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Research Article

Evaluating Discretionary Lane-Changing under Cogested Conditions: An Agent-Based Cellular Automata Model in NetLogo

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Abstract: Lane-changing behavior plays a critical role in shaping traffic dynamics, particularly under congested conditions. This study presents a two-lane traffic simulation model developed in NetLogo, integrating cellular automata and agent-based modeling to investigate the impact of discretionary lane-changing under varying traffic scenarios. The model incorporates key parameters such as acceleration, deceleration, and driver patience to simulate and evaluate vehicle behavior across two configurations: (1) high traffic density with a low proportion of lane-changing vehicles and (2) high traffic density with a high proportion of lane-changing vehicles. Results indicate that in the first scenario, lane-changing vehicles gain notable advantages in speed and travel distance, supported by higher and more stable patience levels. In contrast, the second scenario shows minimal benefits for lane-changing vehicles, with increased driver stress and reduced performance. These findings suggest that selective and context-aware lane-changing improves mobility in constrained environments, while excessive lane-changing under saturated conditions may compromise traffic efficiency. The model offers a useful framework for evaluating behavioral factors in lane-changing and supports future development of intelligent traffic management systems.

Keywords: Lane-changing behavior; Agent-based modeling; Cellular automata; NetLogo simulation; Driver patience; Two-lane traffic flow

Highlights:

- NetLogo model combines cellular automata and agent-based lane-changing.
- Demonstrated that selective lane-changing under high-density traffic enhances vehicle speed, travel distance, and driver comfort.
- Showed that excessive lane-changing diminishes individual and system-wide efficiency, increasing stress and instability in congested flow.
- Provided insights for intelligent traffic management and driver education by emphasizing context-aware, strategic lane-changing.

1. Introduction

According to statistics reported by the Vietnam Ministry of Public Security, more than 21,690 traffic accidents occurred nationwide in 2024, resulting in approximately 10,030 fatalities. A large proportion of these incidents involved motor vehicles, particularly cars, and lane-changing maneuvers continue to be one of the major causes of traffic conflicts and collisions (Van, 2024). Despite these developments, traffic accident rates remain alarmingly high. Lane-changing maneuvers, in particular, significantly increase the likelihood of traffic conflicts and subsequent collisions(Ahmed, Karr, Rouphail, Chase, & Tanvir, 2023; Chauhan, Kanagaraj, & Asaithambi, 2022).

Traffic accidents and congestion caused by lane changing have garnered increasing concern both domestically and internationally. A local study found that about 30 % of crashes on Vietnamese roads are attributable to lane-changing maneuvers. In the U.S., lane-change-related accidents account for approximately 9 % of all traffic incidents (Bar-Gera & Shinar, 2005), while in Germany, they are the fourth most common cause of road accidents. On highways specifically, more than 10 % of crashes are associated with incorrect or unsafe lane changes (Fitch et al., 2009). These figures underscore the importance of understanding drivers' psychological traits - such as patience, risk tolerance, and decision-making - in relation to lane-changing.

Lane-changing behaviour has long been a significant focus in traffic flow research due to its close association with traffic safety, efficiency, and congestion dynamics. Early studies relied heavily on cellular automata (CA) models to simulate microscopic driving behaviours, including lane changes in multi-lane systems. For instance, Maerivoet and De Moor provided a comprehensive overview of CA-based models for road traffic, highlighting their ability to simulate complex interactions using simple rule-based logic (Maerivoet & De Moor, 2005). Building upon these foundations, Nagel et al. proposed a systematic set of lane-changing rules for two-lane systems, demonstrating that the logical structure of such rules has a more significant impact on simulation outcomes than their specific numerical parameters (Nagel, Wolf, Wagner, & Simon, 1998). More recently, agent-based modelling (ABM) has been introduced to better capture the heterogeneity and decision-making processes of individual drivers. Using the NetLogo simulation platform, Zhang et al. developed an agent-based model integrating evolutionary game theory to simulate drivers' lane-changing decisions under different traffic densities (Yin, 2018). Similarly, Sangole et al. employed a hybrid ABM-CA framework to explore driver interactions at uncontrolled intersections, which offers relevant methodological insights for modeling two-lane traffic systems with discretionary lane changes (Sangole, Patil, & Tripathy). These approaches show the methodological potential of combining CA and ABM to capture both rule-based and adaptive driving dynamics.

