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Krishna Kumari R

krishrengan@gmail.com

SRM Institute of Science and Technology

Research Article

Keywords:

Posted Date: October 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-6233310/v1>

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Additional Declarations: No competing interests reported.

Optimizing Traffic Conflict Analysis at Signalized Intersections Using Multi-Scale Cellular Automata

Krishna Kumari. R^{1*}

¹Department of Mathematics,
College of Engineering and Technology,
SRM Institute of Science and Technology,
Kattankulathur-603203, Tamilnadu, India
krishrengan@gmail.com

March 15, 2025

Abstract

Traffic congestion and pedestrian safety at four-way signalized intersections remain critical challenges in urban transportation. This study employs Multi-Scale Cellular Automata (MSCA) to analyze and simulate traffic conflicts between vehicles and pedestrians. Unlike traditional cellular automata, MSCA incorporates multiple spatial and temporal scales, enabling a more detailed representation of traffic dynamics. By defining conflict zones and multi-scale interaction rules, we assess the impact of different signal timing strategies on traffic flow efficiency and safety. The results provide insights into optimizing signalized intersections by leveraging MSCA's hierarchical modeling to minimize delays and enhance pedestrian safety.

AMS Subject Classification: 68Q80, 68Q85

Key Words : Multi-Scale Cellular Automata, Road Intersection, Pedestrian-Vehicular Conflicts.

*Corresponding author

1 Introduction

In India, a significant portion of the mixed traffic flow at urban road intersections is made up of pedestrians [7, 8, 12]. However, they are at a higher risk of suffering injuries and even fatalities in pedestrian-vehicle collisions, making them more vulnerable road users. Therefore, in order to create a safe, effective traffic operation environment, it is crucial to investigate the mechanisms of traffic conflicts between pedestrians and vehicles at intersections [14, 17].

Prior research on traffic conflicts in India mainly concentrated on the following areas:

1. The identification of traffic conflicts and how to assess their seriousness;
2. The prediction of traffic conflicts and how they relate to traffic accidents;
3. The use of technology related to traffic conflicts in safety evaluation.

Nearly all of these studies' findings require data on traffic conflict as a prerequisite. However, the collection of data primarily depends on the investigators' subjective assessment, which cannot ensure consistency between various observations. Furthermore, many studies of traffic conflict focus on vehicle flow rather than the interaction between pedestrians and vehicles, given the rapid growth in urban vehicles and worsening traffic congestion [18, 19, 20].

Multi-Scale Cellular Automata (MSCA) [1, 22] extends the classical cellular automata (CA) framework by incorporating different spatial and temporal scales to simulate complex systems [4]. The adaptability and scalability of MSCA make it well-suited for modeling dynamic urban traffic scenarios. The discreteness of time, space, and state variables allows MSCA to effectively capture pedestrian flow complexities, including conflict resolution at intersections [11, 10].

Pedestrian simulation presents greater challenges compared to vehicle simulation due to its complexity and randomness. However, MSCA provides a robust framework to handle the stochastic nature of pedestrian movement [13, 16]. This model offers a detailed understanding of traffic conflicts by analyzing pedestrian-vehicle

interactions, signal timings, and road-crossing behaviors [15]. Krishna Kumari et al. explored traffic conflicts in signalized intersections through cellular automata simulations, emphasizing the role of adaptive traffic control mechanisms in reducing congestion and improving safety. Their study highlights the potential of multi-scale CA models in optimizing signal timings and predicting traffic flow dynamics [9]. This paper serves as an extended version of the previous study, incorporating advanced multi-scale cellular automata models, refined simulation methodologies, and additional experimental results. We further analyze pedestrian movement at three-way intersections and introduce novel strategies for improving intersection efficiency. The objectives of this study include:

1. Quantitative assessment of crosswalk capacity;
2. Estimation of traffic conflicts between pedestrians and vehicles;
3. Analysis of pedestrian delay caused by these conflicts at signalized intersections [6].

This research explores the impact of pedestrian signal timing and crosswalk width on traffic conflict occurrences. By integrating MSCA-based simulation techniques, this study contributes to the theoretical foundation for assessing pedestrian safety and improving traffic signal optimization [21].

