A Study on the Impact of Overtaking Lane-Changing Behaviour in Expressway Interchange Weaving Areas

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Original Scientific Paper
Submitted: 9 Nov 2023
Accepted: 20 Feb 2024

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Publisher:
Faculty of Transport and Traffic Sciences, University of Zagreb

ABSTRACT

This study investigates the overtaking lane-changing (OLC) behaviour in expressway interchange weaving areas, aiming to analyse these behaviours' causes and potential impacts. Field data are utilised to analyse the statistical characteristics of lane-changing points and spatio-temporal utilisation in weaving areas. A modified NS model, which considers the distribution pattern of vehicle speeds, and a rigid lane-changing rule based on Gaussian distribution are proposed. Additionally, a cellular automaton simulation model is constructed to quantify the influence of OLC behaviour on traffic efficiency and spatio-temporal utilisation based on simulated data. The findings indicate that the imbalanced distribution of lane-changing points and spatio-temporal utilisation in weaving segments, caused by rigid lane-changing behaviour, is an objective factor that triggers OLC behaviour. When the traffic volume in weaving areas ranges from 500 to 1,100 pcu/5 min and the proportion of OLC behaviour is between 0.35 and 0.7, the behaviour will significantly enhance the average vehicle speeds of the outermost lane of the main road and normal rigid lane-changing (NRLC) vehicles, with increases of up to 48% and 51%, respectively. Moreover, OLC behaviour also improves the balance of spatio-temporal utilisation in weaving areas and reduces the average spatio-temporal utilisation. This study clarifies the positive impact of OLC behaviour on expressway interchange weaving areas and provides new research ideas for enhancing the efficiency of these areas.

KEYWORDS

interchange weaving areas; overtaking lane-changing behaviour; lane-changing points; spatio-temporal utilisation; cellular automaton simulation model.

1. INTRODUCTION

Weaving areas are a significant component of urban expressway networks, but the concentrated lane-changing behaviour makes the areas a primary bottleneck which impedes the improvement of safety and efficiency throughout the urban expressway network [1]. The traffic conflicts in weaving areas are fundamentally due to the competition of vehicles for limited spatial and temporal resources. The more types of weaving behaviour, the higher the complexity of the weaving area. Consequently, interchange weaving areas where merging and diverging traffic simultaneously exist [2] encounter greater challenges in traffic management and control.

Previous research mainly focused on convergence or divergence areas of freeways and urban expressways when studying weaving areas, and achieved rich results. For instance, Huang [3] evaluated the effectiveness of traffic guidance facilities in urban underground road convergence and divergence areas, Ma [4] developed a traffic conflict prediction model for urban expressway divergence areas, and Pulugurtha [5] employed microscopic simulation to quantify the service level of weaving sections, convergence areas and divergence areas of freeways. However, compared to convergence or divergence areas, interchange weaving areas involve both converging and diverging traffic, leading to greater complexity in traffic behaviour and organisation. Consequently, interchange weaving areas are always a challenging aspect of weaving area research. Guo [6] proposed a separated ramp design to enhance the operational performance of interchange weaving areas, Liu [7] investigated the lane-changing model in freeway interchange weaving areas, Sun [2], Chen [8] and Ouyang [9], respectively, explored speed prediction models, traffic capacity and traffic accident prediction models in expressway interchange weaving areas. Some achievements in interchange weaving areas have been made, but there remains ample scope for in-depth exploration of lane-changing behaviour within interchange weaving sections.

Existing studies in weaving areas have primarily classified weaving behaviour into two types: free lane-changing behaviour and mandatory lane-changing behaviour. For instance, Bha [10] proposed a lane-changing model specifically for mandatory lane-changing behaviour in weaving areas, whereas Liu [7] developed a lane-changing model encompassing both free and mandatory lane-changing behaviours in interchange weaving areas. However, research on mandatory lane-changing in weaving areas tends to focus on final lane-changing behaviour that achieves the intention of mandatory lane-changing, rather than the OLC behaviour that requires multiple lane-changing within the weaving area. Existing studies on OLC behaviour have predominantly been conducted in highway sections. For example, Pan [11], Choudhari [12], Mahmud [13], Lamouik [14] and Dutta [15], respectively, explored safety influencing factors, models for lane-changing distance and time selection, safety risk prediction models, assisted driving control models and models for lateral and longitudinal control behaviour in highway sections. However, OLC behaviour in weaving areas differs significantly from that in highway sections. Moridpour [16] introduced the concept of OLC behaviour in weaving areas, Li [17] examined merging behaviour models for vehicles performing OLC in highway interchange weaving areas, and Arman [18] pointed out that OLC behaviour frequently occurs in weaving areas. OLC behaviour significantly affects traffic flow operation, yet research on this topic in weaving areas remains limited. Consequently, further investigation is warranted to explore the operational mechanisms, influencing factors and control methods of OLC behaviour in weaving areas.

The investigation of influences on traffic behaviour is a crucial aspect of understanding the underlying mechanisms, and also an important step in exploring the research needs of traffic behaviour. Conducting impact analyses using field data is the most direct research approach. For example, Deng [19] studied the impact of off-street parking on entrance and exit traffic flow using field-collected data and variations in the impedance function. However, obtaining complete and continuous data on traffic behaviour in different scenarios or states can often be challenging. In such cases, simulation methods are often employed to obtain more comprehensive data. For instance, Wang [20] analysed the impact of autonomous driving technology on traffic flow at bottlenecks by simulating car-following behaviour and conducting analysis using the Paramics software. Cellular automata are favoured simulation and modelling tools due to their flexibility and intuitiveness. Baikejuli [21] used cellular automata-based simulation to analyse the relationship between heterogeneous traffic (cars and trucks) and the fundamental diagram of traffic flow and congestion. Yang [22] investigated the impact of trucks on driving speeds and traffic conflicts of passenger cars, and the effects of lane-changing rules on the distribution of vehicles, traffic conflicts and traffic efficiency in dual-lane traffic flow on highways using cellular automata-based simulation. Similarly, Fan [23] studied the influences of autonomous vehicles on traffic flow parameters, such as speed, traffic volume and speed difference in mixed traffic flow by cellular automata-based simulation. These studies also highlight that the selection of evaluation indicators in analysing influences on traffic behaviour is primarily based on potential effects caused by traffic behaviour.

In summary, considering the prominent phenomenon of OLC behaviour in urban expressway interchange weaving areas, this study aims to analyse the traffic flow characteristics of urban expressway interchange weaving areas based on field-collected trajectory data, explore the internal factors that induce OLC behaviour, and the necessity of its existence. By using cellular automata to simulate the traffic behaviour in the interchange weaving area, we quantitatively analyse the potential impacts of OLC behaviour on the interchange area. The paper is structured as follows; the first section explains the data gathering and processing. The second section analyses the basic characteristics of traffic flow, including lane-changing points and spatio-temporal utilisation in the interchange weaving area. The third section models traffic behaviour based on field-collected data and constructs a cellular automaton simulation model for interchange weaving areas. The fourth section conducts a quantitative analysis of the impact of OLC behaviour on traffic flow efficiency and spatio-temporal utilisation in the weaving area using simulation data. The conclusion is presented in the final section.

