

Original Paper

Traffic Control Strategies for Virtual Emergency Lanes on Expressways

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Abstract

Expressway congestion and traffic accidents often hinder the passage of emergency vehicle, while traditional fixed emergency lanes suffer from issues such as low resource utilization and poor adaptability. To address mixed traffic flows comprising connected and automated vehicle, human-driven vehicle, and truck, this paper proposes a dynamic virtual emergency lane control strategy. This strategy creates continuous passage space for emergency vehicle through segmented dynamic allocation of right-of-way and stepwise lane-changing guidance. Based on cellular automata theory, a simulation model for mixed traffic flows is established by integrating the NS model, the IDM following model, and an improved STCA lane-changing rule. Using a 2,000-meter, four-lane expressway as the simulation scenario, the results indicate that, compared to a fixed emergency lane, this strategy can increase peak traffic volume by 30.2% and reduce the congestion rate by 10%–27% under moderate traffic density. It performs best in scenarios with four lanes and a low to moderate proportion of truck. This strategy effectively improves the efficiency of emergency vehicle and the utilization of road resources, making it suitable for emergency management scenarios on smart expressways.

Keywords

intelligent transportation systems, virtual emergency lane, cellular automata, mixed traffic flow

1. Introduction

As vital corridors for medium- and long-distance travel, expressways are characterized by high speeds and continuous traffic flow. However, with the growth of traffic demand, congestion and accidents have become frequent occurrences. The congestion caused by accidents severely hinder the passage of emergency vehicle and may trigger secondary accidents (Kamble & Kounte, 2022).

Regarding the issue of ensuring emergency access, existing research has largely focused on dynamic hard shoulder release and active traffic management strategies. Bhourri et al. (2016) demonstrated through empirical comparisons that dynamic hard shoulder operation can significantly improve travel time reliability; Arora et al. (2023) implemented coordinated control of variable speed limits and hard shoulder openings, effectively improving key indicators such as average speed, traffic volume, and travel time. Due to physical space constraints and the costs associated with long-term occupation, fixed emergency lanes are difficult to deploy on a large scale, and virtual emergency lanes have gradually become a research hotspot. This method relies on V2X and detection data to dynamically open emergency lanes and guide general traffic to yield. Wang (2025) validated the proposed virtual emergency lane strategy for expressways using the VISSIM simulation platform. The results showed that this method can significantly reduce average travel time, queue length, and the number of stops in accident scenarios, and demonstrates good adaptability under different lane closure and traffic saturation conditions.

In terms of modeling methods, cellular automata (CA) are widely used in mixed traffic flow and emergency access research due to their computational efficiency, simple rules, and suitability for micro-level simulation. CA models achieve macroscopic traffic flow emergence through micro-level vehicle evolution rules, effectively revealing the nonlinear evolution mechanisms of traffic systems. Research on traffic flow CA models began with the NaSch model (Nagel & Schreckenberg, 1992), which established the foundation for expressway traffic simulation through rules governing acceleration, deceleration, stochastic slowing, and position updates. Subsequent models such as STCA (Chowdhury et al., 1997) and (Barlovic et al., 1998) gradually optimized mechanisms for following, lane changing, and stochastic slowing to better align with real-world driving behavior. Related studies further incorporated driver heterogeneity, multi-lane interactions, and mixed traffic characteristics, significantly enhancing the models' applicability (Liu & Xiong, 2016). Existing work has integrated rules such as emergency evasion and cooperative lane changing with CA models, providing feasible simulation support for the dynamic management of emergency lanes (Zhao et al., 2020).

In summary, current research still has two shortcomings: first, it is largely based on single-traffic-environment scenarios, with insufficient characterization of mixed traffic flows where CAV, HV, and truck coexist; second, it predominantly employs static or quasi-static control, making it difficult to achieve dynamic right-of-way regulation based on real-time traffic conditions. To address these issues, this paper proposes a virtual emergency lane strategy based on segmented dynamic right-of-way allocation. By implementing stepwise dynamic adjustments to passage permissions in preceding road segments, this strategy constructs continuous and efficient priority routes for emergency vehicle.