2 Preliminaries

In this section, some basic concepts are recalled.

Definition 2.1. *A Multi-Scale Cellular Automaton (MSCA) is an advanced discrete model consisting of a hierarchical grid of cells, where different scales of resolution interact dynamically. Unlike traditional cellular automata, MSCA allows for multi-level interactions, enabling more accurate representations of complex systems. Each cell updates its state over time based on transition rules that incorporate influences from both local and multi-scale neighborhood structures. Formally, MSCA is defined as a 6-tuple:*

$$MSCA = (R, M, A, f, a_0, S)$$

where

- R is a hierarchical grid of cells,
- A is a set of finite states,
- a_0 is the initial configuration, ($a_0 \in A$),
- M is a finite set of neighborhood indices such that for all $r \in R, c \in M : r + c \in R$,
- $f : A^n \rightarrow A$ is the transition function governing the evolution of states, and
- S represents the multi-scale interaction function that enables information flow across different levels of the hierarchy.

Definition 2.2. *Road intersections are the junctions where two or more roads meet, requiring an efficient traffic control mechanism. The dynamics of vehicles and pedestrians at intersections can be effectively modeled using MSCA to capture multi-scale interactions and emergent traffic patterns.*

3 Multi-Scale Cellular Automata Model

The three-way intersection considered in this model is a signalized intersection with a fixed vehicular-pedestrian signal time cycle of 90 seconds. A total of five streams are modeled, consisting of three vehicular streams and two pedestrian streams (see Figure 1). The MSCA-based model simulates two crosswalks at the signalized intersection, where the pedestrian signal follows a cycle of 30 seconds of green light and 60 seconds of red light.

The road segment leading to the intersection consists of two-way, two-lane vehicle roads, each measuring 12 meters in width. The crosswalk is 24 meters long and 3 meters wide. Two pedestrian waiting areas are located on either side of the crosswalk, each accommodating up to 100 people. The crosswalk is discretized into square cells of $0.5m^2$, where each cell is occupied by either a single pedestrian or remains empty.

In the MSCA model, pedestrian movement follows a multi-scale interaction framework, where:

- Local interactions determine pedestrian movement at the microscopic scale, considering stepwise movement across adjacent cells.
- Mesoscopic interactions account for density effects, influencing pedestrian speed and waiting behavior.
- Macroscopic interactions include traffic signals and vehicle flow constraints that impact pedestrian decisions at a broader level.

Pedestrian speeds range from 2 to 6 cells per second, corresponding to real-world velocities of 1 m/s to 3 m/s. Each vehicle is assumed to move at a speed of 6 m/s and occupies a space of 6×5 meters. The model employs an open boundary condition, and each simulation time step corresponds to one second.



Figure 1: Real-Life Three-Way Intersection with Uncontrolled Traffic

In Figure 2, the traffic and pedestrian streams are denoted as follows:

- σ_1 represents the straight-moving vehicle stream towards the right.
- σ_2 represents the straight-moving vehicle stream towards the left.
- σ_3 represents the left-turning vehicle stream.

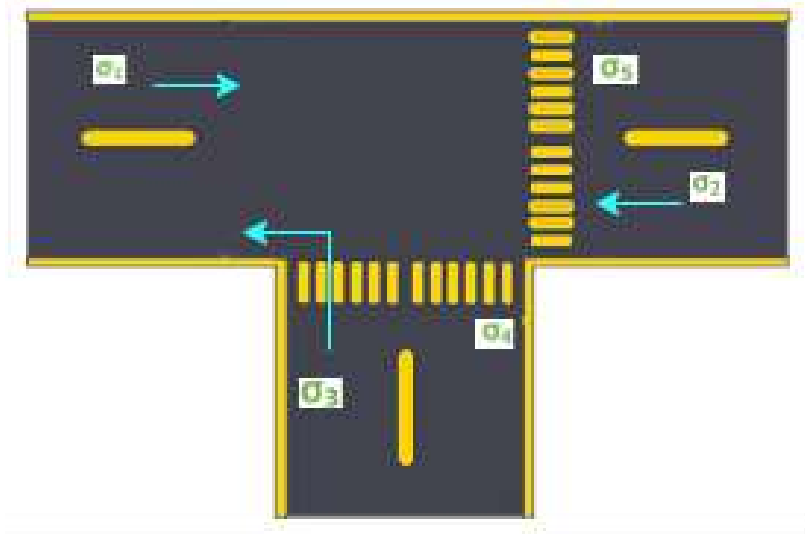


Figure 2: Schematic of the Three-Way Intersection

- σ_4 represents the bidirectional pedestrian stream on a one-way road.
- σ_5 represents the bidirectional pedestrian stream on a two-way road.

