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Dissipative Structure Properties of Traffic Flow in Expressway Weaving Areas

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ABSTRACT

Expressway weaving areas meet dissipative structure characteristics. When traffic states reach a certain range, they exhibit self-organising criticality, and slight changes may trigger unpredictable congestion. This paper examines the correlation between the dissipative structure of the weaving area and key traffic parameters. The range of dissipative structure states in the weaving area is defined through the dissipative structure concept with three-phase traffic flow theory and real traffic data. Based on the fundamental diagram and measured traffic data, the weaving area dissipative structure model characterising the relationship between critical state changes in traffic volume is constructed and validated. Finally, the Cell Transmission Model simulation was used to examine the characteristic relationship between the weaving area dissipative structure state duration, the weaving area length and the weaving flow ratio. The results show that the length of the dissipative structure state is maintained when the traffic flow is self-organised into a free-flow or a congested state positively correlates with the length of the weaving area. Higher weaving flow ratios lead to shorter dissipative structure state durations during congestion formation, and the exact opposite during congestion evacuation. This paper is important for analysing the congestion mechanism and managing congestion.

KEYWORDS

urban expressway; dissipative structure; weaving area; length of weaving area; weaving flow ratio; congestion duration.

1. INTRODUCTION

The stable operation of expressway traffic systems is crucial for the sustainable development of cities and regions. With the acceleration of urbanisation, traffic congestion in the weaving areas of expressways has become increasingly severe, emerging as one of the bottlenecks constraining urban development. In order to analyse and alleviate congestion in these weaving areas, a considerable amount of research has been devoted to simulating and evaluating various static and dynamic configuration schemes.

Previous studies have primarily focused on enhancing weaving areas' throughput capacity. Some studies have referenced throughput capacity calculation and entrance/exit design [1 – 2]. Cai proposed a traffic capacity model for weaving areas by simulating different configurations [3]. Marczak F [4] and HCM2016 [5] presented traffic analysis models for weaving areas. Kashani A introduced three new traffic variables –

weaving flow ratio, traffic flow ratio of entrance and exit ramps – building upon these models, thus optimising the accuracy of the traffic analysis model for weaving areas [6]. Despite subsequent research achieving significant results in establishing logical relationships between the length of weaving areas and traffic flow conditions or service levels [7], these studies have mainly relied on static parameter models. Further in-depth research is required to enhance understanding of dynamic parameters within weaving areas.

Since the 1990s, researchers have focused on the self-organising criticality exhibited by traffic flow [8]. This phenomenon entails that under specific conditions even minor disturbances can potentially trigger widespread congestion in the system, leading to what is commonly referred to as the “butterfly effect” [9]. The concept of self-organisation is employed to comprehend the internal self-organising behaviour and phase transition phenomena within a system under specific conditions. This understanding is crucial for predicting and controlling the behaviour of complex systems, contributing significantly to enhancing system stability, robustness and efficiency. Subsequently, applying self-organisation theories, such as dissipative structure theory, to analyse traffic systems has become a focal point [10 – 12]. The categorisation of traffic flow under self-organising criticality suggests that unquestioningly maximising the output flow of the traffic system in traffic management strategies may not be advisable. Research indicates that urban traffic networks may exhibit self-organising criticality [13 – 15]. This implies non-linear traffic flow behaviour under specific conditions, indicating that when the system approaches a particular state, even slight changes may trigger sudden and unpredictable traffic congestion, resulting in large-scale coordinated behaviour in the entire traffic system [16]. The self-organising criticality implies the existence of a critical state where traffic flow undergoes a phase transition. Suppose urban traffic networks indeed exhibit self-organising criticality. In that case, we need to adopt this novel concept to understand urban road traffic congestion, as it reveals the fundamental causes of congestion. In the field of pedestrian traffic flow, key parameters such as flow, speed and density needed to describe self-organising behaviour have already been identified [17 – 18]. This raises a question: can similar traffic parameters be defined to determine the critical self-organising states of vehicle traffic flow? Although there are differences between pedestrian and vehicle traffic in certain aspects, establishing similar parameter ranges for vehicle traffic flow and their critical transitions can provide crucial insights into understanding the mechanisms of traffic paralysis. Therefore, a vital objective of this study is to determine the characteristic ranges of parameters, such as flow, speed and density, that describe the self-organising critical states of vehicle traffic on expressways.