2. Virtual Emergency Lane Strategy

2.1 Strategy Concepts and Trigger Conditions

Expressways typically designate fixed emergency lanes on the outermost lane or hard shoulder, which are normally off-limits to general traffic. In contrast, virtual emergency lanes do not rely on pre-designated dedicated lanes; instead, following an emergency incident, they adjust right-of-way for the section ahead based on the relationship between emergency vehicle and the accident location, thereby creating a continuous path in space. This mechanism transforms static emergency lanes into “dynamic, step-like dedicated lanes.” As shown in Figure 1, the system dynamically divides road sections and allocates traffic rights based on the location of the incident. By implementing segmented signal control, it enables flexible switching of lane functions, thereby establishing a continuous passage route for emergency vehicle.

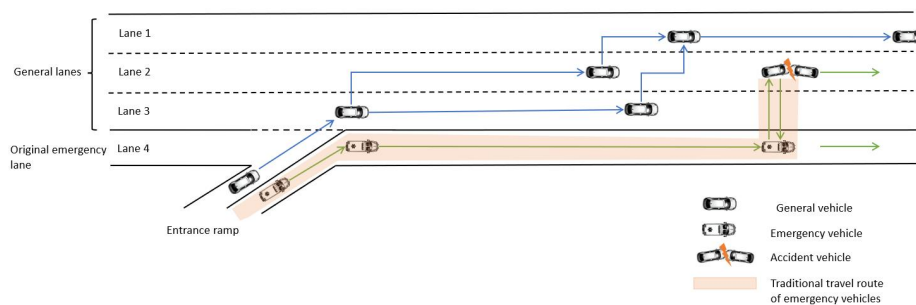


Figure 1. Comparison of Fixed Emergency Lanes and Virtual Emergency Lanes

The conditions for triggering the strategy are as follows: (1) An accident occurs on an expressway section, and the location of the accident has been identified; (2) An emergency vehicle (EV) enters the study section and sends a priority passage request to the vehicle-to-everything (V2X) system and roadside units. The strategy is activated when both conditions are met simultaneously.

2.2 Dynamic Control of Segmented right-of-way

Once the virtual emergency lane strategy is triggered, the road is divided into several contiguous segment units along the direction of travel, and the traffic status of each unit is dynamically updated. The specific control mechanism is as follows:

(1) Segment division: Using the accident site as the reference point, the upstream road section is divided into segments of a fixed length L . Considering drivers' line of sight and information perception capabilities, L is set to 500 m to balance the continuity of information transmission with the feasibility of behavioral responses.

(2) Information dissemination mechanism: Signal lights and variable message signs are installed at the entrance of each segment. Graphical symbols are used to indicate traffic status: a circle indicates normal traffic flow, while a cross indicates that the segment has been opened as a virtual emergency lane, allowing only emergency vehicle to pass, supplemented by text prompts.

(3) Dynamic road access control: Segment statuses are adjusted in real time based on the accident location and the position of emergency vehicle (EV). When an EV is more than 1,500 m from the

accident site, only the segment it is currently in is opened; when it is 1,000–1,500 m from the accident site, the two segments ahead are opened; when it is 500–1,000 m from the accident site, the segment immediately ahead is opened; and when it is less than 500 m from the accident site, it enters the segment designated for straight-through traffic.

2.3 Vehicle Traffic Behavior Rules

During the activation of the virtual emergency lane, different types of vehicles follow distinct behavior rules.

General traffic (HV, CAV, and truck) is prohibited from entering the activated virtual emergency lane and must change lanes or adjust speed based on roadside information; on uncontrolled sections, they continue to follow standard following and lane-changing rules. Specifically, CAV receive control commands via onboard units, while HV and truck rely on roadside infrastructure to execute responses.

The movement of emergency vehicle proceeds in distinct phases. As shown in Figure 2, the first phase is the stepwise lane-changing phase. After entering the expressway from the ramp, emergency vehicle follow the guidance on information boards to gradually shift from the outer lanes to the accident lane in sequential segments. This is followed by the straight-through passage phase, during which the emergency vehicle travels along the final open section adjacent to the accident site to reach the scene directly. Finally, the accident handling and evacuation phase begins; upon arrival, the emergency vehicle cordons off the accident area and departs via existing lanes once the incident has been resolved. This paper focuses on the first two phases, aiming to enhance the passage efficiency of emergency vehicle through dynamic right-of-way allocation while minimizing disruption to the overall traffic flow.