The intersection's traffic light cycle is divided into two main signal groups, illustrated in Figures 3 and 4.

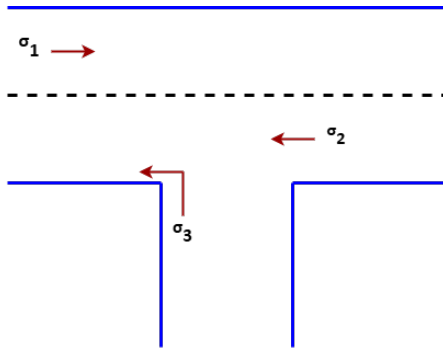


Figure 3: Signal Group 1 (60 seconds)

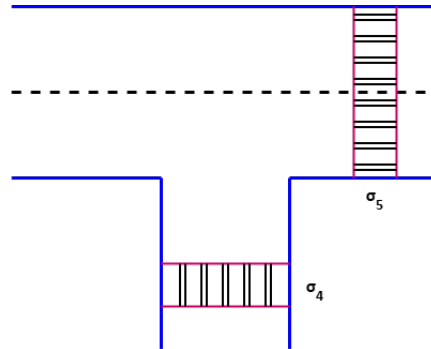


Figure 4: Signal Group 2 (30 seconds)

3.1 Multi-Scale Cellular Automata-Based Rules

3.1.1 Pedestrian Rules

1. The arrival rate of bidirectional pedestrian flow follows a Poisson distribution:

$$P_m = \frac{(\lambda_p t)^m}{m!} e^{-\lambda_p t}$$

where, P_m denotes the probability of m pedestrians arriving during the interval t , with an average pedestrian arrival rate λ_p (capita/second).

2. A multi-scale microscopic pedestrian model considers hierarchical movement rules across different scales:
 - (i) **Microscopic Level (Pedestrian Step-Level)**: Individual pedestrian movement is based on local neighborhood occupancy.
 - (ii) **Mesoscopic Level (Lane-Level Flow)**: Lane utilization and adaptive lane-changing strategies.
 - (iii) **Macroscopic Level (Intersection-Level Dynamics)**: Interactions with traffic signals and pedestrian crosswalk conditions.
3. Pedestrians prioritize forward movement but change lanes adaptively based on traffic density, available empty cells, and perceived delays.
4. The pedestrian velocity $V_{i,j}$ at location $x_{i,j}$ depends on the gap $d_{i,j}$ between the pedestrian and their nearest forward pedestrian:

$$V_{i,j} = \min\{d_{i,j}, v_{i,j}\}$$

The initial velocity of pedestrians in the crosswalk is assigned based on field observations:

$$V_{i,j} = \begin{cases} 2 & \text{if } 0.2 \geq p \geq 0 \\ 3 & \text{if } 0.5 \geq p \geq 0.2 \\ 4 & \text{if } 0.7 \geq p \geq 0.5 \\ 5 & \text{if } 0.9 \geq p \geq 0.7 \\ 6 & \text{if } p > 0.9. \end{cases}$$

where p is a random number between 0 and 1.

5. During peak hours, conflicts arise when multiple pedestrians compete for the same cell. In such cases, a probabilistic priority rule is applied to resolve conflicts.
6. Pedestrians must wait at designated areas during red signals. When the green signal ends, any pedestrian still in the cross-walk faces conflict with vehicles.

