Impact of Road Sign on Traffic Congestion during Road Repair: A Cellular Automaton Model Study

Xi Lin[1*], *Akihito* Nagahama[2], and *Daichi* Yanagisawa[1]

[1]School of Engineering, The University of Tokyo, Tokyo, Japan
[2]Graduate School of Informatics and Engineering, The University of Electro-Communications, Tokyo, Japan

Short Abstract. This study investigates the impact of road signs on traffic congestion during road repairs using a cellular automaton (CA) model. The model simulates an urban dual-lane one-way road, incorporating a designated work zone. Three scenarios are analyzed: Without Sign, With Sign, and Combined Signs. The With Sign scenario includes advance warning signs placed before the work zone, encouraging gradual deceleration and safe lane changes, while the Combined Signs scenario integrates additional signage in the adjacent lane to optimize vehicle spacing and minimize congestion. Simulation results demonstrate that the combined signage approach achieves the most significant traffic improvements by reducing risky lane changes and promoting smoother speed adjustments, thereby alleviating congestion. Additionally, heatmap and density-flow analyses demonstrate improved lane utilization and reduced bottlenecks in scenarios incorporating road signs. The findings underscore the importance of integrating multiple coordinated road signs with behavioral insights for enhanced traffic management near work zones.

1 Introduction

When road segments sustain damage or become otherwise inoperative, road repair is typically undertaken within designated work zones. However, these work zones frequently cause severe congestion, particularly in areas immediately surrounding lane closures, resulting in the formation of bottlenecks. Accordingly, research focused on work zone operations is critical for mitigating such traffic disruptions. Between 2009 and 2011, models accounting for intersection proximity and left-turn ratios were proposed to estimate work zone capacity, thereby establishing a robust framework for capacity management [1-2]. Additional investigations reveal that merging maneuvers by vehicles near work zones precipitate speed-flow oscillations that reduce overall capacity [3], whereas the implementation of ramp metering can alleviate mainline bottlenecks [4]. A continuum model incorporating a golden-ratio-based random parameter to represent mandatory lane-change rates upstream of work zones revealed critical vehicle-density thresholds

* Corresponding author: lin-xi@g.ecc.u-tokyo.ac.jp

triggering congestion and provided insights into lane-change management in tunnels or under heavy-vehicle conditions [5]. Building on this framework, a three-lane ring freeway featuring both a work-zone lane closure and a downstream tunnel was modeled to identify two distinct jam-formation thresholds associated with each feature and to quantify their impacts on travel time and fuel consumption [6].

Road signs play a crucial role in guiding drivers. The number of road names displayed affects driver behavior [7], while visual cues influence environmental perceptions and responses to traffic information [8]. Moreover, low-volume intermittent signage at tunnel entrances improves speed control by aligning drivers' speed perception with safety requirements [9]. Effective sign interpretation thus promotes smoother traffic flow and enhances road safety [10].

Cellular Automata (CA) models, widely used to simulate various traffic conditions, have been extended to work zone scenarios. A detailed two-lane CA model defines normal, merging, and work areas with specific lane-change rules [11]. Findings show lower merging probabilities extend upstream congestion, informing recommendations on merging distances and speed limits.

Although previous studies have advanced our understanding of work zones, the impact of road signs on drivers, and CA-based traffic modeling, they have largely examined these factors independently. In contrast, the present study explicitly integrates drivers' psychological and behavioral responses to road sign directly into CA-based traffic models for work zones. By combining micro-level driver behavior with CA simulation, we aim to provide a more realistic representation of traffic flow and to develop novel strategies for work zone management and congestion mitigation.