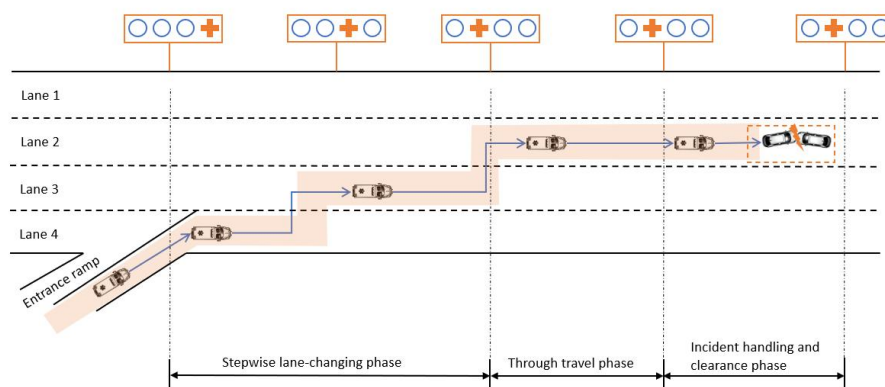


Figure 2. Virtual Emergency Lane Vehicle Travel Phase Diagram

3. Cellular Automata Model

3.1 Model Parameters

This paper models traffic behavior under the virtual emergency lane strategy based on cellular automata theory. Building upon the classic traffic flow cellular automata model, the NS model (Nagel & Schreckenberg, 1992), we introduce a dynamic right-of-way response mechanism for emergency

scenarios to construct a hybrid traffic flow simulation model suitable for virtual emergency lanes.

The following basic assumptions are established: Only four vehicle types—EV, CAV, HV, and truck—are permitted on the simulated road section; EV possess V2X communication capabilities and can interact in real time with CAV and roadside systems; the dynamic acceleration and deceleration processes during lane changes are neglected.

For the emergency scenario, an accident location is set on the target road section, after which emergency vehicle enter the system via the road entrance, thereby triggering the virtual emergency lane strategy to simulate the emergency response process under sudden incident conditions. The remaining variables and simulation parameters in the model are detailed in Table 1.

Table 1. Model Variables

Variable	Meaning
$S_i(t)$	Vehicle state of cell i at time t
$L_i(t)$	The indicator status of cell i at time t
$x_i(t)$	The position of vehicle i at time t
$v_i(t)$	The velocity of vehicle i at time t
v_{max}	Maximum speed limit
$d_i(t)$	Distance between Vehicle i and the vehicle ahead in this lane

In particular, the cell state $S_i(t)$ and the indicator light state $L_i(t)$ are defined by the following binary functions:

$$S_i(t) = \begin{cases} 1, & \text{no car} \\ 0, & \text{have a car} \end{cases}$$

$$L_i(t) = \begin{cases} 1, & \text{light on (no entry)} \\ 0, & \text{light off (entry permitted)} \end{cases}$$

3.2 Priority Control for Emergency Vehicle

Immediately after an accident occurs, the indicator lights along the affected section of the road illuminate to prevent other vehicles from entering the accident area; at the same time, the system updates the indicator lights section by section to open a virtual emergency lane and provides real-time guidance via variable message signs.

(1) Accident vehicle stationary:

$$\begin{cases} v_i(t+1) = 0 \\ x_i(t+1) = x_i(t) \end{cases} \quad (1)$$

(2) Signal triggered in the accident area:

$$\text{if } v_{acc}(t) = 0, \text{ then } L_{f(x_{acc})}(t+1) = 1 \quad (2)$$

A road segment signal indicator is defined to indicate the location of the virtual emergency lane segment. Its index function is: $f(x) = \left\lfloor \frac{x}{500} \right\rfloor + 1$, where 500 is the length of the road segment (in meters); x_{acc} is the specific location of the accident; x_{emer} is the real-time position of the emergency vehicle; $L_{f(x_{acc})}$ is the signal light status corresponding to that position, which is set to the “on” state in the next time step.