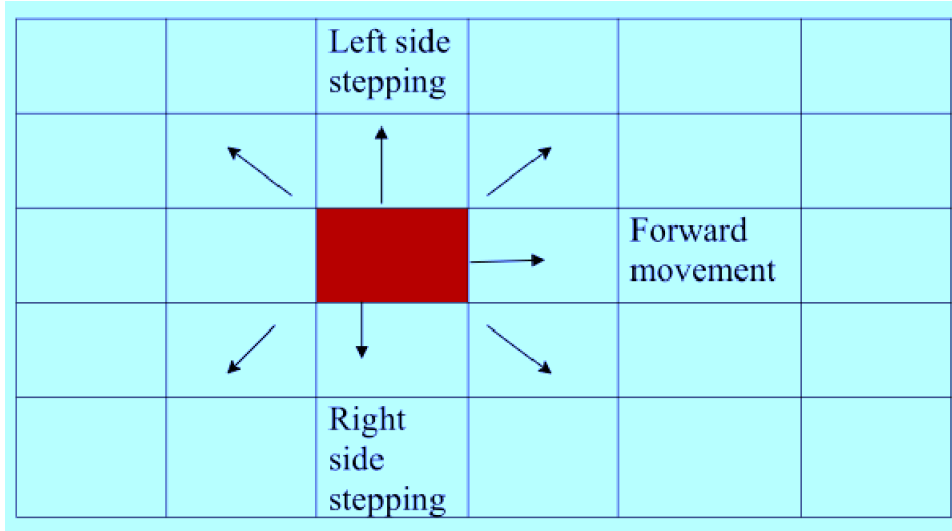


Figure 5: Pedestrian movement based on multi-scale rules

3.1.2 Vehicle Rules

- 1) The arrival rate of vehicular flow follows a Poisson distribution similar to pedestrians.
- 2) Vehicles are subject to multi-scale traffic rules:
 - (i) **Microscopic Level:** Individual vehicle motion follows stochastic gap acceptance rules.
 - (ii) **Mesoscopic Level:** Lane selection depends on congestion and pedestrian interference.

- (iii) **Macroscopic Level:** Vehicles interact with signals and pedestrian crossings dynamically.
- 3) When the pedestrian signal is green, vehicles cannot enter the crosswalk unless the pedestrian arrival rate is below a predefined threshold.

3.1.3 Areas of Conflict

Conflicts between pedestrians and vehicles occur in two critical areas:

- (1) **Left-Turning Vehicle Conflict** (σ_3 vs. σ_4): During signal phase 2, left-turning vehicles conflict with pedestrian flow due to permissive left turns on red.
- (2) **Straight-Moving Vehicle Conflict** (σ_1, σ_2 vs. σ_5): Pedestrians crossing face conflicts with straight-moving vehicles under permissive straight-on-red conditions.

3.1.4 Conflict Patterns and Resolution Rules

Conflicts follow three primary patterns:

- (1) A vehicle occupies a pedestrian's target cell.
- (2) Pedestrians are within a vehicle's intended path.
- (3) Both a pedestrian and a vehicle attempt to move to the same cell simultaneously.

To resolve conflicts, the following rules apply:

- (1) Vehicles have priority when occupying a pedestrian's target cell. Conversely, if the target cell of the vehicle is occupied by pedestrians, priority is given to the pedestrians.
- (2) If both a pedestrian and a vehicle have the same target, priority is randomly assigned with a probability of 0.5.

3.1.5 Boundary Conditions

Two types of boundary conditions exist in MSCA-based traffic modeling:

- (1) **Periodic Boundary Condition:** Suitable for analyzing steady-state traffic conditions with a fixed density.
- (2) **Open Boundary Condition:** More realistic for dynamic traffic flow, allowing vehicles and pedestrians to enter and exit the system probabilistically.

This model uses the **open boundary condition** to better simulate real-world pedestrian-vehicle interactions.

4 Simulation of the Model

In this simulation, the concept of Multi-Scale Cellular Automata (MSCA) serves as the foundational framework for modeling the intricate dynamics between pedestrians and vehicles at a signalized intersection. Unlike traditional Cellular Automata (CA), MSCA enables the integration of different spatial and temporal scales, allowing a more realistic representation of urban traffic dynamics. The urban space is transformed into a hierarchical grid R , where each distinct region symbolizes a multi-scale cell within the MSCA grid structure. These cells encapsulate various resolution levels, dynamically adapting to the density of pedestrians and vehicles.