Satisfying the conditions of dissipative structures is the primary criterion for self-organising criticality, and dissipative structure theory provides a novel perspective for understanding the internal dynamics of complex systems. Dissipative structures represent a dynamic arrangement within open systems that maintains stability under various input conditions [9]. Chen and Nie observed that urban road traffic systems satisfy the conditions of dissipative structures [19 – 20]. Subsequently, Mo [21] conducted simulations based on dissipative structures to analyse traffic flow. By simulating the traffic dissipative structure in a single road segment, He established a simulation model for the traffic dissipative structure of urban road networks. However, research on dissipative structure in weaving areas of expressways is relatively limited. To gain a deeper understanding of the correlation between weaving areas and dissipative structures, this study intends to investigate further the critical states of dissipative structures in weaving areas, aiming to better reveal the dynamic patterns of traffic flow in these areas. The current key issue is investigating the phase transition between ordered and disordered flow states, which requires a clear delineation of traffic states and determining the critical values of parameter changes corresponding to the overall system state changes. There still needs to be a mature framework for dividing traffic states to analyse the critical states of dissipative structures in the flow of weaving areas.

The three-phase traffic flow theory, which serves as a fundamental framework for studying the formation and dissipation of congestion [22], has been widely applied in transportation engineering literature [23]. The distinction between free flow, Synchronised flow and wide moving jam within this theory provides valuable insights for discerning critical states in dissipative structures. The integration of the three-phase traffic flow theory with the concept of dissipative structures has formed a comprehensive framework. This integration contributes to a more holistic understanding of the dynamic interactions between traffic parameters and dissipative structures. On the other hand, the application of self-organising dissipative structure theory in the context of static traffic parameters and their correlation with criticality has yet to be widely explored in transportation engineering literature. The association between dissipative structure conditions and weaving area parameters (such as length and weaving flow ratio) remains to be determined. Therefore, delineating the traffic parameter ranges, defining the self-organising critical states of road traffic flow and exploring the relationship between dissipative structure conditions and weaving area parameters, such as length and weaving flow ratio, is essential.

This paper aims to investigate the correlation between traffic parameters and dissipative structure in the weaving area and to define the range of dissipative structure states in the expressway traffic system by combining the concept of dissipative structure from the self-organisation theory and the three-phase traffic flow theory. After the theoretical analysis, the dissipative structure model of the weaving area is derived by combining the fundamental diagram. Then, the dissipative structure and simulation models are verified based on the measured traffic data. Finally, we simulate different weaving areas of urban expressways to explore the relationship between dissipative structure, weaving area length and weaving flow ratio. This study will help us understand and manage traffic congestion in urban expressway systems.

2. METHODOLOGY

2.1 Theoretical analysis

Dissipative structure implies that a closed system eventually reaches a uniformly disordered state due to entropy generation [9]. However, when an open system exchanges substances with the outside world and reaches a specific critical point, the negative entropy flow from the outside world counteracts the entropy generation in the system so that the system leaps from a disordered state to a more advanced ordered state, i.e. the formation of a dissipative structure.

Dissipative structure generation needs to satisfy three conditions: the system is open, far from equilibrium and has a rising and falling effect. Once the dissipative structure is generated, the system can self-organise. The expressway transportation system meets these three conditions. Firstly, the exchange of traffic flow constantly occurs between the expressway network and the urban conventional road network, classifying it as an open system. Secondly, the traffic states of individual segments within the expressway system exhibit differences, indicating a departure from equilibrium. Finally, there are fluctuations in vehicle speed and segment density within the traffic flow over minimal time intervals, signifying the presence of fluctuations.