2. DATA COLLECTION

The data for this study were collected from the interchange weaving area of Chengdong Expressway in Nanjing, China. The physical structure of the interchange weaving area is shown in *Figure 1*, which is composed of a three-lane main road and a two-lane auxiliary road, each of which has a speed limit of 60 km/h. The main road and auxiliary road are separated by green belts upstream and downstream of the interweaving area. Lane 1 of the main and lane 2 of the main road and the two lanes of the auxiliary road can change lanes with each other in the interweaving section and its upstream and downstream range. Lane 3 and lane 2 of the main road are divided by solid lines and cannot change lanes with each other. The study specifically focused on a 120-meter segment within the interchange weaving area. Video collection was conducted using a drone positioned at a height of 120 meters above the lanes during clear weather on a weekday morning rush hour, between 7:30 and 8:30. The videos were then processed using the A.R.C.I.S system, developed by the UCF Intelligent and Secure Transportation Lab, to extract the pixel coordinates of vehicles. The initial data obtained included vehicle ID, length, width and the pixel coordinates of the front, back and centre of the vehicles. Subsequently, a homography transformation was applied to map the pixel coordinates to the Cartesian coordinate system.

This study classifies the rigid lane-changing behaviours in the interchange weaving area into three categories based on field observations: NRLC behaviour on the main road (as shown in the dashed trajectory of vehicle A in *Figure 1*), NRLC behaviour on the auxiliary road and OLC behaviour on the main road (as shown in the solid line trajectory of vehicle A in *Figure 1*). The NRLC behaviour applies to vehicles that have already changed lanes to lane 1 on either the main road or the auxiliary road before entering the interchange area. These vehicles can accomplish the goal of rigid lane-changing by making a single lane-changing within the interchange weaving area. The OLC behaviour on the main road entails vehicles overtaking slower vehicles ahead and merging into the auxiliary road. In this study, vehicles that continue to travel on lane 2 of the main road after entering the weaving segment are referred to as OLC vehicles. For instance, in *Figure 1*, vehicle A overtakes vehicle B within the weaving segment. The lane-changing process is determined based on Wang's, Chen's and Zhao's research [24]-[26], the vehicle is considered to have completed a lane-changing when it deviates from the centreline of its original lane and no longer has a velocity opposite to the lane-changing direction, successfully moving to the centreline of the adjacent lane.

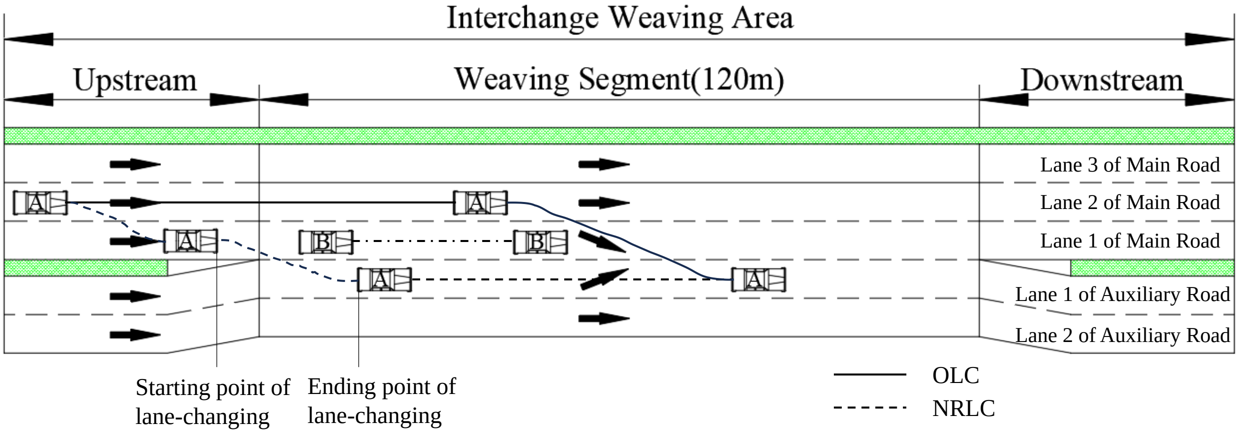

Figure 1 – Schematic diagram of interchange weaving area and overtaking lane-changing behaviour

Following the extraction and processing of vehicle data, real-time position, speed and lane-changing information for all vehicles in the aerial video can be acquired. A total of 8,110 vehicles were collected in the interchange weaving area, yielding 2,770 instances of rigid lane-changing behaviour. Specifically, there were 1,115 NRLC vehicles on the main road, 1,215 NRLC vehicles on the auxiliary road and 440 OLC vehicles on the main road. Among the vehicles exhibiting rigid lane-changing behaviour on the main road in the interchange weaving area, OLC vehicles constituted 28% of the total. This finding suggests that within the interchange weaving area, a portion of drivers have demonstrated a proactive inclination towards OLC behaviours.

Based on the assessment of instantaneous traffic safety risk and comprehensive traffic safety risk, this paper aims to study the prediction method of traffic safety risk in the urban expressway interchange weaving area where lane-changing behaviour is concentrated. The research results can provide a theoretical basis for traffic safety risk prediction and driving assistance in interchange weaving areas.

3. TRAFFIC FLOW CHARACTERISTIC ANALYSIS IN THE INTERCHANGE WEAVING AREA

3.1 Distribution characteristics analysis of lane-changing points

The selection of lane-changing points lies at the core of the lane-changing process and significantly impacts path, efficiency and safety. This study separately analysed the distribution of lane-changing points for three types of rigid lane-changing behaviours in the interchange weaving area: NRLC behaviour on the main road, NRLC behaviour on the auxiliary road and OLC behaviour on the main road. The OLC behaviour encompasses two stages: changing from lane 2 of the main road to lane 1 of the main road and changing from lane 1 of the main road to lane 1 of the auxiliary road. *Figure 2* vividly illustrates the statistical results, with the weaving segment's interval on the x-axis spanning from 25 to 145.

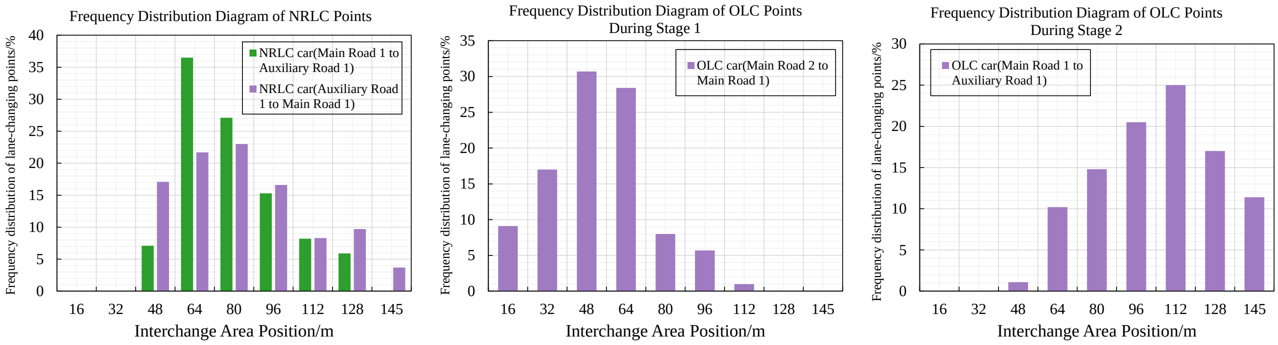

Figure 2 – Statistical chart of the distribution of vehicle lane-changing points in the interchange weaving areas

By analysing the distribution of lane-changing points in rigid lane-changing behaviours, the following observations can be made.