Within this structured environment, the simulation employs a comprehensive set of finite states A to describe the conditions of both pedestrians and vehicles at different scales. Pedestrian states range from dynamic movements, waiting phases, and multi-agent interactions to conflict resolution states. Similarly, vehicles transition through states encompassing motion, halting, and congestion levels. The initiation of the simulation corresponds to the establishment of the initial configuration a_0 , defining the starting positions and states of pedestrians and vehicles. As the simulation evolves, the neighborhood M dynamically adjusts based on proximity and density variations, capturing interactions across multiple scales—thus aligning with the MSCA principle of adaptive neighborhoods.

The core of the simulation lies in the implementation of a transition function f , where a set of multi-scale rules governs the evolution of states for both pedestrians and vehicles. For instance, the transition from a waiting state to a moving state for pedestrians is contingent on not only the signal turning green but also the density-dependent influence from neighboring cells. This rule-based transition function aligns with the MSCA paradigm, enabling dynamic adaptation of rules based on traffic conditions at different scales. By drawing parallels between MSCA principles and the simulation results, we emphasize how multi-scale interactions provide a robust framework for accurately modeling the complex dynamics of pedestrian-vehicle interactions in an urban setting. The simulation highlights how structured and adaptive rule-based modeling enhances the understanding of traffic congestion, conflicts, and pedestrian flow patterns.

This model is based on two assumptions:

- (1) Traffic rules should be followed by both pedestrians and vehicles without engaging in intentional red light running. Only pedestrians who are still crossing at the end of the green light exhibit the red light running behavior.
- (2) Since pedestrian conflicts at lower densities have minimal safety impact, this model primarily focuses on conflicts arising at higher densities.

The model uses Python as a simulation platform. The flowchart in Figure 5 depicts the process for simulating conflicts. Among them, the *vehicle decision 1* denotes whether pedestrians are present in the target area, while the *vehicle decision 2* denotes whether pedestrians are approaching the target area. The logic behind the pedestrians in *pedestrian decision 1* and *pedestrian decision 2* follows the same adaptive decision-making approach.

4.1 Simulation Results

The above Python code visualizes the relationship among pedestrian flow, vehicle flow, and the number of conflict events at a signalized intersection using a 3D scatter plot. The simulation

Algorithm 1 Multi-Scale Cellular Automata for Pedestrian-Vehicle Conflicts

```

1: Inputs: Macro-scale grid size, Micro-scale grid size, Pedestrian
   density, Vehicle density
2: Outputs: Conflict intensity map
3: Initialize: Macro-scale grid  $\mathcal{G}_M$  and Micro-scale grid  $\mathcal{G}_m$  with
   zeros
4: Generate pedestrian and vehicle densities:
5:    $P_M \leftarrow$  Linearly spaced pedestrian density at macro-scale
6:    $V_M \leftarrow$  Linearly spaced vehicle density at macro-scale
7:    $P_m \leftarrow$  Interpolated pedestrian density at micro-scale
8:    $V_m \leftarrow$  Interpolated vehicle density at micro-scale
9: function UPDATEMACROSCALE( $\mathcal{G}_M, V_M$ )
10:  for all cells  $(i, j)$  in  $\mathcal{G}_M$  do
11:    if Random probability  $< V_M[j]$  then
12:       $\mathcal{G}_M[i, j] \leftarrow \min(\mathcal{G}_M[i, j] + 1, 5)$ 
13:    end if
14:  end for
15:  return  $\mathcal{G}_M$ 
16: end function
17: function UPDATEMICROSCALE( $\mathcal{G}_m, P_m, V_m$ )
18:  for all cells  $(i, j)$  in  $\mathcal{G}_m$  do
19:    if Random probability  $< P_m[i]$  and Random probability
     $< V_m[j]$  then
20:       $\mathcal{G}_m[i, j] \leftarrow \mathcal{G}_m[i, j] + 1$ 
21:    end if
22:  end for
23:  return  $\mathcal{G}_m$ 
24: end function
25: Update macro and micro-scale grids:
26:  $\mathcal{G}_M \leftarrow$  UPDATEMACROSCALE( $\mathcal{G}_M, V_M$ )
27:  $\mathcal{G}_m \leftarrow$  UPDATEMICROSCALE( $\mathcal{G}_m, P_m, V_m$ )
28: Compute conflicts:  $C \leftarrow \sum \mathcal{G}_m$  along axis 0
29: Reshape  $C$  to match grid dimensions for visualization
30: Output: 3D visualization of conflict intensity