According to the classical thermodynamic expression concerning the entropy balance in an open system, the entropy increment of an open system is the sum of the internally generated entropy and the entropy flow obtained from the external environment. The entropy increment for an open system is denoted as $ds=d_is+d_es$, where ds represents the entropy increment of the entire macroscopic system, d_is is the internal entropy generation, $d_is \geq 0$, and d_es is the entropy value acquired by the system from the external environment. This signifies that the entropy of an open system comprises both internally generated entropy and externally introduced entropy. Under the entropy increase principle, the entropy produced by irreversible processes within the system is always non-negative. However, the total entropy of an open system may be negative, as the input of negative entropy from the external environment may exceed the system's internal entropy generation. When the inflow of negative entropy from the external environment surpasses the internal positive entropy generation, the total entropy of the system decreases, leading the system toward an ordered state. When entropy generation and negative entropy flow mutually offset, the system reaches a steady state, representing the state of minimum entropy production.

Based on this, when the inflow of traffic into the weaving area on the expressway exceeds the outflow, the external environment introduces positive entropy to the system, leading to an increase in segment entropy and a tendency towards disordered traffic states. Conversely, negative entropy flow can offset a portion of entropy generation, resulting in a tendency towards ordered traffic states when the outflow surpasses the inflow. When the traffic flow in the weaving area reaches a steady state, the increment in traffic tends toward zero, and the flow of entropy both within and outside the segment mutually offsets, maintaining a non-equilibrium steady state. Therefore, the expressway weaving area system conforms to the characteristics of dissipative structures.

Dissipative structures emerge near the critical point of internal fluctuations within a system, manifesting as a phase transition between ordered and disordered states. Therefore, it is essential to conduct a detailed classification of the states of the traffic system, determining the extent of changes in traffic parameters that can be known as an alteration in the overall system state. The three-phase traffic flow theory precisely captures the congestion formation and dissipation processes, providing a framework for describing the transition of congestion within dissipative structures.

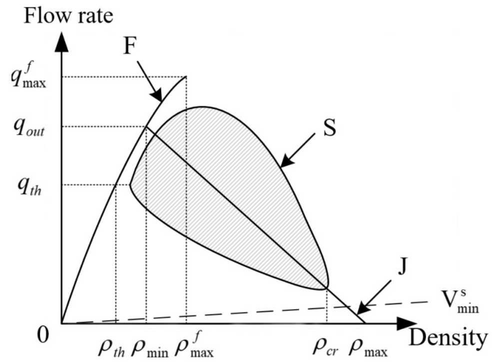


Figure 1 – Density-flow relationship in three-phase traffic theory

where ρ_{th} is the S-F phase transition density threshold, and $q_{th}$is the corresponding flow rate threshold; ρ_{min} is the F-S minimum phase transition density, and q_{out} is the flow rate at the minimum phase transition density; ρ^f_{max} is the maximum density in the F state, and q^f_{max} is the maximum flow rate in the F state; ρ_{cr} is the density threshold for the S-J phase transition; and ρ_{max} is the blocking density.

The advantage of the three-phase theory framework lies in its consideration of the nucleation nature of traffic jams at bottleneck locations, initially proposed by Kerner. Based on extensive empirical data, he obtained the density-flow relationship diagram under the three-phase traffic theory (see *Figure 1*), categorising traffic flow states into free flow (F), synchronised flow (S) and wide moving jam (J). According to this theory, capacity represents a critical point, and disturbances at this critical point can trigger a collapse from free flow to synchronised flow, ultimately leading to congestion. This aligns with dissipative structures generated at the unstable critical point during the transition from order to disorder.