Firstly, in NRLC behaviours, 86% of rigid lane-changing points on the main road and 78.4% on the auxiliary road concentrate within the initial 60% of the weaving segment. Additionally, it is worth noting that the peak of lane-changing points on the main road occurs slightly earlier than on the auxiliary road.

Secondly, in the specific case of OLC behaviour on the main road, 88.7% of lane-changing points for lane 1 of the main road changing to lane 1 of the auxiliary road are observed in the last 40% of the weaving segment.

Thirdly, the distribution of lane-changing points for rigid lane-changing behaviours indicates that NRLC primarily occurs in the front part of the weaving segment to expedite the completion of requirements, resulting in limited utilisation of the rear part of the weaving segment. Conversely, when OLC on the main road leverages the distribution characteristics of lane-changing points in the weaving segment and utilises the rear part of the weaving segment space to attain a balanced distribution of all lane-changing points, it enhances the operational efficiency of the interchange area.

3.2 Characteristic analysis of spatial-temporal utilisation rate

Analysing the impact of rigid lane-changing behaviours on lane-changing points reveals significant variations in the spatio-temporal utilisation rate of adjacent lanes within the weaving segment. To measure the influence of rigid lane-changing behaviours on the spatio-temporal utilisation rate of lanes, we analysed the spatio-temporal utilisation rate characteristics of three lanes: lane 2 of the main road, lane 1 of the main road and lane 1 of the auxiliary road. The spatio-temporal occupancy rate represents the ratio of time in which the road is occupied by the traffic flow, and its calculation method is presented in *Equation 1*. *Figure 3* illustrates the calculation results.

$$\alpha_j = \frac{\sum_{i=1}^{n} x_j(i)}{y} \tag{1}$$

j: lane positions number;
α_j: the spatio-temporal occupancy rate of the corresponding lane position;
n: the number of vehicles passing through position j;
x_j (i): the duration of the i_th vehicle occupying that position;
y: the total length of the statistical period.

From the figure shown above, several conclusions can be drawn.

1) Although vehicles intending to overtake need to utilise main road 2 before completing the lane-changing from main road 2 to main road 1, the overall spatio-temporal utilisation rate on main road 2 remains relatively low, stabilising at approximately 15%.
2) The distributions of the spatio-temporal utilisation rates on lane 1 of the main road and lane 1 of the auxiliary road are quite similar. In the first 40% of the weaving segment, both lane 1 of the main road and lane 1 of the auxiliary road exhibit utilisation rates higher than 20%. The maximum spatio-temporal utilisation rate for lane 1 of the main road is approximately 30%, while lane 1 of the auxiliary road reaches about 25%. However, within the last 60% of the weaving segment, the utilisation rates on both lane 1 of the main road and lane 1 of the auxiliary road gradually decrease and tend to align with the utilisation rate observed on lane 2 of the main road.
3) Notably, the weaving segment shows significantly higher utilisation rates on lane 1 of the main road and lane 1 of the auxiliary road in the first half compared to the second half. This discrepancy can be attributed to the specific distribution of lane-changing points influenced by rigid lane-changing behaviours. The distinct distribution pattern of utilisation rates within the weaving segment objectively presents more opportunities and possibilities for selecting lane-changing points during the second stage of OLC behaviour.

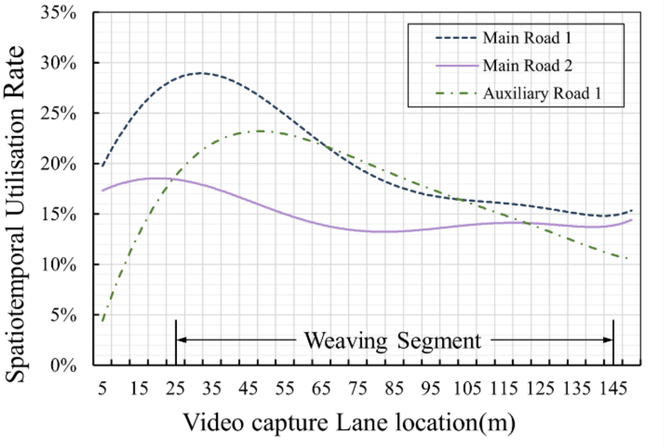

Figure 3 – Analysis of lane spatio-temporal occupancy rate

3.3 Statistical characteristics analysis of lane driving speeds

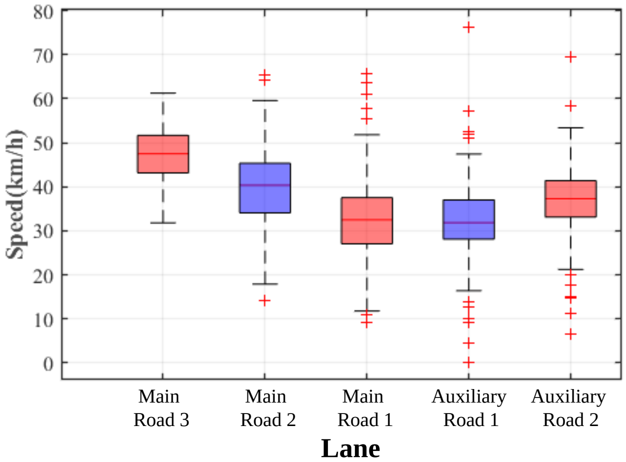

Figure 4 – Statistical characteristics of driving speeds of different lanes in the weaving segment

The statistical results regarding the driving speeds in different lanes of the weaving segment are depicted in *Figure 4*. Main road 3 strictly prohibits lane-changing under practical management, leading to the highest driving speed with an average of approximately 47 km/h. Main road 2 and lane 2 of the auxiliary road primarily involve straight driving, coupled with some instances of non-rigid lane-changing and OLC behaviours. Consequently, their driving speeds are comparatively lower compared to lane 3 of the main road, averaging 41 km/h and 37 km/h, respectively. The demand for rigid lane-changing predominantly arises on lane 1 of the main road and lane 1 of the auxiliary road. As a result of the impact of rigid lane-changing behaviour, the driving speeds on lane 1 of the main road and lane 1 of the auxiliary road are relatively reduced, averaging at 32 km/h and 31 km/h, respectively. The adjacent lanes of the main road and the auxiliary road in the weaving segment are significantly influenced by rigid lane-changing behaviour, thus forming bottleneck points that require enhancement of the operational efficiency of the weaving segment.