```

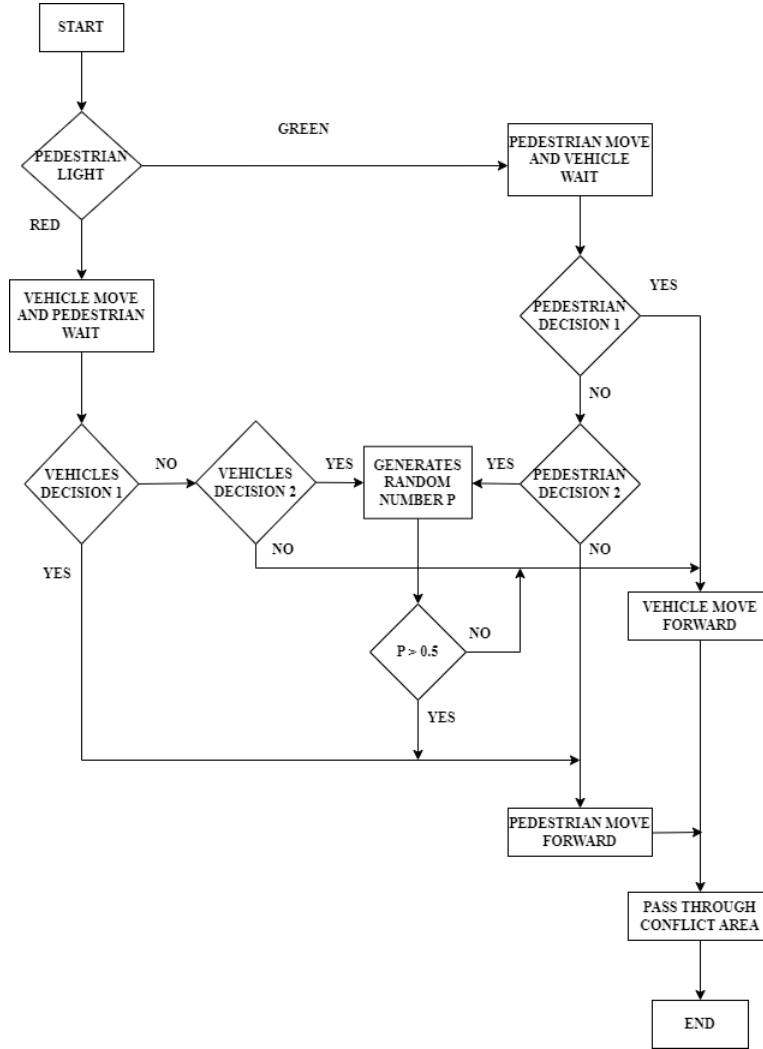


Figure 6: The flowchart illustrating the simulation process

dynamically adjusts resolution based on congestion levels, applying the MSCA paradigm to refine interactions at critical densities. This enhances the accuracy of conflict detection and traffic behavior analysis.

The duration of pedestrian conflict delay is the time pedestrians take to stop avoiding oncoming traffic. If the delay exceeds a threshold, pedestrians may cross despite the red light, influencing the overall system dynamics.

The relationship between pedestrian flow, vehicle flow, and total

Algorithm 2 Multi-Scale Cellular Automata Simulation for Conflict Delay

```
1: Inputs: Pedestrian density  $P_d$ , Vehicle density  $V_d$ , Grid size  
   ( $M, N$ )  
2: Outputs: Conflict delay matrix  $Z$   
3: function SIMULATECONFLICTDELAY( $P_d, V_d, M, N$ )  
4:   # Initialize macro and micro grids  
5:    $macro\_grid \leftarrow$  Random values in  $M \times M$  grid  
6:    $micro\_grid \leftarrow$  Zero matrix of size  $N \times N$   
7:   # Update macro-scale (vehicle dynamics)  
8:   for each cell  $(i, j)$  in  $macro\_grid$  do  
9:     if random probability  $< V_d$  then  
10:       $macro\_grid[i, j] \leftarrow \min(macro\_grid[i, j] + 0.1, 1)$   
11:    end if  
12:  end for  
13:  # Update micro-scale (pedestrian-vehicle  
    conflicts)  
14:  for each cell  $(i, j)$  in  $micro\_grid$  do  
15:    if random probability  $< P_d$  and random probability  $< V_d$   
    then  
16:       $micro\_grid[i, j] \leftarrow micro\_grid[i, j] + 1$   
17:    end if  
18:  end for  
19:  return  $micro\_grid$   $\triangleright$  Conflict delay matrix  
20: end function
```