(3) Dynamic guidance for the virtual emergency lane:

$$L_i(t+1) = \begin{cases} 1, & f(x_{emer}) \leq i \leq f(x_{acc}) \\ 0, & i < f(x_{emer}) \\ 0, & i > f(x_{acc}) \end{cases} \quad (3)$$

3.3 Model for Vehicles Traveling at the Same Speed

(1) Acceleration rules:

① HV and truck: Follow the NS model rules; if the current speed has not reached the maximum speed and there is sufficient headway to the vehicle ahead, accelerate.

$$v_i(t+1) = \min[v_i(t) + 1, v_{\max}], d_i > v_i(t) + 1, v_i(t) < v_{\max} \quad (4)$$

② CAV: Since connected and automated vehicles are better able to perceive factors such as vehicle spacing, speed differences, and relative velocity, the classic Intelligent Driver Model (IDM) (Treiber and Kesting, 2013)[10], with dynamic acceleration parameters set to simulate vehicle acceleration behavior:

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

In Equation (5), is the dynamic acceleration calculated based on the IDM model:

$$a = a \left[1 - \left(\frac{v}{v_{\text{des}}} \right)^\delta - \left(\frac{d^*(v, \Delta v)}{d} \right)^2 \right] \quad (6)$$

(2) Deceleration rules:

① HV and truck:

$$v_i(t+1) = \max[v_i(t) - b_i, \frac{d_i(t)}{T}] \quad (7)$$

② CAV:

$$v_i(t+1) = \max[v_i(t) - b_i, \frac{d_i(t) - s_0}{T}] \quad (8)$$

In Equation (8), is the minimum safe distance at rest, used to calculate the minimum safe following distance from the vehicle ahead; is the vehicle’s comfortable deceleration rate; and is the safe time-to-headway. Once the deceleration brings the headway to the desired value, the vehicle will maintain a constant following distance.

(3) Stochastic smoothing:

$$v_i(t+1) = \max[v_i(t) - b_i - w, 0] \tag{9}$$

$$w = \begin{cases} b_i, & \text{if } \text{rand}() < p_{\text{slow}} \\ 0, & \text{else} \end{cases} \tag{10}$$

In Equations (9) and (10), b_i represents additional stochastic deceleration; w represents stochastic

slowing; p_{slow} is a stochastic probability adjusted based on Richards' plant growth curve

$p_{\text{slow}} = 0.1 + 0.5(1 + M \cdot e^{-0.05\rho})^{-\frac{1}{0.95}}$; M denotes the maximum number of vehicles that can be accommodated per kilometer of roadway; ρ denotes the traffic density on the road.

(4) Location update:

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{11}$$

3.4 Lane-changing Model for General Vehicles

The prerequisites for lane-changing behavior include the motivation to change lanes and an assessment of lane-changing safety. This lane-changing model is based on the STCA model proposed by Chowdhury et al. (1997), with modifications.

(1) Lane-changing model with emergency vehicle

In scenarios involving emergency vehicle, the lane-changing behavior of general vehicles must comprehensively consider guidance information from the vehicle-road coordination system and execute lane-changing maneuvers based on real-time prompts to ensure the unobstructed flow of the emergency lane.

① Motivation for lane-changing:

$$\begin{cases} d_i(t) < \Delta t \min[v_i(t) + a_i, v_{\text{max}}] \\ d_{i,\text{sidefront}}(t) > d_i \\ L_{f(x_i)}(t) = 0 \end{cases} \tag{12}$$

In Equation (12), $d_{i,\text{sidefront}}$ denotes the distance between the vehicle and the vehicle ahead in the

adjacent lane; $d_{i,\text{sideback}}$ denotes the distance between the vehicle and the vehicle behind in the adjacent lane.