4. CONSTRUCTION OF CELLULAR AUTOMATON SIMULATION MODEL

4.1 Construction of car-following and lane-changing models

Car-following behaviour rules

The NS model is utilised as the foundation for simulating car-following behaviour, where the vehicle positions are updated using the equation $x_{i,j}(t+1) = x_{i,j}(t) + v_{i,j}(t)$. Here, v_{max} represents the maximum velocity of the vehicles, and the vehicle velocity falls within the range of 0 to v_{max}. In addition, the NS model incorporates a random deceleration rule.

Considering the statistical characteristics of vehicle speeds in the interchange weaving area, a speed adjustment coefficient ρ is incorporated into the modelling of the following behaviour rules to enhance the optimisation of acceleration and deceleration. The probabilities of vehicle acceleration and deceleration are denoted as p_{speedup} and p_{slowdown}, respectively.

$$p_{speedup} = \begin{cases} 1 & v_{i,j}(t) < \rho * v_{max} \\ \dfrac{1}{1+\exp\,(a \cdot v_{i,j}(t) - b)} & v_{i,j}(t) \geq \rho * v_{max} \end{cases} \tag{2}$$

$$p_{slowdown} = \begin{cases} 0 & v_{i,j}(t) < \rho * v_{max} \\ 1 - \dfrac{1}{1+\exp\,(a \cdot v_{i,j}(t) - b)} & v_{i,j}(t) \geq \rho * v_{max} \end{cases} \tag{3}$$

In the equation, $\rho = v_{average}/v_{max}$, $v_{average}$ represents the average driving speed of different lanes in the statistical data, $a = \left(\ln\left(\frac{1}{p_2} - 1\right) - \ln\left(\frac{1}{p_1} - 1\right)\right)/\left((1-\rho)\cdot v_{max}\right)$, $b = \ln\left(\frac{1}{p_2} - 1\right) - a \cdot v_{max}$, $p_1 = \lim\limits_{x \to e} \ln(x)$, $p_2 = \lim\limits_{x \to 1} \ln(x)$. The vehicle acceleration rule is denoted as $v_{i,j}(t+1) = \min\left[v_{i,j}(t) + 0.1, v_{max}\right]$. The vehicle deceleration rule is denoted as $v_{i,j}(t+1) = \max\left[v_{i,j}(t) + 0.1, 0\right]$.

Rigid lane-changing rules

K-S test was used to analyse the distribution characteristics of vehicle lane-changing points in the interweaving area. The result shows that the data conform to the normal distribution. Then a Gaussian curve fitting equation was established to determine the lane change point. The K-S test results and Gaussian fitting equation are as follows:

Table 1 – The significance results of the K-S test of vehicle lane-changing points distribution

	NRLC car (main road 1 to auxiliary road 1)	**NRLC car (auxiliary road 1 to main road 1)**	**OLC car (main road 2 to main road 1)**	**OLC car (main road 1 to auxiliary road 1)**
Sig.	0.091	0.200	0.168	0.200

$$y = y_0 + \frac{A}{\omega \cdot \sqrt{\frac{\pi}{2}}} \cdot \exp\left[-2\left(\frac{x - {x_c}^2}{\omega}\right)\right] \tag{4}$$

In the equation, y_0 represents the offset; x represents the lane-changing frequency position; x_c represents the peak centre position; ω represents the half-width of the Gaussian peak; A represents the peak area. The adjustment coefficients for each lane-changing direction and the results of the hypothesis test are shown in *Table 2*.

Table 2 – Gauss fitting coefficients and test

Adjustment coefficients and test indicators	**Main road 1 to auxiliary road 1**	**Auxiliary road 1 to main road 1**	**The first stage of OLC**	**The second stage of OLC**
y_0	0.025	0.020	0.011	-0.010
x_c	71.7875	76.010	52.026	107.585
ω	29.195	47.677	37.594	62.042
A	12.4766	13.169	14.494	18.868
Skewness	1.196	0.012	0.080	0.091
Kurtosis	0.463	-1.632	1.482	1.183
Goodness of fit/R²	0.898	0.846	0.967	0.946

According to the data presented in *Table 2*, it is evident that all the sample skewness and kurtosis values are below 2 [27], suggesting a Gaussian distribution of lane-changing frequency. Consequently, a Gaussian distribution model, denoted as C(x), can be employed to represent the lane-changing probability.

$$C(x) = a_1 + a_2 \cdot \exp\left[-\left(\frac{x - a_3}{a_4}\right)^2\right] \tag{5}$$

In the equation, a_1 represents the vertical offset of the function; a_2 represents the peak limit value; a_3 represents the horizontal offset; a_4 represents the distribution curve shape parameter.

Free lane-changing rule

The difference in velocity, v_x, between the preceding vehicle in the target lane and the preceding vehicle in the current lane, is taken as the decision factor for determining the lane-changing probability of the target vehicle. It is only valid if the safety distance requirements are satisfied for both the preceding and succeeding vehicles involved in the lane-change scenario. When v_x is equal to zero, the lane-changing probability of the target vehicle is denoted as $p3$, which is set to 0.05 in this study. On the other hand, when v_x is equal to v_{max}, the lane-changing probability of the target vehicle is referred to as $p4$, with a value of 0.8 in this investigation. Therefore, a logistic curve-based model is constructed to represent the free lane-changing probability, as shown in *Equation 6*:

$$p_{i,j}^{L}(t) = p_{i,j}^{R}(t) = \frac{1}{1 + \exp\left(-\frac{a}{5} \cdot v_x(t) + b\right)} \tag{6}$$

In the equation, $b = \ln\left(1/(p_3 - 1)\right)$, $a = \left(b - \ln\left(1/(p_4 - 1)\right)\right)/v_{max}$, $v_x(t) = v_{i+n,j+1}(t) - v_{i,j+1}(t)$.

4.2 Validation of simulation model

To examine the efficacy of the cellular automaton simulation model created based on the aforementioned models, this research takes the interchange weaving area of Chengdong Expressway in Nanjing as the research object. By incorporating the physical dimensions of the interchange weaving area, a cellular automaton simulation model is constructed. *Table 2* presents the baseline parameter configurations for the simulation model. Using collected traffic flow data as input, the main road traffic load is set at 3,960 pcu/h, while the auxiliary road traffic load is set at 2,640 pcu/h. The proportion of rigid lane-changing vehicles on the main road is 32%, while on the auxiliary road is 36.5%. Among the rigid lane-changing vehicles on the main road, 28% exhibit OLC behaviour. The generation of vehicles adheres to a Poisson distribution, with the initial velocity of vehicles adhering to the statistical characteristics of actual traffic flow.