2 Model Description

2.1 Overview

This research investigates the influence of road signs in alleviating traffic congestion during road repair activities by employing a CA model (discrete time). The road is represented as a series of discrete 5-meter segments (cells), providing a structured framework for traffic flow analysis. A 1000-meter, two-lane urban road operating in a single direction is modeled, with a designated work zone spanning 20 meters (cells No. 150-153) in Lane 1, as shown in Fig. 1. Vehicles, each occupying a single 5-meter cell, navigate this road under varying conditions influenced by the presence or absence of road signs. To maintain a consistent traffic density, periodic boundary conditions are applied, ensuring that vehicles reaching the road's endpoint are regenerated at the origin.

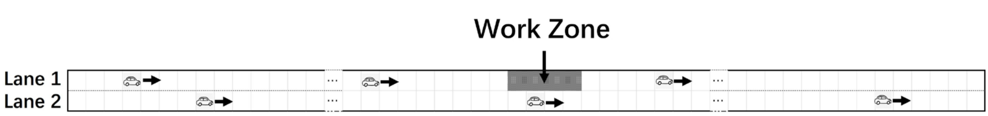

Fig. 1. Configuration of the Dual-Lane One-Way Road.

2.2 Basic Rules

The vehicle movement rules in this model are derived from the Nagel-Schreckenberg (NaSch) model [12]. The motion of each vehicle within a lane is updated through the following four steps:

a) Acceleration: If a vehicle's current speed is below the maximum, it increases by 1:

$$v_i' = \min\left(v_i\left(t\right)+1, v_{\max}\right). \quad (1)$$

b) Deceleration: To avoid collisions, a vehicle slows down if the distance to the vehicle ahead is less than its speed:

$$v_i'' = \min\left(v_i', d_i\left(t\right)\right). \tag{2}$$

c) Randomization: A vehicle's speed may decrease by 1 with a probability p_{slow}, accounting for random factors like driver behavior or road conditions:

$$v_i\left(t+1\right) = \max\left(v_i'' - 1, 0\right). \tag{3}$$

d) Vehicle movement: Each vehicle advances by a distance equal to its updated velocity:

$$n_i\left(t+1\right) = n_i\left(t\right) + v_i\left(t+1\right), \tag{4}$$

where, $v_i(t)$ and $v_i(t+1)$ represent the velocity of vehicle at the time t and $t+1$. $n_i(t)$ and $n_i(t+1)$ represent the position of vehicle at the time t and $t+1$. $d_i(t)$ is distance to the vehicle ahead, $d_i(t) = n_{i+1}(t) - n_i(t) - 1$. $n_{i+1}(t)$ represents the position of preceding vehicle and $v_{\max}$ is the maximum velocity.

The NaSch model primarily addresses single-lane traffic. In this study, lane-changing behavior is integrated based on proactive motivation, probabilistic decision-making, and safety considerations, as detailed below.

a) Safety distance: Safety distance is defined by the maximum velocity of the vehicle:

$$d_{\text{safe,front}} = d_{\text{safe,back}} = v_{\max}. \tag{5}$$

b) Motivation: A vehicle is motivated to change lanes when the distance to the vehicle ahead is less than its desired speed. Additionally, some vehicles may attempt lane changes even without being directly impeded. A probabilistic lane-changing factor p_{change} captures this stochastic behavior, reflecting the variability in driver decision-making. Therefore, motivation conditions can be described as follows:

$$\text{Motivated to merge with probability} \begin{cases} 1, \text{ if } d_i\left(t\right) < \min\left(v_i\left(t\right)+1, v_{\max}\right) \\ p_{\text{change}}, \text{ if } d_i\left(t\right) \ge \min\left(v_i\left(t\right)+1, v_{\max}\right) \end{cases}. \tag{6}$$

c) Safety conditions: Lane-changing is allowed if the target cell is unoccupied and the distances to vehicles in the target lane (ahead and behind) exceed the safety distance:

$$\text{Merge allowed, if} \begin{cases} d_{\text{next,back},i}\left(t\right) > d_{\text{safe,back}} \text{ and,} \\ d_{\text{next,front},i}\left(t\right) > d_{\text{safe,front}} \text{ and,} \\ c_{\text{next},i}\left(t\right) = 0, \end{cases} \tag{7}$$

where, $d_{\text{safe, front}}$ and $d_{\text{safe, back}}$ represent the safety distances. $d_{\text{next,front},i}(t)$ and $d_{\text{next,back},i}(t)$ measure the front and back distances in the target lane. $c_{\text{next},i}(t)$ is a Boolean variable representing the presence of vehicle in the target cell of adjacent lane at the time t.