Empirical studies using real-world data have further validated and refined these simulation models. Utilizing the NGSIM dataset, Chauhan et al. examined temporal and spatial characteristics of lane-change maneuvers, proposing classification frameworks based on merging duration and vehicle spacing (Chauhan et al., 2022). Meanwhile, Ahmed et al. identified extreme lane-change behaviors and linked them with increased crash likelihood, particularly under congested freeway conditions (Ahmed et al., 2023). To integrate traffic flow theory with lane-changing behavior, Jin introduced a kinematic wave theory model that incorporates lane-changing intensity as a new variable, allowing for the analysis of collective impacts such as bottleneck formation in merging zones (Jin, 2010). Furthermore, recent research has extended these models to account for emerging vehicle technologies. Wang et al. modeled lane-changing interactions among connected vehicles using interaction potential functions, showing that vehicle-to-vehicle communication can reduce unnecessary lane changes and enhance flow stability (Li, Qu, Chen, Yang, & Cui, 2024). These findings suggest that integrating connected driving systems into agent-based lane-changing simulations may offer a pathway to more realistic and predictive traffic models.

Despite this progress, existing models often overlook psychological parameters such as driver patience and urgency, which play a decisive role in discretionary lane-changing, especially in mixed traffic conditions common in developing countries. This omission limits the realism of existing models and reduces their applicability in contexts like Vietnam. Addressing this gap requires a modelling environment that not only supports CA and ABM but also enables flexible integration of behavioural parameters.

NetLogo offers distinct advantages for this purpose. As a multi-agent simulation platform, it provides an intuitive environment for combining CA rules with agent-level decision-making, while also allowing explicit modelling of behavioural factors such as patience. Its flexibility and visualisation capabilities make it particularly suitable for exploratory studies of lane-changing in congested traffic, where both rule-driven and adaptive processes interact.

This study therefore develops a two-lane traffic simulation model in NetLogo to investigate discretionary lane-changing under varying traffic conditions. By incorporating acceleration, deceleration, and driver patience into the model, we aim to evaluate how the proportion of lane-changing vehicles affects individual and overall performance in congested environments. Two contrasting scenarios are examined: (1) high traffic density with few lane-changing vehicles and (2) high traffic density with many lane-changing vehicles. In doing so, this study contributes to filling the gap in modelling psychological and behavioural dimensions of lane-changing, while also demonstrating the applicability of NetLogo as a flexible simulation tool for traffic behaviour analysis in developing country contexts. Furthermore, the model is just applied to car-dominated road segments such as expressways, where motorbikes are restricted. This assumption allows us to focus on the lane-changing behaviour of cars under congested conditions, while acknowledging that Vietnam's urban traffic involves more complex mixed flows.

2. Methodology

2.1 Model Development Based on the NetLogo Platform

2.1.1 Overview of NetLogo Simulation Environment

NetLogo is a multi-agent programmable modelling environment developed at Northwestern University (Wilensky, 1999), widely used for simulating complex adaptive systems in both natural and social sciences. Compared with commercial traffic simulation software such as VISSIM, AIMSUN, or SUMO, NetLogo offers several advantages that motivated its selection in this study: (1) Accessibility and flexibility: NetLogo is open-source and free, reducing barriers for researchers in developing countries, while commercial software often requires expensive licenses. (2) Behavioural modelling capability: Unlike traditional microscopic traffic simulators that emphasise vehicle kinematics, NetLogo's agent-based framework allows the integration of psychological variables such as driver patience and urgency. (3) Rapid prototyping and visualisation: NetLogo provides a user-friendly interface with sliders and monitors for real-time parameter adjustments, making it easier to explore multiple traffic scenarios interactively. (4) Compatibility with cellular automata: NetLogo naturally supports CA grid-based representations of roadways, enabling integration of both deterministic rules (acceleration, deceleration, gap acceptance) and adaptive behaviours (lane changes driven by patience).

In NetLogo, agents are generally categorized into two types: turtles and patches. Patches represent road infrastructure, while turtles represent vehicles moving across the grid. The simulation progresses in discrete time steps, called "ticks". At each tick, vehicles update their states (speed, lane position, patience level) based on local interactions with surrounding vehicles and predefined rules.