Table 3 – Basic parameter settings for simulation

Variables	**Parameter settings**	**Corresponding actual values**
Spatial length of cells/cell	3000	[150 m]
Lane width/cell	9	[3.5 m]
Number of lanes/lane	5	5
Range of weaving segment/cell	[510, 2850]	[25 m, 145 m]
Vehicle maximum speed v_{max}/(cell*fps^{-1})	12	[60 km/h]
Vehicle body length/cell	90	[4.5 m]
Simulation time step/fps	9000	[5 min]

The traffic flow characteristics analysis of the interchange weaving area reveals a notable disparity in spatio-temporal utilisation, which facilitates OLC behaviour and motivates more vehicles to select this behaviour. Consequently, the spatio-temporal utilisation rates of main road 2, main road 1 and auxiliary road 1 are chosen as indicators to validate the efficacy of the cellular automaton simulation model. To mitigate the influence of random seeds on simulation outcomes, 50 independent simulations are conducted with fixed parameter values. The average spatio-temporal utilisation rates at different positions in the three lanes are calculated and compared to the actual spatio-temporal utilisation rates of each lane. *Figure 5* displays the comparison results.

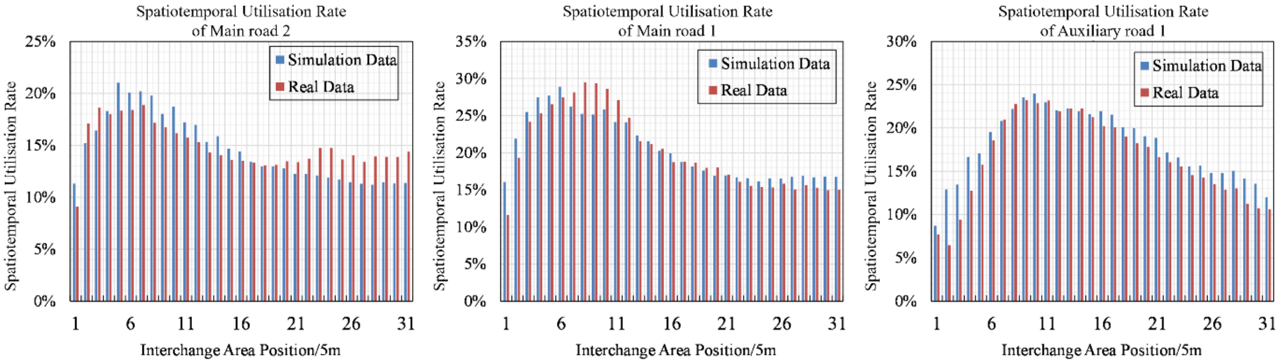

Figure 5 – Comparison of spatio-temporal utilisation rates of three lanes in simulated and actual environments

The figure presented above illustrates the consistent variation trends observed in the spatio-temporal utilisation rates of the three lanes in both the simulated and actual environments. Calculating the average error between the simulation data and actual data at various positions within the interchange weaving area reveals that the average errors for main road 2, main road 1 and auxiliary road 1 are 1.67%, 4.38%, and 2.69%, respectively. These findings signify that the cellular automaton simulation model constructed in this study can reasonably reproduce the operational state of actual traffic flow within interchange weaving areas.

5. INFLUENCE ANALYSIS OF OLC BEHAVIOUR ON INTERCHANGE WEAVING AREAS

This study aims to examine the influence of OLC behaviour on interchange weaving areas. The independent variables considered in this analysis are the traffic load and the proportion of OLC vehicles in the weaving area. The effects of these variables on lane travel efficiency, lane-changing vehicle travel efficiency and the spatio-temporal utilisation rate of the weaving segment will be explored. The traffic load of the weaving area is measured by the total number of vehicles within a simulated time step of 5 minutes. Five levels of traffic load are considered: 350 pcu, 550 pcu, 750 pcu, 950 pcu and 1,150 pcu. Each level corresponds to specific traffic volumes: 840 pcu/h/ln, 1,320 pcu/h/ln, 1,800 pcu/h/ln, 2,280 pcu/h/ln and 2,760 pcu/h/ln, respectively. The ratio of main road traffic volume to auxiliary road traffic volume is fixed at 1.5. The proportion of OLC vehicles is defined as the ratio between OLC vehicles and all rigid lane-changing vehicles on the main road. This ratio ranges from 0 to 0.7. All other parameters are based on actual statistical data and are considered to be fixed values. To reduce the impact of randomness on the simulation results, the data used in the impact analysis are the average of 50 simulations.

5.1 The impact analysis on the efficiency of interweaving weaving sections

The analysis of the efficiency impact on the interchange weaving area is depicted in *Figure 6*. The heatmap illustrates the variations in the average speed across different lane types, including main road 2, main road 1 and auxiliary road 1, as well as vehicles with different lane-changing types, including OLC vehicles, NRLC vehicles on the main road, NRLC vehicles on the auxiliary road. Additionally, it displays the effects of changes in traffic volume and the proportion of OLC vehicles in the interchange weaving area. From the horizontal changes in colour blocks in the figure, it is evident that the average speed of different lanes and types of lane-changing vehicles decreases as the traffic volume in the interchange weaving area rises. From the vertical changes in colour blocks in the figure, it can be observed that under a fixed traffic load, the average speed of auxiliary road 1, OLC vehicles and NRLC vehicles on auxiliary roads only experience slight changes. However, when the traffic volume ranges between 500 – 900 pcu/5min, there is a significant increase in the average speed of main road 2, main road 1 and NRLC vehicles on main road 1.

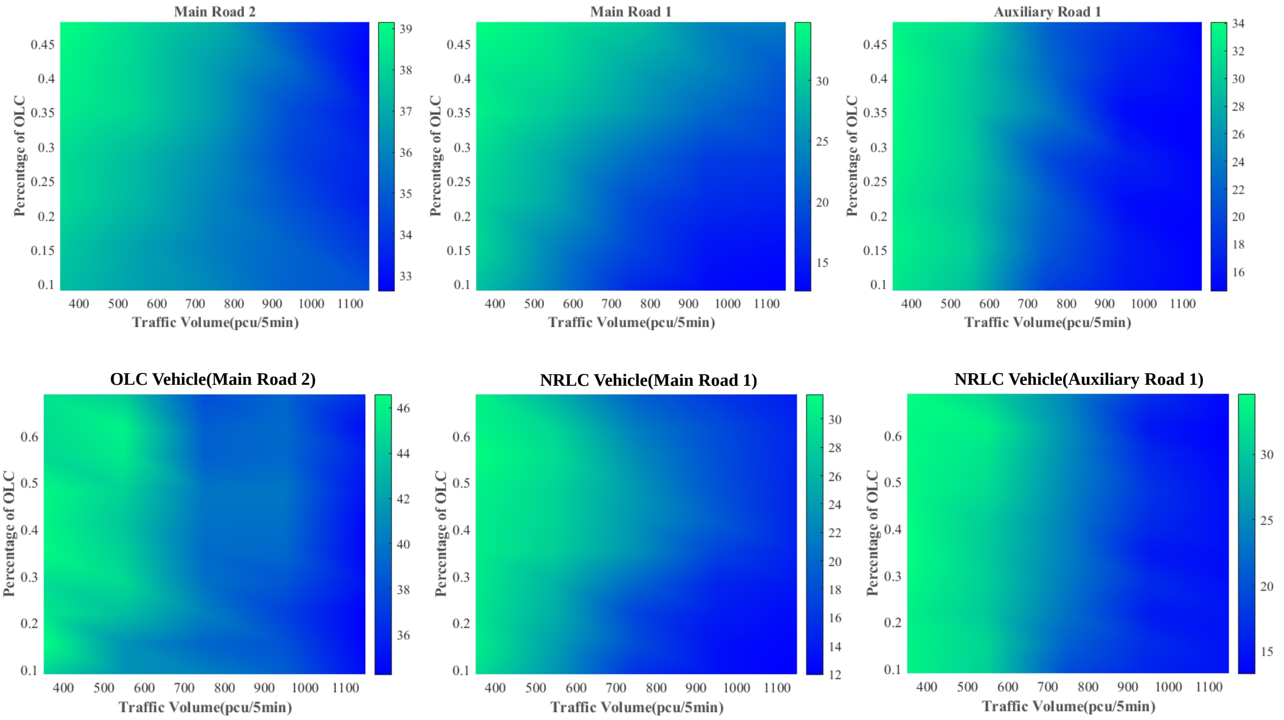

Figure 6 – Heatmap of OLC behaviour impact on different lanes (top three images) and lane-changing vehicles (bottom three images)