d) Change lane: Once all conditions are met, the vehicle's lane index is updated:

$$m_i\left(t+1\right) = m_i\left(t\right) \pm 1, \tag{8}$$

where, $m_i(t)$ and $m_i(t+1)$ are the lane index (Lane 1, 2) of vehicle at the time t and $t+1$.

2.3 Simulation

In simulation, each vehicle occupies a length of 5 meters, equivalent to 1 cell on the road, and the maximum speed is set at 90 km/h, allowing vehicles to move 5 cells per time step. Vehicles are evenly allocated between the two lanes, with half generated in each lane to replicate balanced traffic conditions. Vehicle density in the simulation ranges from 0 to 0.8, corresponding to 0% to 80% of the cells (including work zone) are occupied by vehicles. The probability of randomization p_{slow} is set to 0.3, based on the numerical settings used in the simulation by Pan et al., simulating real-world factors like driver distractions and road conditions [13]. Similarly, the lane-changing probability p_{change} is set to 0.3, reflecting the stochastic and unpredictable nature of human driving behavior. Each simulation runs for 10,000 time steps to ensure system stability and facilitate data collection under steady-state conditions. Key performance indicators, including average flow and speed, as well as other relevant indicators, are computed after the 9,000th time step to evaluate traffic efficiency, congestion levels, and lane utilization. All simulations in this study were conducted using MATLAB R2024A.

3 Scenarios

This study first establishes a baseline scenario to represent traffic conditions on a dual-lane one-way road without road repair, following the fundamental rules described earlier. When a work zone is introduced, an initial scenario without traffic guidance, such as road signs, is analyzed. To improve traffic flow near the work zone, road signs are introduced as a mitigation measure.

3.1 Without Sign

Research on driver behavior during the yellow light phase at intersections identifies a critical threshold of 100 meters, within which drivers shift from passive observation to active decision-making [14]. This concept is similarly applicable to work zones, where the absence of advance warning signs can provoke abrupt driver reactions. As vehicles approach within 100 meters (equivalent to 20 cells) of a road repair area, drivers in the affected lane often display aggressive behaviors such as sudden braking and risky lane changes. As illustrated in Fig. 2, the area $\mathrm{R_r}$ of sudden braking and risky lane-changing is consistently located within the 100-meter stretch preceding the work zone, encompassing cells No. 130-149.

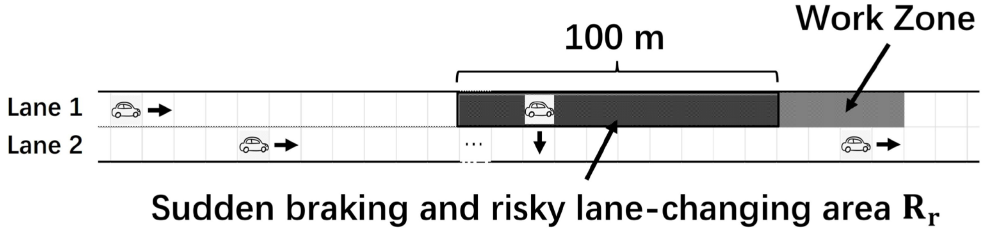

Fig. 2. Spatial Distribution of Sudden Braking and Risky Lane-changing Area Near Work Zones.