The workflow of the two-lane traffic simulation model is summarised in Figure 1, which links the inputs, the NetLogo process, and the outputs. Inputs comprise traffic density, the composition of lane-changing and non-lane-changing vehicles, acceleration and deceleration parameters, and the maximum driver patience level. During the process, vehicle agents interact on a cellular-automata grid in discrete time steps; patience decreases whenever braking occurs, and once patience reaches zero a lane-change manoeuvre is triggered, while acceleration and deceleration rules update speeds dynamically according to local gaps. The model generates outputs in real time, including plots of system-wide and observed-vehicle speeds, driver-patience profiles, and vehicle trajectories; total travel distances are computed and exported for subsequent analysis in MATLAB. Figure 1 therefore illustrates how user-defined parameters are entered, processed within the NetLogo engine, and translated into quantitative performance measures.

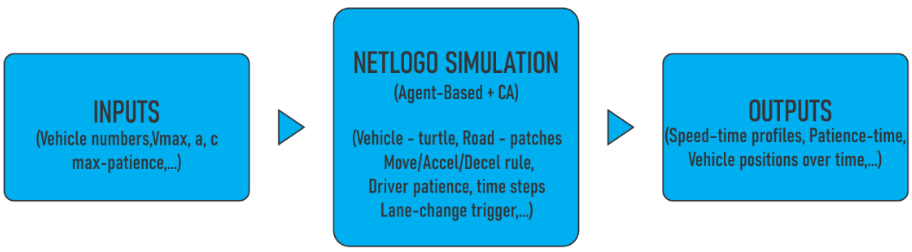

Figure 1. Input–process–output workflow of the NetLogo-based two-lane traffic simulation model

2.1.2 Simulation of Lane-Changing Behavior in a Two-Lane Traffic System

The lane-changing behavior simulation is implemented in NetLogo, where vehicles are divided into two types: (1) yellow-colored vehicles, which are permitted to change lanes, and (2) other-colored vehicles, which are restricted to a single lane. Varying traffic scenarios are modeled by adjusting the relative proportions of these two vehicle types. For the purpose of targeted observation, one lane-changing vehicle is randomly selected and labeled as the "observed vehicle", whose behavior is monitored to evaluate system performance under different traffic conditions. The basic structure of the two-lane cellular-automata roadway was developed based on the Traffic 2-Lanes model in the NetLogo Models Library (Wilensky, 1997).

In this NetLogo implementation, the roadway is represented as a two-lane grid of patches. Each patch corresponds to one unit cell, and the total number of patches along the horizontal axis defines the simulated road length. The total number of patches can be easily adjusted in the model settings. In this study, the length of each lane was set to 40 patches, corresponding to 40 distance units in the simulation environment. This abstraction allows the roadway to remain homogeneous and straight, without incorporating additional geometric details such as curvature, pavement type, or road class.

Traffic density is therefore derived indirectly from the input 'total number of vehicles' divided by the road length. Lane-specific volumes are not predefined; instead, vehicles are randomly allocated across the two lanes at initialization, reflecting heterogeneous and stochastic distributions observed in real traffic. The ratio of lane-changing to non-lane-changing vehicles is explicitly defined as an input parameter, but their precise lane allocation is random at the start of each run. This setup enables variability across simulations and allows traffic patterns to emerge dynamically.

Several sliders are introduced into the model interface to allow dynamic parameter tuning:

- Number of cars: controls overall traffic density.
- Number of lane-changing cars: adjusts the count of yellow-coloured vehicles capable of changing lanes.
- Acceleration and Deceleration sliders: define how quickly vehicles accelerate or slow down based on distance to Up front cars.
- Maximum patience value: reflects the driver's psychological tolerance level before initiating a lane change. In this study, the maximum patience was set at 50 units, which provided a balanced representation of driver tolerance - large enough to avoid excessive lane-changing but moderate enough to capture cyclic lane-changing behaviour under congested conditions.

The model includes three real-time plots:

- Car Speed Chart: displays the average speed of all vehicles as a dotted curve and the speed of the observed vehicle as a solid line.
- Driver Patience Chart: shows average patience across all drivers and the specific patience level of the observed vehicle.
- Cars per lane: indicates lane-specific traffic volume.

2.2 Model Implementation

Upon initialization, the model generates lane-changing and non-lane-changing vehicles based on the specified slider values. All vehicles travel from left to right. The "Monitor Observed Vehicle" and "Track Observed Vehicle" buttons on the control panel allow users to follow the behavior of the selected vehicle throughout the simulation.

Initially, all vehicles are assigned identical speeds, while patience levels are randomly initialized. Vehicles adjust their speeds dynamically based on the gap to the car in front. When the leading distance is sufficiently large, a vehicle will accelerate at the rate defined by the Acceleration slider. If the gap becomes too small, the vehicle decelerates in proportion to the speed of the car ahead, with the deceleration slider determining the braking strength. Each time a vehicle is forced to brake, its patience level decreases. When patience reaches zero, the vehicle initiates a lane-change maneuver, overtakes the slower vehicle, and then resumes acceleration. Upon successful completion of the lane change, the patience value is reset to the predefined maximum.