② Conditions for safe lane changing:

CAV:

$$\begin{cases} L_{f(x_i)}(t) = 0 \\ d_{i,sidefront}(t) > d_i \\ d_{i,sideback}(t) > v_i(t) \cdot T \end{cases} \quad (13)$$

HV and truck:

$$\begin{cases} x_i(t) - 500 \times \left\lfloor \frac{x_i(t)}{500} \right\rfloor < 50 \\ L_{f(x_i)}(t) = 0 \\ d_{i,sidefront}(t) > d_i \\ d_{i,sideback}(t) > v_i(t) \cdot T \end{cases} \quad (14)$$

In Equation (14), the 50-meter perception range is determined with reference to standard traffic sign placement requirements, typical driver reaction times (1.5–2 s), and common urban travel speeds (40–60 km/h), as well as the corresponding braking distances derived from these parameters. The

condition $500 \times \left\lfloor \frac{x_i(t)}{500} \right\rfloor < 50$ is defined to satisfy the visual perception requirement for traffic signals.

(2) Lane-changing model in the absence of emergency vehicle

In the absence of emergency vehicle, a vehicle's lane-changing behavior is primarily determined by its individual traffic conditions, which dictate whether there is a motivation to change lanes and whether the conditions for safe lane changing are met.

① Motivation to change lanes:

$$\begin{cases} d_i(t) < \Delta t \min[v_i(t) + a_i, v_{\max}] \\ d_{i,sidefront}(t) > d_i(t) \end{cases} \quad (15)$$

② Safety requirements for lane changes

HV and truck:

$$d_{i,sideback}(t) - v_{\max} + \min[v_i(t) + a_i, v_{\max}] > 1 \quad (16)$$

CAV:

$$d_{i,sideback}(t) - \min[v_{i+1}(t), v_{\max}] + \min[v_i(t) + a_i, v_{\max}] > 1 \quad (17)$$

4. Simulation Analysis of Strategy Effectiveness

4.1 Simulation Setup

The simulation scenario is set on a 2,000-meter-long, one-way, four-lane expressway section. It is based on a cellular automata model with a cell size of 1 m and a time step of 1 s. Open boundary

conditions are adopted, with an increasing sequence $\alpha \in [0,1]$ for the probability of vehicle entry and a decreasing sequence $\beta \in [0,1]$ for the probability of exit closure, to simulate the dynamic process of gradually increasing traffic flow and the formation of congestion.

Table 2. Parameter Value Table

Parameter	Meaning	Unit	Values
L_{veh}	Different vehicle lengths	cells	6,5,5,10
V_0	Different initial vehicle speeds	cells/s	33,27,25,25
V_{max}	Different maximum vehicle speeds	cells/s	33,27,25,25
a_{max}	Different maximum vehicle accelerations	cells/s ²	33,30,30,30
b	Vehicle comfort deceleration	cells/s ²	1

Note. The parameter value sequences correspond to different vehicle types: from left to right, they are EV, CAV, HV, and truck.

To verify the effectiveness of the virtual emergency lane strategy in expressway emergency traffic scenarios, comparative simulation experiments were conducted. By combining the spatio-temporal trajectory characteristics of the lanes with the overall traffic flow-density relationship of the system, a comprehensive analysis of traffic conditions under different operating modes was performed. The parameters were set as follows: 0.2 for the proportion of truck, 0.3 for the CAV penetration rate, and 0.5 for the vehicle lane-changing probability. The two schemes included in the comparison are shown in Table 3.

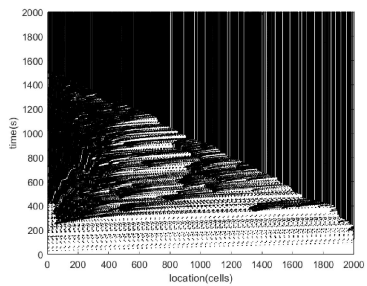
Table 3. Design of a Comparative Experimental Protocol

strategy sequence	Core Settings	Access Rules
Fixed Emergency Lane	The outermost lane is an emergency lane reserved exclusively for EV.	Reserved for EV; non-EV are prohibited from entering; lanes are not open to general traffic except in emergency situations
Virtual emergency lane	The outermost lane is dynamically opened and closed.	Through segmented traffic control and real-time guidance, priority lanes are dynamically established for EV, while non-EV must follow posted directions