To address the unique dynamics and risks of driver behavior near road repair area, special rules are introduced:

a) Sudden braking rule: When a vehicle enters the sudden braking area $\mathrm{R_r}$, the basic update rules (1)-(3) no longer apply. Instead, the vehicle's velocity is immediately set to zero in the next time step:

$$v_i\left(t+1\right)=0,\ \ \text{if}\ n_i\left(t\right),m_i\left(t\right)\in \mathrm{R_r}. \tag{9}$$

b) Risky lane-changing rules: Unlike the basic lane-changing mechanism (5)-(8), in the risky lane-changing area $\mathrm{R_r}$, drivers exhibit aggressive behavior, prioritizing rapid lane changes over careful distance evaluation. The rules are as follows:

$$m_i\left(t+1\right)=m_i\left(t\right)+1,\ \ \text{if}\begin{cases} n_i\left(t\right),m_i\left(t\right)\in \mathrm{R_r}\ \text{and,} \\ c_{\text{next},i}\left(t\right)=0. \end{cases} \tag{10}$$

To prevent collisions during lane changes in target lane, the following vehicles in target lane must consider safety factors. Specifically, when observing vehicles from the repair lane making risky lane changes, they often choose to decelerate to avoid potential collisions.

$$n_{\text{next},i-1}(t+1)=\begin{cases} n_i(t)-1, & \text{if } n_{\text{next},i-1}(t)+v_{\text{next},i-1}(t+1)\geq n_i(t) \\ n_{\text{next},i-1}(t)+v_{\text{next},i-1}(t+1), & \text{if } n_{\text{next},i-1}(t)+v_{\text{next},i-1}(t+1)< n_i(t) \end{cases}, \quad (11)$$

where, $n_{\text{next},\ i\text{-}1}(t)$ and $n_{\text{next},\ i\text{-}1}(t+1)$ represent the position of the following vehicle in target lane at the time t and $t+1$. $v_{\text{next},\ i\text{-}1}(t+1)$ is the velocity of the following vehicle in target lane at the time $t+1$.

3.2 With Sign

To improve traffic flow near work zone, urban traffic managers often strategically position road sign to guide drivers. To mitigate aggressive driving behaviors caused by unexpected conditions within 100 meters of a work zone, it is crucial to place road sign farther away, at least 125 meters (25 cells) in advance of the repair site. In the "With Sign" scenario, the sign not only alerts drivers to the upcoming work zone but also imposes a reduced speed limit of 36 km/h (2 cells per time step). This early notification helps drivers decelerate smoothly rather than braking abruptly. Additionally, the signs display messages such as "Construction Ahead, Please Merge Safely," encouraging cautious and deliberate lane-changing behavior. By providing advanced warning and promoting safe merging, these measures effectively reduce the likelihood of sudden maneuvers and contribute to overall traffic safety near construction areas. Figure 3 highlights the placement of road sign along with the area R_g for gradual deceleration and gentle lane-changing.

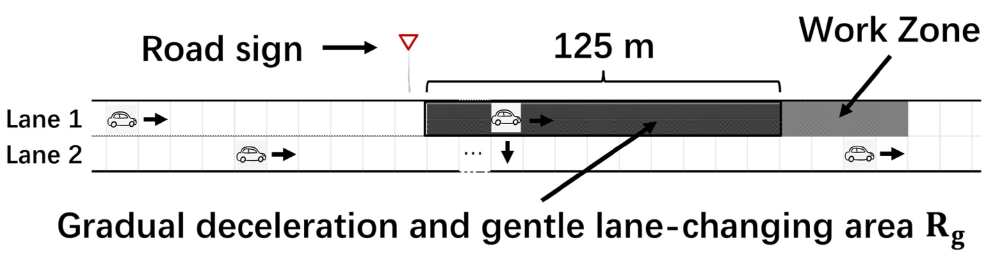

Fig. 3. Spatial Distribution of Road Sign, Gradual Deceleration and Gentle Lane-changing Area.