To evaluate model performance under different traffic conditions, two hypothetical scenarios are tested: Scenario 1: High traffic density with a low proportion of lane-changing vehicles. Scenario 2: High traffic density with a high proportion of lane-changing vehicles. In our implementation, each lane is set to 40 patches in length, and one patch is assumed to represent approximately 5 m (the average vehicle length), corresponding to a 200 m roadway segment per lane. With a total of 30 vehicles distributed across the two lanes (15 vehicles per lane), the average spacing is about 13 m per vehicle, which reflects a congested traffic state with frequent interactions rather than free-flowing conditions. This setting ensures active lane-changing behaviour can be observed while avoiding complete gridlock.

In this study, only two contrasting scenarios were considered, representing the extreme conditions of low versus high proportions of lane-changing vehicles. This design allows us to clearly demonstrate the behavioural and performance differences between selective and excessive lane-changing under congested traffic. Intermediate or additional scenarios can certainly be incorporated within the same framework, and we acknowledge this as a direction for future work.

3. Research results

3.1 Scenario 1: High traffic density with a low proportion of lane-changing vehicles

In Scenario 1, the total number of vehicles is set to 30, with only 6 vehicles (20%) designated as lane-changing agents. This setup represents a congested road environment where the majority of vehicles remain in their initial lanes. Based on realistic driving dynamics - where deceleration events typically outnumber acceleration ones - the acceleration and deceleration parameters were set to 0.008 and 0.02, respectively.

As shown in Figure 2, the lane-changing behavior of the selected (observed) vehicle exhibits a clear advantage in both speed and mobility. The Car Speeds chart indicates that the speed curve of the observed vehicle consistently remains above the average speed curve of all vehicles, suggesting that lane-changing can yield improved mobility even in high-density traffic. Notably, the observed vehicle is able to maintain higher speeds more frequently due to its ability to escape slow-moving clusters.

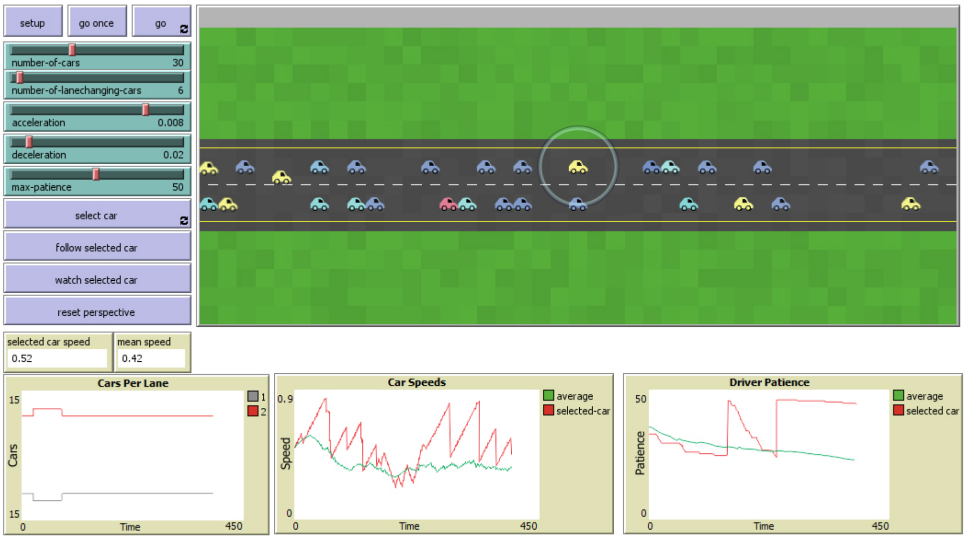

Figure 2. Lane-changing simulation under high traffic density with low lane-changing proportion: vehicle positions, speed, and patience analysis.

In the Driver Patience chart, the observed vehicle maintains higher patience values relative to the average throughout the simulation. This implies fewer braking events and a smoother driving experience. A notable observation is the cyclic pattern of the patience curve for the lane-changing vehicle: once its patience threshold reaches zero, it performs a lane change, and the patience value is restored to its maximum of 50 units. During the simulation, the observed vehicle maintained patience levels on average about 15–20% higher than the system-wide mean. This cyclical behavior, evident in the repeated return to 50 units, is absent in the average trend, further illustrating the efficiency of discretionary lane changes.