Figure 1 shows that the traffic reaches a critical value at the capacity state that may trigger the F-S phase transition. The traffic flow state may undergo a phase transition at any time, i.e. [ρ_{min}, ρ_{max}], the density interval range. The micro-behaviour of vehicles leads to this state being a substable state far from the equilibrium state. The capacity is close to the maximum value when the expressway traffic enters the dissipative structure. In this respect, the capacity state conforms to the description of the dissipative structure. However, dissipative structures represent a stable state; thus, there is still a distinction from the traffic capacity state. Further delineation of the range of dissipative structure states needs to be accomplished through empirical data.

2.2 Data collection

This study requires two sets of traffic data, one for analysing the critical states of dissipative structures and another for model simulation validation.

According to the research objectives, it is necessary to acquire typical traffic flow data covering various traffic states for accurate theoretical analysis. To achieve this, we obtained the traffic flow data for the Whitemud Drive (WMD) expressway provided by the Intelligent Transportation Systems Research Center at the University of Alberta, Canada [24]. This dataset includes flow, speed and density information and was primarily used to delineate the dissipative structure range in the weaving area of expressways. The specific study segment is located at the circular detector VDS1018 in the east-to-west direction of Whitemud Drive (WMD), as depicted in *Figure 2*. There is a right-side entrance ramp upstream and a left-side exit ramp downstream at Terwillgar Dr. The segment maintains a consistent three-lane configuration throughout its length, with each lane equipped with detectors. The dataset covers traffic flow, speed and density data from 5 to 27 August 2015. To investigate the traffic flow phase transition process, 24-hour flow data is analysed, and a specific day with significant peak flow variations is selected. The speed variations on that day are then analysed, and monitoring points where traffic congestion occurs are identified based on the time-varying speed chart. This dataset's maximum flow rate for a single lane is approximately 2430 vehicles per hour. The directional Annual Average Daily Traffic (AADT) was as high as approximately 100,000 vehicles.

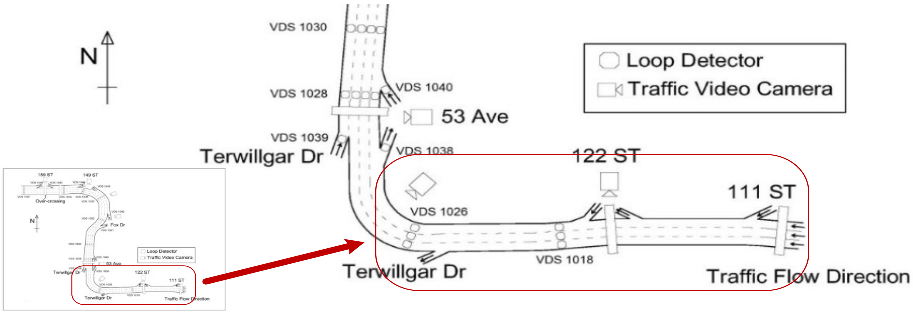


Figure 2 – Whitemud Drive study section

A drone near Qimen Road on the North-South Expressway in Hefei, China, collected the second dataset (DNSE1). Speed, density and flow data were extracted using the Tracker video tracking software. Each drone flight lasted a maximum of 15 minutes. *Figure 3* shows this expressway segment includes a 450-meter-long weaving area with three lanes and first-in and last-out ramps. Data collection occurred during the morning and evening peaks on three precise weekdays in October 2021. The observation time spanned 30 minutes before and after the morning and evening peaks to capture saturated conditions. The observation periods were from 7:00 a.m. to 9:00 a.m. and 4:30 p.m. to 7:00 p.m.