To analyse the impact of traffic volume and the proportion of OLC vehicles on main road 2, main road 1 and NRLC vehicles on the main road, a comparison of average speeds in the environment without OLC behaviour is conducted. It examines the extent of improvement in the average speeds of main road 2, main road 1 and NRLC vehicles on the main road under different proportions of OLC vehicles in various environments. The findings are presented in a three-dimensional graph, as displayed in *Figure 7*. Additionally, contour maps depicting the improvement levels of average speed for main road 1 and NRLC vehicles on the main road with improvement levels of 20%, 30% and 40% are shown in *Figure 8*.

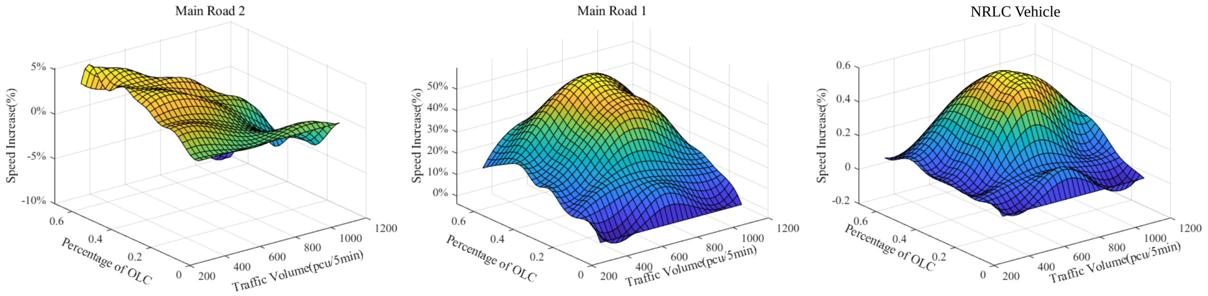

Figure 7 – Influence of OLC vehicles proportion on main road 2, main road 1 and NRLC vehicles

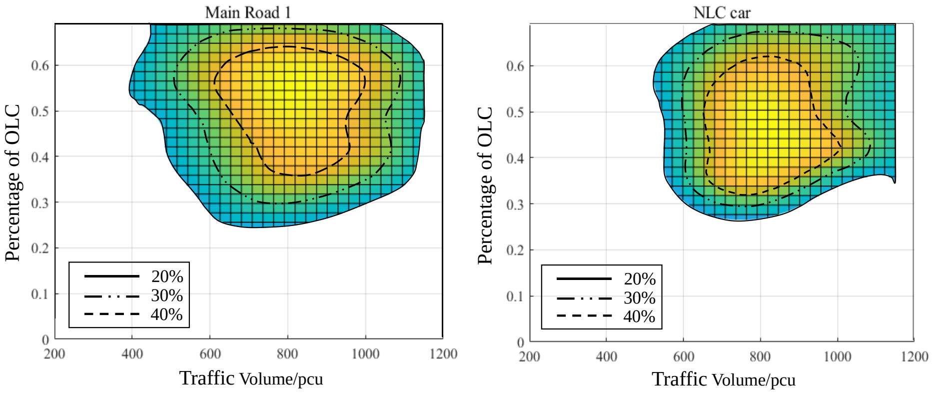

Figure 8 – Contour map of the average speed enhancement level of OLC vehicles to the average speed of lane 1 of the main road and NRLC vehicles on the main road

From *Figure 7* and *Figure 8*, the following conclusions can be drawn.

1) OLC behaviour significantly improves the traffic efficiency of lane 1 of the main road and NRLC vehicles on the main road. However, it has a slight negative impact on main road 2 under certain conditions. Overall, OLC behaviour has a positive impact on the traffic efficiency of interchange weaving sections.
2) When the traffic load is less than 500 pcu/5 min, the lane-changing vehicles experience relatively less congestion, and the improvement in traffic efficiency due to OLC behaviour is relatively small, not exceeding 20%. However, when the traffic load exceeds 1,100 pcu/5 min, the overall traffic operation in the interchange weaving area becomes significantly congested, resulting in a reduced impact of OLC behaviour on the traffic efficiency of the interchange weaving area.
3) For lane 1 of the main road, when the traffic volume is 500 – 1,100 pcu/5 min and the proportion of OLC behaviour is 0.3 – 0.7, the average speed will be improved by at least 20%. When the traffic load is 700 – 1,000 pcu/5 min and the proportion of OLC behaviour is 0.35 – 0.65, the average speed will be improved by at least 30%. When the traffic volume in the interchange area is about 800 pcu/5 min and the proportion of OLC behaviour is about 0.55, the level of increase in average speed can reach up to 48%.
4) For NRLC vehicles on the main road, when the traffic volume in the interchange area ranges from 500 to 1,150 pcu/5 min and the proportion of OLC behaviour is between 0.35 and 0.7, the average speed improvement is not less than 20%. Similarly, when the traffic volume ranges from 600 to 1,000 pcu/5 min and the proportion of OLC behaviour is between 0.35 and 0.6, the average speed improvement is not less than 30%. Notably, when the traffic volume is approximately 750 pcu/5 min and the proportion of OLC behaviour is about 0.48, the increase in average vehicle speed can reach up to 51%.
5) The highest improvement in average speed for lane 1 of the main road and NRLC vehicles on the main road occurs when the proportion of OLC behaviour ranges from 0.35 to 0.65.

5.2 Analysis of the impact on the spatio-temporal utilisation of the weaving segment

Figure 9 illustrates the spatio-temporal utilisation distribution of three roads: lane 2 of the main road, lane 1 of the main road and lane 1 of the auxiliary road. This distribution is shown under varying traffic volumes and proportions of OLC vehicles in the weaving segment. The horizontal coordinate represents the location of the weaving segment, while the vertical coordinate represents the proportion of OLC vehicles. Low occupancy rates are denoted by the colour blue.