To quantitatively evaluate driving performance, the area under the speed-time curves was computed using the trapezoidal integration function (trapz) in MATLAB. The total travel distance of the observed vehicle was calculated to be 233.086 units, whereas the average distance covered by all vehicles was 163.216 units. This significant difference (approximately 43% increase) demonstrates the effectiveness of lane-changing strategies under constrained traffic conditions.

In summary, under high-density traffic with a limited number of lane-changing vehicles, those capable of maneuvering between lanes gain a substantial advantage in travel speed and distance. The results underscore the role of adaptive behavior and driver psychology (patience dynamics) in enhancing traffic flow efficiency for individual vehicles.

3.2 Scenario 2: High traffic density with a high proportion of lane-changing vehicles

In Scenario 2, the total number of vehicles remains at 30, but the number of lane-changing vehicles increases substantially to 24. This configuration represents a highly congested roadway where discretionary lane-changing behavior is widespread. As in Scenario 1, the acceleration and deceleration parameters are set at 0.008 and 0.02, respectively. These values were selected to reflect realistic congested driving dynamics, where deceleration is typically stronger and more frequent than acceleration. The parameters were calibrated through preliminary runs to ensure model stability and plausible vehicle interactions under constrained conditions. The simulation results are presented in Figure 3.

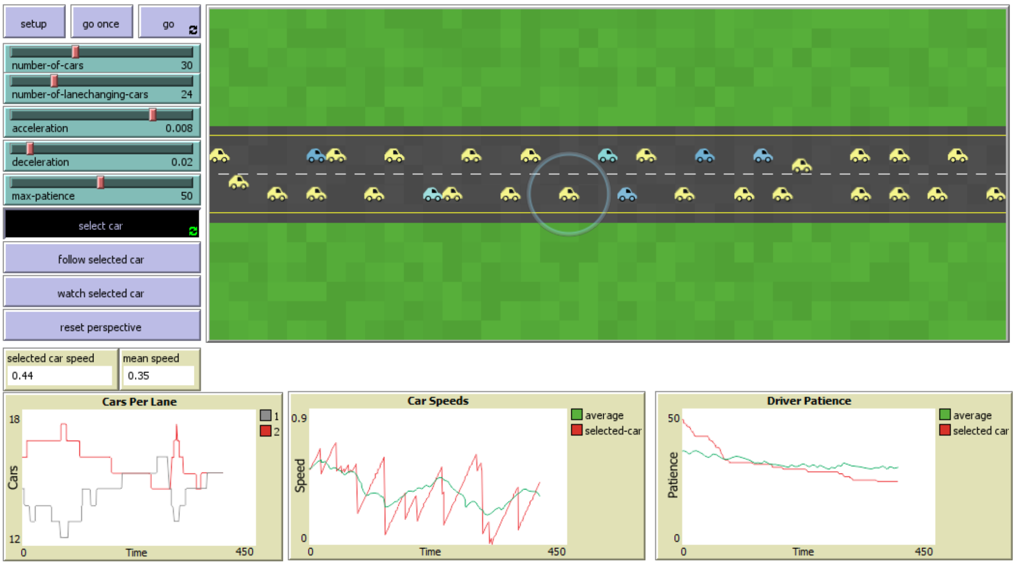

Figure 3. Traffic simulation under high congestion and frequent lane-changing: vehicle positions, speed, and patience analysis.

From the Car Speeds chart, the speed profile of the selected (observed) vehicle shows fluctuations that closely track the average speed curve, with no significant deviation or sustained advantage. The computed travel distances using trapezoidal integration (via trapz in MATLAB) illustrate this observation: the average travel distance of all vehicles is 132.609 units, while the observed vehicle covers 128.369 units. The very small difference, indicates that in environments where many drivers frequently change lanes, the individual advantage of discretionary lane-changing is diluted and may become counterproductive.

The Driver Patience chart provides additional insights. The patience value of the observed vehicle is generally lower than the average, indicating frequent braking and less smooth driving. Unlike scenario 1, no clear cyclic pattern appears because the observed vehicle changes lanes too frequently to restore patience to its maximum of 50 units. On average, the observed vehicle's patience level remained approximately 10 - 15% lower than the system-wide mean, reflecting reduced tolerance and higher stress levels. The absence of large restorative cycles in the patience curve (as seen in Scenario 1) suggests that either the driver changed lanes too frequently, or he did not restore driving comfort after lane-changing maneuvers. These trends reflect a scenario where excessive lane-changing may lead to increased mental load, reduced efficiency, and diminished control benefits.