Multi-Scale Cellular Automata: Pedestrian-Vehicle Conflicts

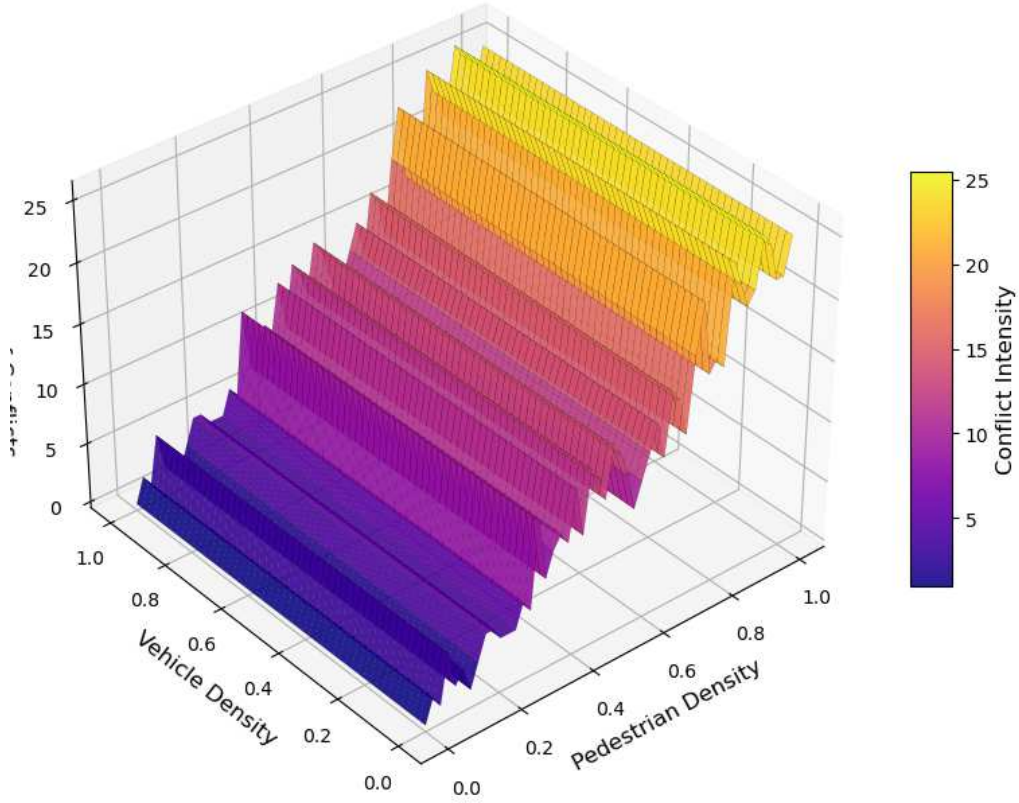


Figure 7: Relationship between the pedestrian/vehicle flow and the conflicts

conflicts is depicted in Figure 7.

As vehicle density rises, conflict delay increases for a given pedestrian density. Beyond a critical density, the system transitions between different behavioral regimes, highlighting the advantages of MSCA in capturing these emergent patterns. Figure 8 illustrates how pedestrian flow interacts with vehicle movement, revealing adaptive patterns based on multi-scale resolution adjustments. The MSCA framework thus provides a more refined approach to understanding and mitigating conflicts in urban traffic scenarios.

