyzed in Figure 8b. The energy dissipation profile shows that queues before the crosswalk and prior to the lane's exit increase the energy dissipation. In addition, Figure 8b reveals that queue formation, which characterizes the jamming phase, is strongly influenced by the extraction rate β .

In contrast to the effects observed in the jamming phase, at gridlock ($\alpha_p \geq 0.8$ for any combination of α and β), the lowest levels of CO_2 and E_d/m emissions are present. This

is explained by the fact that gridlock takes place when traffic is at a complete standstill and there are no moving vehicles. Indeed, by analyzing the energy dissipation profile of Figure 8d, one can observe that there is no energy dissipation along the lane.

To finish the discussion about CO₂ emissions and energy dissipation, the observed effects in maximum current and congestion phases are analyzed. Figure 6a shows a planar surface with CO₂ emissions values close to 2.5 g/s, that matches the maximum current phase depicted in Figure 4a. A similar feature can also be observed when energy dissipation is analyzed (see Figure 7a). In the maximum current phase, the only fluctuations of speed (stop-and-go) occur in the crosswalk's vicinity and at the lane's exit, remaining in free-flow conditions in the rest of the lane. Hence, when the energy dissipation profile is analyzed (Figure 8a), only two peaks with the highest levels of E_d are observed. Indeed, such peaks correspond to mid-lane and end-lane locations, where small queues are formed as depicted in the space-time diagram of Figure 5b. Another important observation is that the highest energy dissipation energy is observed in the vicinity of the crosswalk, where a drastic change in speed of vehicles (i.e., high speed and the low speed induced by the crosswalk) induces a large energy dissipation.

Figure 7. Energy dissipation as a function of α_p and β , for different values of α ; (a) $\alpha = 0.1$, (b) $\alpha = 0.4$, (c) $\alpha = 0.7$, and (d) $\alpha = 1$.

As stated in Section 3.1, during the congestion phase, the system is preparing to transit to the gridlock; therefore, the average energy dissipation decreased considerably. However, from Figure 8c, it can be noted that the remaining vehicle interactions are caused due to the queue before the crosswalk. Therefore, the congestion is mainly influenced by α_p contrary to the jamming phase where queue formation is promoted by β .

Figure 8. Energy dissipation profile: (a) Maximum Current, (b) Jamming, (c) Congestion, (d) Gridlock.

3.3. Towards a Comparison of Raised Crosswalk against Zebra Crosswalk

This subsection shows coarse simulation results of a zebra crosswalk, as a first approach to understand the difference against the raised crosswalk. The experiment was conducted by setting the vehicle injection rate $\alpha = 0.4$, for all combinations of the rates related to pedestrian entrance and vehicle extraction (α_p and β). As can be observed from Figure 9a,b, the results show some similar features as the depicted in Figures 3b and 4b. Qualitatively, the change is seldom observed when traffic flow is analyzed. Conversely, as for the energy dissipation and CO₂ emission, the change can be easily observed. A sharp increase in the CO₂ emission and dissipation energy is observed nearby the boundary between phases namely maximum current and congestion. In that case, it can be said that the boundary line presents a higher change in the speed of vehicles where the acceleration and deceleration become often in the system.

From these preliminary results, one can glimpse that to perform a fair comparison between these two systems, a more detailed study is needed. Further studies would be focused on analyzing, from a fine-grained scale, and the way acceleration and deceleration events are carried out in each system. In fact, the comparison should be more detailed to show when a strategy overcomes the other by comparing many metrics such as safety factors (vehicle–pedestrian and vehicle–vehicle accident probabilities), energy consumption, and even pedestrians' flow.

Figure 9. Analyzing the effects of an unsignalized zebra mid-block crosswalk for $\alpha = 0.4$; (a) traffic flow as a function of α_p and β , (b) phase diagram in the plane (α_p, β) , (c) CO₂ as a function of α_p and β , and (d) energy dissipation as a function of α_p and β .