When compared directly with Scenario 1, the contrast becomes evident. The travel distance of the observed vehicle decreased from 233.086 units in Scenario 1 to 128.369 units in Scenario 2, while the average distance of all vehicles dropped from 163.216 units to 132.609 units. Likewise, the observed vehicle's patience was on average 15–20% higher than the system-wide mean in Scenario 1, but about 10–15% lower in Scenario 2. These comparisons confirm that discretionary lane-changing provides measurable benefits under limited competition but loses its effectiveness, and may even become counterproductive, when most vehicles attempt to change lanes simultaneously.

Overall, in scenarios with high lane-changing density, discretionary lane changes do not yield a measurable advantage in travel distance or speed. In fact, driver behavior becomes more reactive and less stable, which could increase the risk of conflict and compromise overall traffic flow. These findings support the hypothesis that lane-changing is most beneficial when applied selectively in low-competition traffic contexts, rather than ubiquitously in dense, multi-agent scenarios.

4. Conclusions and recommendations

This study developed a two-lane traffic simulation model using cellular automata and agent-based modeling in NetLogo to assess the impact of lane-changing behavior under varying traffic conditions. By incorporating parameters such as acceleration, deceleration, and driver patience, the model captured both individual and overall traffic performance across scenarios with different proportions of lane-changing vehicles. In scenario 1, with high traffic density and few lane-changing vehicles, lane-changing proved advantageous - yielding higher speeds, longer travel distances, and more stable patience levels for the selected vehicle. This suggests that selective lane changes in congested conditions can improve mobility and driver comfort. In contrast, scenario 2, with many lane-changing vehicles, showed minimal difference between the selected vehicle and traffic average in both distance and patience, reflecting increased stress and reduced efficiency. These results highlight that excessive lane-changing in dense traffic may diminish its intended benefits and destabilize traffic flow.

Based on the simulation findings, several practical recommendations can be made to improve traffic flow efficiency and driver experience in congested environments. First, selective lane-changing behavior should be encouraged in high-density traffic through public awareness initiatives or in-vehicle guidance systems that promote strategic rather than frequent or impulsive maneuvers. Second, psychological parameters such as driver patience should be integrated into traffic flow models and management strategies, as they significantly influence decision-making and system-wide performance. Third, the development of lane-changing assistance systems capable of assessing real-time traffic context and dynamically recommending or restricting lane-change actions - especially in congested networks - could help reduce unnecessary disturbances and improve overall stability. In addition, raising public awareness of the risks associated with frequent or impulsive lane-changing is equally important. Campaigns on traffic safety, driver education programmes, and licensing curricula should incorporate guidance on strategic lane-changing. By combining behavioural awareness with technological support, traffic management can more effectively balance individual driving flexibility with network-wide safety and efficiency.

Several limitations should be acknowledged. First, only two scenarios were analysed to contrast extreme conditions; future extensions should incorporate a wider range of traffic densities, varying patience levels and intermediate lane-changing proportions for a more comprehensive evaluation. Second, the numerical results have not yet been verified against previously published studies or commercial traffic simulation software. Future work will therefore focus on validating the proposed model using empirical traffic data and benchmark simulations (e.g., VISSIM or AIMSUN) to enhance its reliability and applicability. Third, the graphical display in NetLogo does not strictly preserve real-world vehicle proportions, which may visually depict cars as being very close to each other. This is a limitation of the visualisation rather than an indication of unsafe driving behaviour. Finally, the present model only considers car-dominated conditions, such as expressways where motorcycles are restricted. Extending the framework to heterogeneous traffic, which is characteristic of Vietnam, would further improve its realism and relevance.

In summary, while discretionary lane-changing has the potential to enhance mobility, its benefits are context-dependent and diminish when overapplied. Traffic management strategies should therefore balance individual flexibility with network-wide safety and efficiency. These findings directly address the central aim of this study - to evaluate discretionary lane-changing under congested conditions using an agent-based cellular automata model in NetLogo with explicit integration of driver patience - and show that psychological factors play a decisive role: higher patience supports smoother and more beneficial lane-changing, whereas reduced patience under widespread lane changes results in stress, instability, and diminished performance. Taken together, the results highlight both the potential and the limitations of lane-changing as a strategy for improving mobility in developing-country contexts.

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