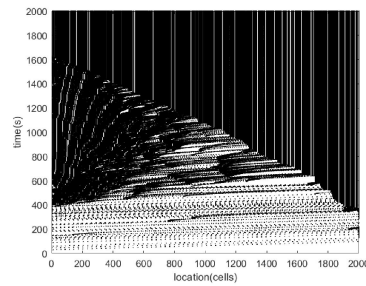
4.2 Spatiotemporal Trajectory Evolution Analysis

Figure 3 shows the spatiotemporal trajectories of four lanes (Lanes 1–4) under the two modes. The left

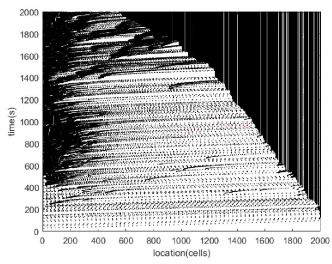
side shows the fixed emergency lane mode, while the right side shows the virtual emergency lane mode. Different colors in the figure represent different types of vehicles. A comparison shows that under the virtual emergency lane mode, congestion develops more slowly in each lane. The onset of congestion in the spatio-temporal diagram is significantly delayed, and its location is shifted further back. For example, under the fixed emergency lane mode, Lane 1 already exhibits significant congestion around time step 400, whereas under the virtual emergency lane mode, this phenomenon only gradually emerges after time step 600. At the end of the simulation, the congestion length of Lane 2 was located at approximately the 200 mark on the vertical axis in the traditional mode, whereas in the virtual emergency lane mode, it shifted backward to near the 400 mark, indicating that the queue length was effectively reduced. The above results demonstrate that the virtual emergency lane strategy can delay the formation of congestion and slow its upstream propagation, thereby significantly improving the overall operational efficiency of the road section.