Special rules are introduced:

a) Gradual deceleration rules: When vehicles enter the gradual deceleration area R_g, those traveling at speeds exceeding 36 km/h are subjected to controlled deceleration as directed by the road signage. The basic update rule (4) is replaced by the special updated rules (12)-(13) in this area:

$$v_i^{g}(t+1)=\begin{cases} v_i(t+1)-1, & \text{if } n_i(t), m_i(t)\in R_g \text{ and } v_i(t+1)>2 \\ v_i(t+1), & \text{if } n_i(t), m_i(t)\in R_g \text{ and } v_i(t+1)\leq 2 \end{cases}, \quad (12)$$

$$n_i(t+1)=n_i(t)+v_i^{g}(t+1). \quad (13)$$

b) Gentle lane-changing rules: In the gentle lane-changing area R_g, vehicles merge smoothly into the target lane based on road sign instructions. Unlike the basic lane-changing rule (6), which depends on situational motivations, all vehicles in this area share a common motivation to merge upon seeing the road sign. Another key difference lies in distance considerations. While basic lane-changing rules (5) and (7) balance both forward and rear safety distances, gentle lane-changing prioritizes rear safety to avoid conflicts with following vehicles. The merge occurs when the forward gap in the target lane is larger than the forward gap in the current lane, enabling vehicles to change lanes promptly upon recognizing the work zone. The gentle lane-changing rules are:

$$m_i(t+1) = m_i(t)+1, \text{ if } \begin{cases} n_i(t), m_i(t) \in \mathrm{R_g} \text{ and,} \\ d_{\text{next,front},i}(t) > d_i(t) \text{ and,} \\ d_{\text{next,back},i}(t) > d_{\text{safe,back}} \text{ and,} \\ c_{\text{next},i}(t) = 0. \end{cases} \tag{14}$$

3.3 With Combined Sign

In the "With Sign" scenario, the road sign is employed to regulate traffic flow within the repair lane, ensuring that vehicles navigate the work zone safely. Expanding on this, the "Combined Signs" scenario integrates additional signage in the adjacent lane to enhance the smooth flow of vehicles around the work zone. The signage in the adjacent lane is specifically designed to promote close following of the preceding vehicle while maintaining safety. Within the repair lane, the signage typically includes merging instructions followed by guidance emphasizing close following under safe conditions. As depicted in Figure 4, the designated close-following area is located in the adjacent lane, covering cells No. 125-153 and spanning a distance of 145 meters.

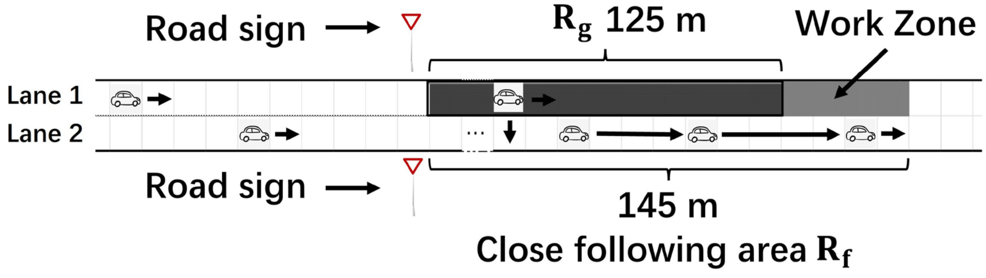

Fig. 4. Spatial Distribution of Road Sign, $\mathrm{R_g}$ and $\mathrm{R_f}$.

The special updated rules are as follows:

a) Gradual deceleration rules: Similar to the "With Sign" scenario.

b) Gentle lane-changing rules: Similar to the "With Sign" scenario.

c) Close following rules: When a vehicle enters the designated close-following area $\mathrm{R_f}$, its velocity is dynamically adjusted to optimize spacing while ensuring safety and maintaining efficiency. This adjustment ensures that the vehicle maintains a minimal but safe distance from the preceding vehicle without exceeding the prescribed speed limits. The special updated rule (15) in this area would replace basic rules (1)-(3):

$$v_i(t+1) = \min\left(d_i(t), v_{\max}\right), \text{ if } n_i(t), m_i(t) \in \mathrm{R_f}. \tag{15}$$

4 Results Analysis

4.1 Fundamental Diagram Analysis

The fundamental diagram includes the relationships between density-flow and density-speed. Average flow is defined as the mean number of vehicles crossing the boundary per time step, measured after the 9,000th step. Average speed is the mean velocity of all vehicles, also recorded after the 9,000th step. Simulations were performed for density values ranging from 0 to 0.8. The results are presented in Fig. 5.