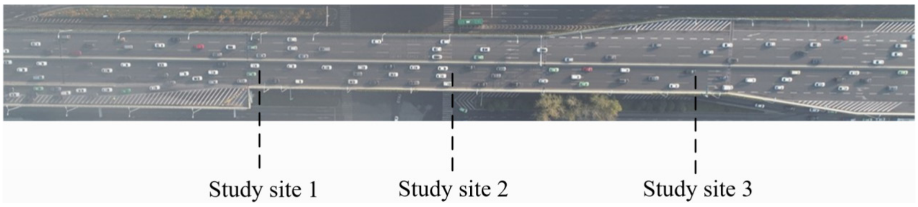


Figure 3 – Data collection scene

The collected data was subjected to analysis, with the weaving section divided into three survey points: the entrance ramp (study site 1), the weaving bottleneck (study site 2) and the exit ramp (study site 3). During the data processing, datasets exhibiting pronounced peak flow variations were selected as input data for subsequent model validation. The morning peak period extended from 7:45 a.m. to 8:30 a.m., with the maximum flow reaching nearly 6800 veh/h. The evening peak period occurred from 5:15 p.m. to 6:30 p.m., with the maximum flow approaching 5600 veh/h, and the post-peak flow levelled off to approximately 2600 veh/h. These periods encompassed a comprehensive transition in traffic states from free flow to synchronised flow. The congested synchronised traffic state persisted for approximately 30–45 minutes.

2.3 Research result

We investigated the relationship between the conditions for forming traffic flow dissipation structures in expressway weaving areas based on WMD freeway traffic data and three-phase traffic flow theory. The results of the analysis show that the WMD data's flow-density relationship remains generally consistent with that described by the three-phase traffic flow theory. *Figure 5* reveals that when density is lower than 16 veh/km, speed is hardly affected by the growth in density, maintaining around 80 km/h. At this point, the density is considered as ρ_{th}. As the density approaches the minimum critical density ρ_{min}, approximately 25 veh/km, there is a slight decrease in speed, but it remains relatively high. It can be observed that as the density exceeds the minimum critical density ρ_{min}, shown in *Figure 4*, the increase in flow rate does not decrease. At this point, the maximum flow rate for a single lane can reach 2430 veh/h, but the fewer scattered data points near the maximum flow indicate an unstable state. The traffic state gradually undergoes a phase transition, and the density and traffic volume passing through each sub-interval in extremely small time intervals cannot be maintained at a stable value. This suggests the presence of minor perturbations in traffic parameters, i.e. fluctuation effects.

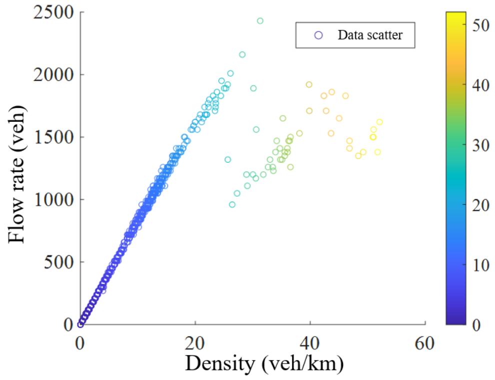


Figure 4 – Flow and density diagram

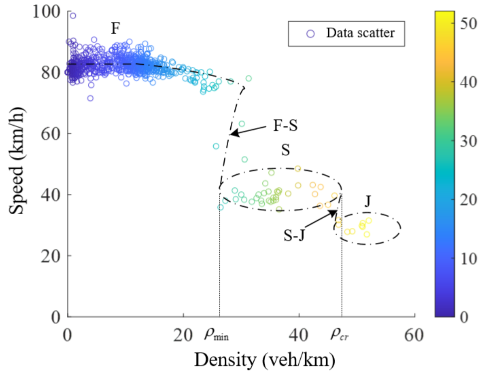


Figure 5 – Velocity and density diagram

In this period, the number of input vehicles is greater than the number of output vehicles at both ends of the weaving area, the entropy flow from the outside world is positive and the entropy value of the road section increases, which makes the traffic state move towards the direction of disorder, and the likelihood of congestion is elevated. Traffic parameters before the minimum phase change density are characterised by near-maximum capacity, high speeds and low densities until a certain lower threshold of density is reached ρ_{th}, where the traffic state is at the desired level. At this time, the vehicle increment in the weaving area should tend to zero, the entropy value obtained by the road section from the outside world, i.e. the negative entropy flow brought about by the vehicles flowing into and out of the road section, and the entropy generation brought about by the micro-behaviour of the vehicles inside the road section are just offset, and the road section is in a non-equilibrium steady state.