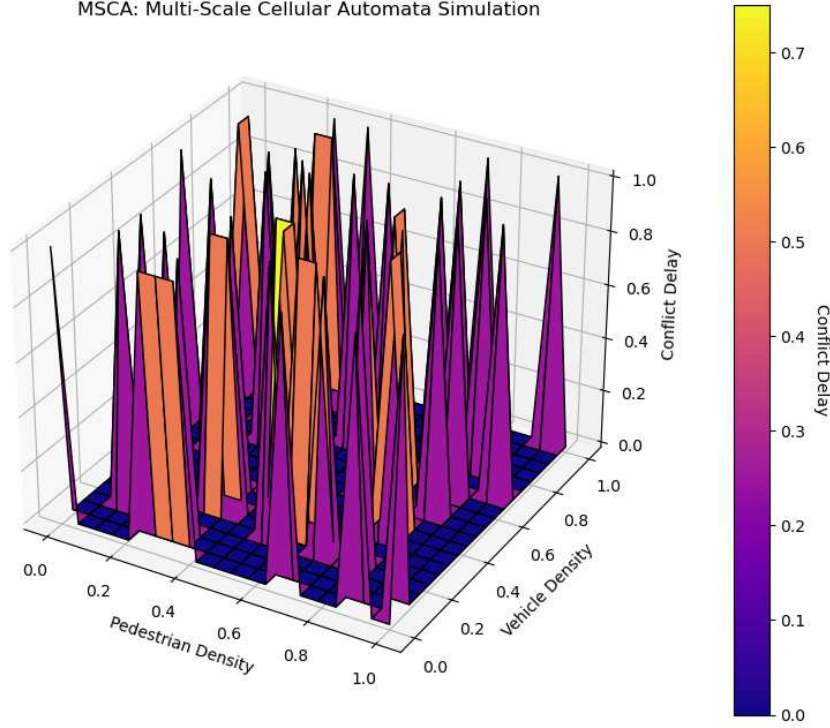


Figure 8: Relationship between the pedestrian/vehicle flow and the total conflict delay

5 Conclusion

This study presents a **Multi-Scale Cellular Automata (MSCA)** approach for modeling pedestrian-vehicle interactions at signalized intersections. By integrating multi-scale dynamics, our model captures both microscopic pedestrian behavior and macroscopic traffic flow, offering a comprehensive framework for understanding collision risks and traffic delays.

5.1 Key Findings

1. **Hierarchical Influence of Vehicle Density on Delay:**
The MSCA model demonstrates a multi-level interaction where increasing vehicle density leads to prolonged delays at both the **local (pedestrian crossings)** and **global (intersection throughput)** scales.

2. **Multi-Scale Fluctuations in Pedestrian Flow:** Unlike conventional cellular automata models, our approach captures the **non-linear pedestrian density fluctuations** at different spatial and temporal resolutions, revealing emergent congestion patterns.
3. **Conflict Event Characterization Across Scales:** By defining **multi-scale conflict events**, we highlight critical zones of high collision probability, enabling better traffic safety interventions.
4. **Scalability for Traffic Optimization:** The proposed MSCA framework provides a scalable methodology for modeling complex urban traffic systems, making it adaptable for future research in **dynamic intersection control and pedestrian-centric urban planning**.

5.2 Future Research Directions

1. **Adaptive Pedestrian Management at Multiple Scales:** Investigate how localized pedestrian movement patterns influence intersection-wide traffic dynamics and develop control strategies accordingly.
2. **Multi-Scale Conflict Mitigation Strategies:** Design predictive models for real-time pedestrian-vehicle conflict detection, incorporating sensor-based traffic monitoring.
3. **Validation with Empirical Data:** Calibrate and validate the MSCA model using real-world traffic datasets to enhance accuracy and applicability in urban mobility planning.
4. **Multi-Resolution Dynamic Signal Control Algorithms:** Implement adaptive signal control systems that respond to pedestrian and vehicle densities at different spatial-temporal scales.
5. **Integration into Smart Traffic Systems:** Explore the deployment of MSCA-based models within **intelligent transportation systems (ITS)** for real-time urban traffic management.

5.3 Implications for Urban Traffic Engineering

This MSCA-based approach contributes to the development of **next-generation urban traffic models**, offering a **multi-resolution perspective** on pedestrian-vehicle interactions. The insights from our study can inform policymakers, transportation engineers, and urban planners in designing **safer, more efficient** signalized intersections.

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