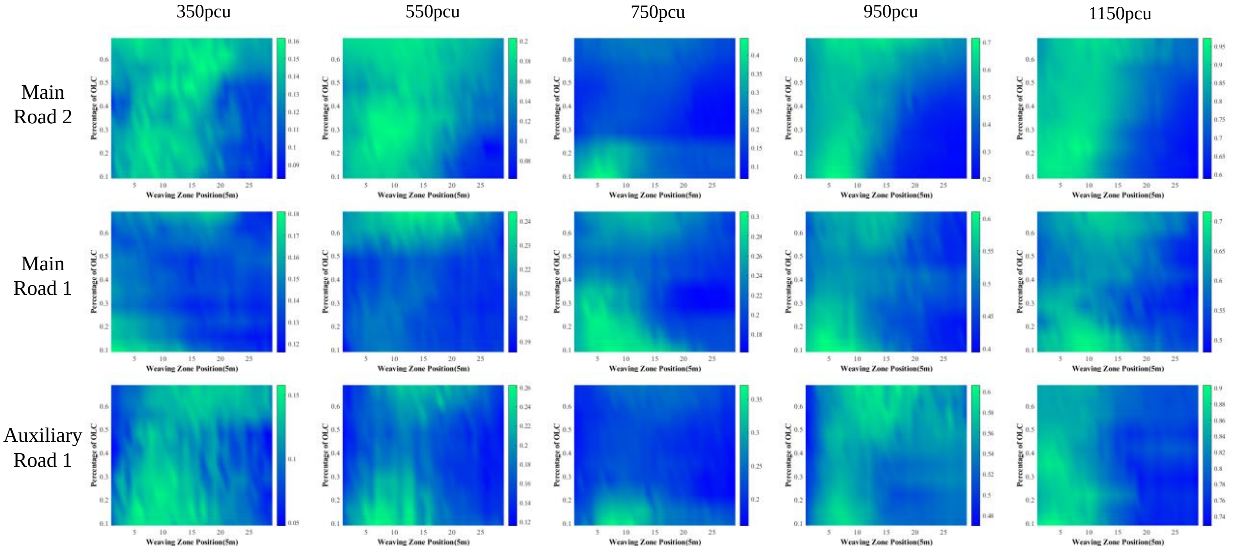

Figure 9 – Lane spatio-temporal map under different parameter settings

By analysing the figure, it is evident that in the absence of OLC behaviour, the sections with high spatio-temporal utilisation rates on the three lanes are primarily concentrated in the front half (green area). This aligns with the earlier analysis of the true spatio-temporal utilisation distribution in the interchange weaving area. As the proportion of OLC behaviour gradually increases to 0.5, the green area begins to disperse and fade, indicating a shift from a concentrated distribution to a more uniform one. When the proportion of OLC behaviour exceeds 0.5, the green area starts to concentrate and deepen once again.

This study aims to quantify the impact of the proportion of OLC vehicles on the spatio-temporal utilisation rate of the weaving segment. To achieve this, the variance of the spatio-temporal utilisation rate is calculated under specified traffic volumes and proportions of OLC vehicles. This calculation allows for the characterisation of the uniformity of the spatio-temporal utilisation rate in each lane. A higher variance indicates greater unevenness in the spatio-temporal utilisation rate, which is detrimental to the service capacity of the interchange weaving area. *Equation 7* presents the calculation formula for the variance of the spatio-temporal utilisation rate of each lane. Additionally, *Figure 10* displays the calculation results and the fitting curve. Furthermore, *Figure 11* presents the relationship curve between the average spatio-temporal utilisation rate of the merging segment and the proportion of OLC vehicles under specified traffic volumes,

$$Var(X)=\int_{0}^{\max(x)}(x-\mu)^{2}f(x)\,dx \tag{7}$$

where μ is the mean spatio-temporal utilisation rate of the lane, x is the position on the lane, and $f(x)$ is the fitting function of the spatio-temporal utilisation rate curve.

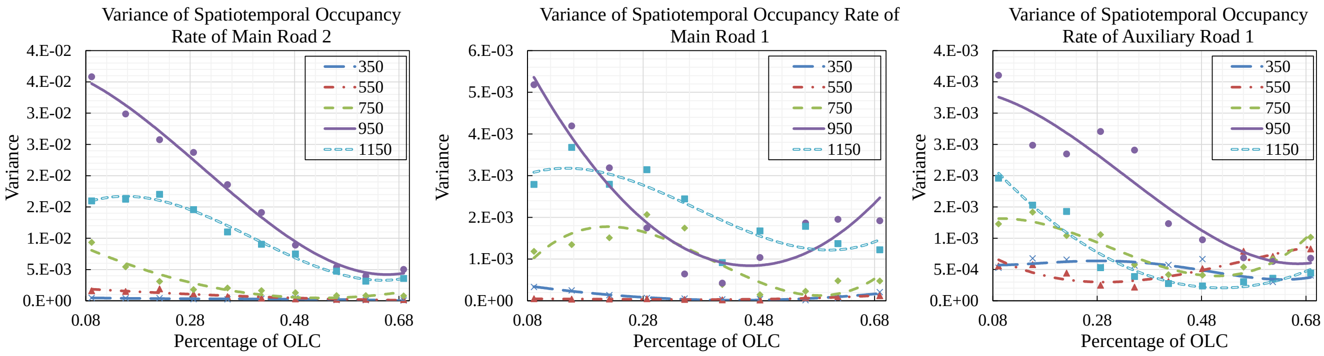

Figure 10 – Variance of the spatio-temporal utilisation rate for main road 2, main road 1 and auxiliary road 1