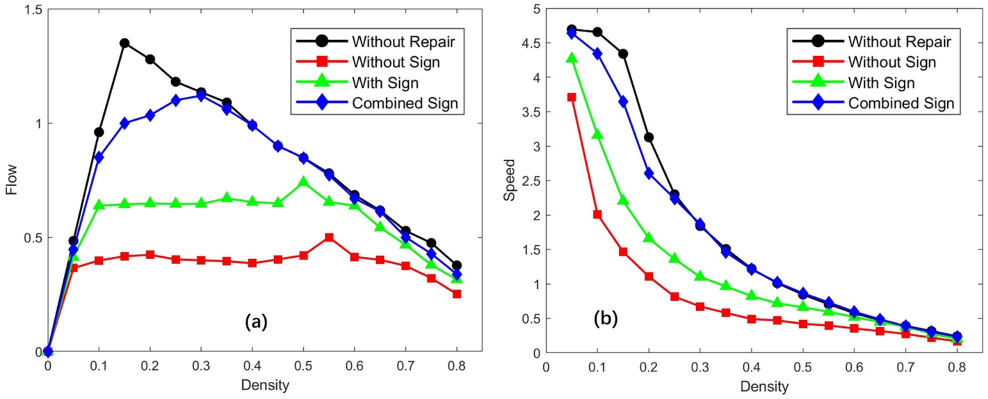

Fig. 5. Flow-Density (a) and Speed-Density (b) Relationship in different scenarios.

The relationship between flow and density illustrates how traffic flow evolves with variations in vehicle density under different scenarios. At low densities, traffic flow increases nearly linearly as vehicles benefit from sufficient space for unobstructed movement. However, as density approaches critical levels, the flow plateaus and eventually declines due to congestion effects. The presence of work zones significantly reduces the maximum achievable flow. Among the scenarios analyzed, those involving road signs generally exhibit improved flow compared to the "Without Sign" scenario. This improvement can be attributed to the guiding effect of road signs in reducing abrupt braking and erratic lane-changing behavior.

Similarly, the speed-density relationship reveals an inverse correlation between average speed and vehicle density. At low densities, vehicles maintain near-maximum speeds due to minimal interaction with other vehicles. As density increases, average speeds decline sharply, particularly in scenarios without traffic guidance. The scenarios with road signs demonstrate higher average speeds at medium densities, emphasizing the effectiveness of gradual deceleration and merging rules in maintaining smoother traffic conditions.

Notably, the "Combined Signs" scenario, which integrates multiple road signs, achieves the highest performance across both flow-density and speed-density relationships. This outcome underscores the synergistic effects and complementary benefits of incorporating multiple traffic signs to guide drivers more effectively. Moreover, in the "With Sign" scenario, the presence of road signs markedly reduces congestion when compared to the "Without Sign" scenario, further validating the positive impact of structured traffic management measures.

4.2 Heatmap Analysis

To more thoroughly examine the influence of road signs, we conduct a detailed comparison of distinct driving behaviors, specifically sudden braking versus gradual deceleration, and risky lane-changing versus gentle lane-changing, along with their effects on traffic flow and congestion. The heatmap illustrates the proportion of time each cell in a two-lane road model is occupied by vehicles after the 9,000th simulation step, with values ranging from 0 (free-flowing) to 1 (persistent congestion). By visualizing occupancy patterns, the heatmap highlights potential bottlenecks and evaluates the effectiveness of traffic management strategies: uniformly distributed occupation suggests smoother flow, whereas clusters of high occupation indicate inefficiencies. Figure 6 presents heatmaps for both "With Sign" and "Without Sign" scenarios at representative density levels (0.1, 0.3, 0.5), offering deeper insights into how traffic evolves under varying conditions. In the heatmaps, the central black area represent the work zones.