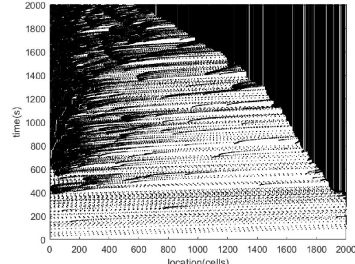
(a) Fixed emergency lane mode, Lane 1



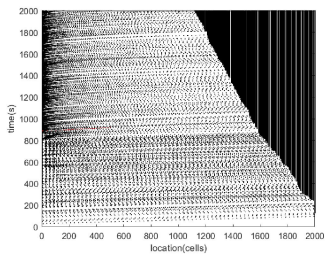
(b) Virtual emergency lane mode, Lane 1



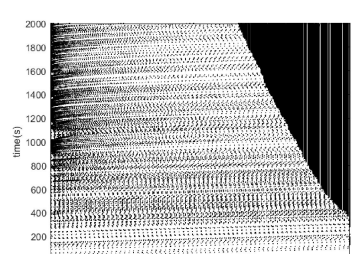
(c) Fixed emergency lane mode, Lane 2



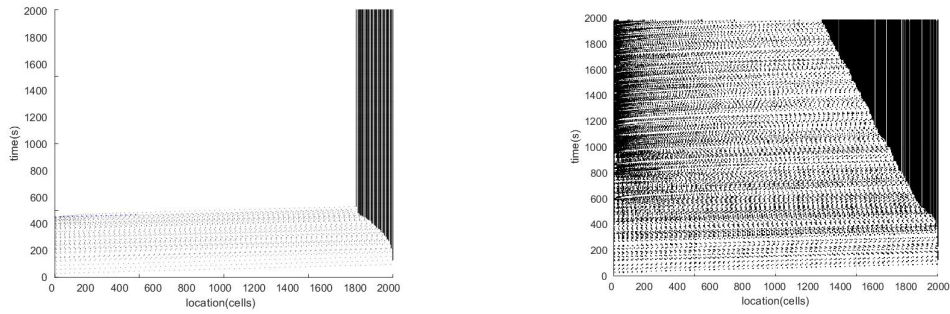
(d) Virtual emergency lane mode, Lane 2



(e) Fixed emergency lane mode, Lane 3



(f) Virtual emergency lane mode, Lane 3



(g) Fixed emergency lane mode, Lane 4

(h) Virtual emergency lane mode, Lane 4

Figure 3. Comparison of Spatio-temporal Trajectories

4.3 Analysis of Flow-density Results

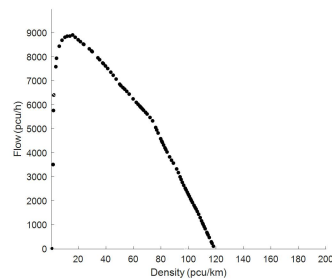
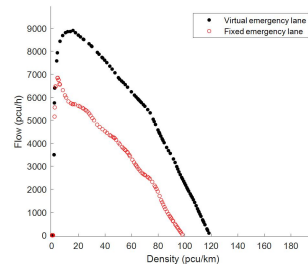
This paper considers both passenger cars and truck in a expressway setting. Different vehicle types vary in size and driving characteristics, and thus occupy road space to varying degrees. If vehicle counts are used directly for statistical analysis, the results may not accurately reflect actual traffic volume. Therefore, the concept of Passenger Car Units (pcu) (Patel & Dhamaniya, 2021) is introduced when calculating traffic volume and density. Using the traffic impact of a standard passenger car as a benchmark, vehicles of different types are converted to pcu to more accurately reflect the actual impact of various vehicle types on road capacity and traffic congestion in mixed traffic flows. Table 4 lists the pcu conversion factors for each vehicle type.

Figure 4 illustrates the volume-density relationship resulting from the virtual emergency lane control strategy under a CAV penetration rate of 30%. In the low-density phase (0–20 pcu/km), traffic is in a free-flow state, with volume gradually increasing as density rises and vehicles moving relatively smoothly; when density exceeds 20 pcu/km, volume begins to decline, entering a synchronized flow phase characterized by low relative speeds between vehicles. Once density reaches 75 pcu/km, traffic volume drops significantly, and traffic gradually enters a congested state. This trend aligns with traffic flow theory, validating the validity of the constructed model.

Figure 5 compares the traffic-density relationships of the fixed emergency lane control strategy and the virtual emergency lane strategy under identical conditions. Under low-density conditions, the difference in traffic volume between the two strategies is minimal, and both systems maintain high capacity. As density further increases, the advantages of the virtual emergency lane strategy gradually become apparent. Its peak traffic volume reaches 8,902.8 pcu/h, a 30.2% increase over the peak of 6,837.6 pcu/h achieved by the existing strategy. These results demonstrate that the virtual emergency lane strategy can enhance road capacity under medium-to-high density conditions. By dynamically adjusting lane usage, this strategy enables vehicles to utilize road resources more efficiently.

Table 4. pcu Conversion Factor

Vehicle Type	pcu
HV and CAV	1.0
truck	2.0
EV	1.5

**Figure 4. Virtual Emergency Lane Density-flow Plot****Figure 5. Density-flow Comparison Plot**

5. Conclusion

This paper addresses the issues of reduced emergency passage efficiency and low lane utilization on expressways by proposing a dynamic virtual emergency lane control strategy and constructing a simulation model for validation. Theoretically, it offers new approaches for modeling and simulating smart expressway emergency management, including segmented dynamic right-of-way allocation and stepwise lane-changing guidance, while also improving the cellular automata lane-changing rules under mixed traffic conditions. Simulation results indicate that, compared to fixed emergency lane models, this strategy, without altering the physical road structure, effectively enhances lane utilization efficiency while ensuring rapid passage for emergency vehicle. It increases peak traffic volume by 30.2% and maintains higher system capacity under medium-to-high traffic density conditions, demonstrating excellent congestion resistance. Compared to existing research, this strategy addresses the issues of poor flexibility and low resource utilization associated with traditional fixed emergency lanes, while fully accounting for the characteristics of mixed traffic flows in intelligent transportation

environments. However, it still lacks validation regarding adaptability to multi-lane conditions and more complex traffic scenarios. In the future, factors such as ramp merging and driver heterogeneity could be further integrated to optimize the model and control strategy, thereby enhancing the method's feasibility for engineering applications.

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