4. Conclusions

In this paper, the interaction between vehicles and an unsignalized mid-block raised crosswalk was studied using computational simulation. A pedestrian-vehicle cellular automaton model was developed representing open-boundary conditions with rates α for injection and β for extraction, whilst pedestrians enter from a waiting zone to the crosswalk at rate α_p . Taking traffic flow as the order parameter, the phase diagram was constructed identifying four phases: maximum current, jamming, congestion, and gridlock. It was observed that the crosswalk becomes a bottleneck due to the pedestrians' influx, producing a vehicles reservoir that acts as an alternative injection rate that prevents the emerging of a free-flow phase, even when β is much greater than α . Indeed, in this system, there are free-flow conditions only during the maximum current phase. However, the maximum current phase drops with the increase in α , while the gridlock phase is reached when the pedestrian entrance rate α_p is greater than 0.8. The CO₂ emission and the energy dissipation were also evaluated, and it was found that the maximum values were observed during the jamming phase due to the queue formation of stop-and-go vehicles all along the lane. Conversely, the minimum values were located in the gridlock phases where traffic is at a complete standstill. The carbon dioxide emissions show the same

features such as the energy dissipation, as both of them have a relationship with speed variation. Along the same lines, the instantaneous energy dissipation was evaluated. It was observed that although the maximum current phase has free-flow conditions, speed changes caused by the crosswalk, and the lane's exit induces energy dissipation peaks. One of the implications of our study is to reveal that always giving priority to pedestrians over vehicles can worsen the traffic flow situation and induce gridlock. The results also provide an insight that raised crosswalks are not suited for roads intended for high traffic volumes; therefore, their installation must be performed according to the road hierarchy. In this sense, the main contribution of this work is to provide a novel reference framework to depict the traffic physics involved with raised crosswalks, so that showed results can motivate the development of microscopic simulation tools or forecasting guidelines for urban planning.

This study also was complemented with a brief analysis of a zebra crosswalk, where it was glimpsed that to achieve a fair comparison against a raised crosswalk a more dedicated study is needed, incorporating additional qualitative and quantitative parameters, such as safety factors or accident rates.

Further extensions of this work would consider the incorporation of additional variables to improve the model towards mimicking more realistic scenarios. In this sense, the future work will be focused on exploring the effects of multi-lane roads as well as the analysis of drivers yielding when combining with overtaking maneuvers.

Author Contributions: Conceptualization, J.R.P.C. and N.L.; methodology, J.R.P.C. and N.L.; software, J.R.P.C. and J.C.P.S.; validation, J.R.P.C., N.L., J.C.P.S. and J.L.Z.L.; formal analysis, J.R.P.C., N.L., J.C.P.S. and J.L.Z.L.; investigation, J.R.P.C., N.L. and J.C.P.S.; data curation, J.R.P.C., N.L. and J.L.Z.L.; writing—original draft preparation, J.R.P.C., N.L., J.C.P.S. and J.L.Z.L.; writing—review and editing, J.R.P.C., N.L., J.C.P.S. and J.L.Z.L.; visualization, J.L.Z.L.; supervision, J.R.P.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Construction of the Phase Diagram

In order to give a more detailed explanation about how the phase diagram was constructed, please consider Figure A1. It can be noticed that the four phases are defined from the variation of traffic flow. When flow is at its maximum level, for all combinations of α and β , it can be said the system is in the maximum current (MC) phase. The limits of this phase are depicted in Figure A1, where the area of MC can be seen when $\beta \geq 0.5$ (see the red circle that shows the point where the flow reaches its maximum) and $\alpha_p \leq 0.3$.

Figure A1. A 2D plot of flow (q) variation with respect to the extraction rate (β), for several values of pedestrian entrance rate (α_p).

Contrasting to MC, gridlock is characterized by the fact the flow becomes zero. In the studied system, the gridlock appears when α_p exceeds 0.8. In Figure A1, the lines representing the flow variation for $\alpha_p \geq 0.8$ are overlapped from the yellow-circled point.

The jamming phase is defined when the flow is still stable and the microscopic characterization of the vehicles shows the stop-and-go event over the whole system (see Figure 5b). Jamming worsens if α_p increases, as shown in Figure A1 between the two blue-circled points.

Finally, the congestion phase depends strongly on α_p and β , which means as α_p increases the traffic flow worsens until becomes null. In this way, it can be deduced that in the present study this phase is only the preparation phase, where the system transitions to the gridlock (see the inclined line that separates the other phases and that decreases if β decreases). In other words, if the boundary of the three phases is correctly determined, the fourth phase can be defined directly from the line that separates the others phases.

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