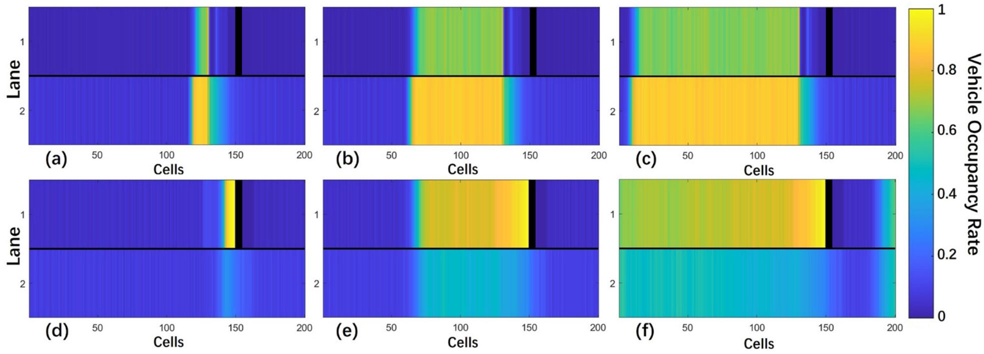

Fig. 6. Heatmaps Comparing Vehicle Occupancy in Without-Sign Scenario (a), (b), (c): densities at 0.1, 0.3, 0.5 vs. With-Sign Scenario (d), (e), (f): densities at 0.1, 0.3, 0.5.

Figure 6 provides a clear contrast between the “Without Sign” and “With Sign” scenarios across three representative traffic densities (0.1, 0.3, 0.5). In the “Without Sign” scenario, drivers notice the work zone only at a late stage, leading to sudden braking that stops vehicles in the repair lane from approaching the area near the work zone. These drivers then attempt risky lane changes, triggering sudden deceleration and causing congestion to spread upstream, especially near cell No. 130. This occurs because vehicles in the target lane must slow down to accommodate unsafe merges. The outcome is non-uniform occupancy in both lanes, with congestion clusters evident farther upstream.

By contrast, in the “With Sign” scenario, advance warning allows drivers to decelerate gradually and to shift lanes more cautiously. Rather than forcing abrupt slowdowns, drivers approach the work zone at lower speeds and wait for a safe chance to change lanes. This gentler lane-changing behavior, combined with controlled deceleration, greatly reduces the likelihood that occupancy will cluster in bottlenecks. Even at higher density levels, the target lane experiences less spillover congestion, because vehicles are willing to remain in the repair lane until an appropriate lane-change opportunity arises.

5 Discussions and Conclusion

This study highlights the effectiveness of road signs in mitigating traffic congestion near work zones, with particular emphasis on the advantages of combined signage strategies. The results demonstrate that the "With Sign" scenario significantly improves traffic flow by reducing sudden braking and risky lane changes. Moreover, the "Combined Signs" scenario achieves the best overall performance, leveraging multiple signs to enhance lane utilization and encourage safe merging and close-following behavior. These findings suggest that a coordinated signage system is crucial for optimizing work zone traffic management.

Future work should investigate dynamic signage, real-time traffic data and heterogeneous driver behaviors to refine these strategies. Since our analysis employs the NaSch cellular automaton, which has known limitations in capturing realistic lane-change dynamics, future studies could adopt enhanced automata or full microsimulation models with explicit lane-change algorithms to address this shortcoming. Field trials would further validate and extend these findings. Overall, integrating advanced traffic models with empirical behavioral data promises safer and more efficient work-zone management.

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