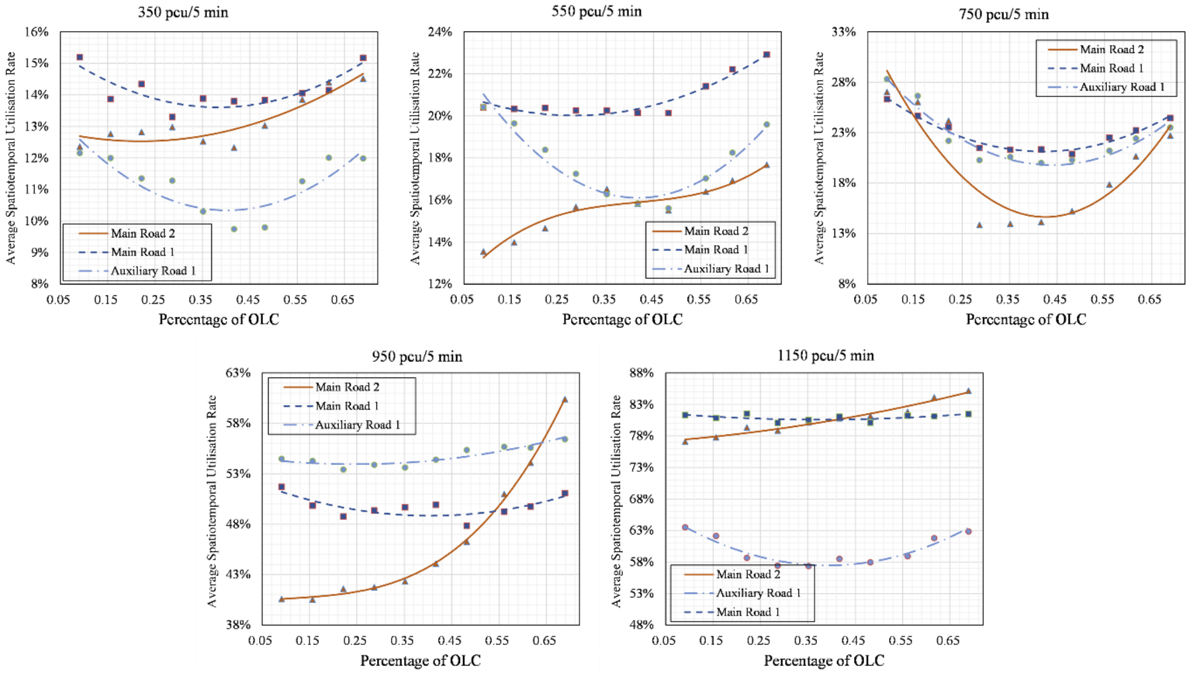

Figure 11 – Relationship between the average spatio-teporal utilisation rate and the proportion of OLC vehicles

Based on *Figure 10*, several key observations can be made. Firstly, when the traffic volume in the interchange weaving area is below 550 pcu/5 min, the initial variance of the spatio-temporal utilisation rate on the three lanes is already low, indicating a lack of significant improvement from the proportion of OLC vehicles. Secondly, when the traffic volume exceeds 750 pcu/5 min, an increase in the proportion of OLC vehicles causes the variance of the spatio-temporal utilisation rate on the three lanes to initially decrease, followed by an increase. The lowest variance of the spatio-temporal utilisation rate on the three lanes is observed at a proportion of OLC vehicles ranging from 0.45 to 0.6.

Based on the observations from *Figure 11*, several important findings can be highlighted. Firstly, as the proportion of OLC vehicles increases, there is a noticeable decrease followed by an increase in the average spatio-temporal utilisation rates of lane 1 of the main road and lane 1 of the auxiliary road. This trend is more prominent when the traffic volume in the interchange weaving area is below 750 pcu/5 min, and it becomes less significant when the traffic volume exceeds 950 pcu/5 min. Secondly, the average spatio-temporal utilisation rate of main road 2 consistently increases alongside the proportion of OLC vehicles. However, the overall average spatio-temporal utilisation rate of main road 2 does not surpass that of main road 1. Lastly, different traffic volumes in the interchange weaving area show that the range of OLC vehicle proportions associated with low average spatio-temporal utilisation rates for lane 1 of the main road and lane 1 of the auxiliary road is between 0.3 and 0.5.

6. CONCLUSION

This study delves into the influence of OLC behaviour in interchange weaving areas of expressways. Through the field collection of traffic data, the study examines the characteristics of lane-changing behaviour and traffic operations within this area. A cellular automaton traffic simulation model is developed to replicate the traffic dynamics in the weaving area. By considering traffic demand and the proportion of OLC vehicles as independent variables, the study employs simulation techniques to quantitatively assess the impact of OLC behaviour on operational efficiency and the spatio-temporal utilisation of the interchange weaving area. This study can serve as a reference for future research on the urban expressway interchange weaving areas, and provide certain theoretical support for traffic in the future intelligent networked environment. The main conclusions of the study can be summarised as follows.

1) Based on the distribution of vehicle lane-changing points, the lane-changing points for NRLC behaviour in the interchange weaving area are predominantly concentrated within the first 60% section of the interchange weaving area. Furthermore, the spatio-temporal utilisation of the interchange weaving area exhibits a significant imbalance, with higher utilisation in the first half compared to the second half. This uneven distribution of lane-changing behaviour and spatio-temporal utilisation in the interchange weaving area contributes to a significant number of OLC behaviours.
2) A cellular automaton traffic simulation model is developed based on measured data and traffic flow characteristics. The model optimises the behaviour rules for car-following, rigid lane-changing and free lane-changing to accurately simulate the operational status of traffic flow and the distribution characteristics of spatio-temporal utilisation in the interchange weaving area.
3) In terms of traffic efficiency in the interchange weaving area, the OLC behaviour has a significant impact when the traffic demand is within the range of 500 – 1,100 pcu/5 min and the proportion of OLC behaviour is between 0.35 – 0.7. In these conditions, the OLC behaviour considerably improves the traffic efficiency of lane 1 of the main road and NRLC vehicles on the main road. The average speed for lane 1 and NRLC vehicles on the main road can increase by up to 48% and 51%, respectively.
4) Regarding spatio-temporal utilisation in the interchange weaving area, the presence of OLC vehicles has a significant positive impact. When the traffic demand exceeds 550 pcu/5 min, OLC vehicles significantly improve the spatio-temporal utilisation balance in all three lanes. The most notable improvement occurs when the proportion of OLC vehicles is between 0.45 and 0.6. Additionally, when the traffic demand is below 750 pcu/5 min, a proportion of OLC vehicles can also reduce the average spatio-temporal utilisation of lane 1 of the main road and lane 1 of the auxiliary road.

Along the stream of this study, several elements of future research can be identified. Firstly, in terms of the impact analysis of spatio-temporal utilisation in interchange weaving areas, only five scenarios under different traffic volumes have been studied. Whether there is other impact on different lanes under continuous changes in traffic volumes still needs to be studied. Secondly, the effects of OLC behaviour vary for different lanes and types of lane-changing vehicles. It is crucial to explore how to determine the optimal proportion of OLC behaviour in specific scenarios. Thirdly, the data utilised in this study originated from one interchange weaving area on an expressway. Future investigations should encompass data collection from multiple interchange weaving areas and various types to validate the research findings. Lastly, OLC behaviour may lead to more safety hazards while improving the operational efficiency of interchange weaving areas. To comprehensively evaluate the feasibility of OLC behaviour, in-depth research can be conducted to scientifically guide OLC behaviour through lane-changing assistance and active cooperation to find the best solution to balance efficiency and safety.

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城市快速路互通交织区超车换道行为影响研究

摘要：
研究聚焦快速路互通交织区的超车换道现象，旨在探索超车换道行为出现的原因和带来的可能影响。利用实测数据，分析互通交织区在换道点分布和时空利用率上的统计特征，提出考虑车辆速度分布规律的改进 NS 模型和基于 Gaussian 分布的刚性换道规则，构建互通交织区元胞自动机仿真模型，基于模拟数据量化超车换道行为对交织区通行效率和时空利用率的影响。结果表明，刚性换道行为换道点和交织段车道时空利用率分布不均衡是诱发超车换道行为的客观因素，当交织区交通负荷为 500-1100pcu/5min 且超车换道行为占比为 0.35-0.7 时，超车换道行为可显著提高主线最外侧车道和常规刚性换道车辆的平均车速，提升水平可分别高达 48%和 51%。同时，超车换道行为还可以改善交织区时空利用率的均衡性并降低平均时空利用率。研究明确了超车换道行为对快速路互通交织区的积极影响，可为交织区效率提升提供新的研究思路。

关键词：
互通交织区，超车换道行为，换道点，时空利用率，元胞自动机