Self-organised criticality implies the existence of a critical state where the traffic flow undergoes a phase transition. This critical state is a dissipative structure, and in this study we define it as a dissipative structure state before congestion formation. Through the analysis, the traffic dissipative structure state should be the traffic state where free flow has not undergone phase transition and is close to the phase transition threshold. The traffic density interval is $[\rho_{th}, \rho_{min})$ which is a state of high speed, low density and high flow rate, in which flow rate is similar to that of the state that enters synchronised flow. However, speed differs from synchronised flow, and the traffic delay of the expressway's mainline traffic in the dissipative structure's state is much smaller than that of the synchronised flow state.

The analysis of the WMD data can only show that the expressway weaving area has dissipative structural properties. However, observing the phase transition alone often does not comprehensively explain the underlying mechanism. Therefore, relevant models are needed to describe the relationships of the system's internal structure.

2.4 Modelling of dissipative structures in the weaving areas

Analysing the dynamic behaviours of congestion formation and dissipation in traffic systems utilised the three-phase traffic flow theory. However, this remains conceptual, and there is a need for fundamental models to comprehend these dynamic behaviours. The triangular fundamental diagram is a visual representation associated with measurable traffic variables, approaching three-phase behaviour while defining functional relationships between traffic parameters. It supports traffic flow analysis and modelling. It is worth noting that some studies have revealed the self-organised criticality of the movement wave models in the transition region between free flow and congestion, as well as many other related traffic models [16]. This further advances our work.

For the dissipative structure analysis, we will consider the system's internal and external energy dissipation to evaluate its state. In the expressway weaving area system, the traffic flow in and out of the system is considered the exchange of internal and external energy, and the upstream, downstream and on-ramp vehicle movements in and out are regarded as the input and output of energy. By studying the change in traffic volume per unit of time, we can understand the energy changes within the system. Since the weaving area dissipative structure contains nonlinear dynamical processes such as positive and negative feedback mechanisms, it keeps the transportation system in a non-equilibrium state. Therefore, we take a single weaving area section of an expressway as an example to analyse the effect of the net increment of the section on the traffic density as well as the feedback effect of the traffic density on the net increment of the section [21]. A model of the weaving area dissipative structure is then constructed to describe the interrelationships between the change of traffic volume and the change of traffic state in the weaving area. The total amount of traffic in the weaving area is shown in *Equation 1*.

$$Q = Q_0 + \Delta Q + \Delta Q^{'} \tag{1}$$

where: Q is the total amount of traffic in the weaving area; Q_0 is the initial traffic in the weaving area; ΔQ is the incremental traffic on the mainline in the weaving area [$\Delta Q= q_2-q_1$]; $\Delta Q'$ is the traffic on the ramp where the expressway exchanges traffic with the general urban road [$\Delta Q'=q_{out}-q_{in}$]; q_1 and q_2 are the volumes of traffic driving into and out of the weaving area, respectively [*pcu/h*]; q_{in} and q_{out} are the traffic volumes on the entrance and exit ramps, respectively [*pcu/h*].

Equation 1 is derived from time t, $Q=l\rho$, where Q denotes the total amount of traffic on the roadway in unit time to reflect the fluctuation of roadway state caused by the change of traffic volume, which can better estimate the dissipative structure. ρ denotes the traffic density on the roadway in unit time, l is the length of weaving area. The unit time is selected as 5 minutes in this study. The derivation is shown in *Equation 2*.

$$\frac{d\rho}{dt} = \frac{d\Delta Q}{ldt} + \frac{d\Delta Q^{'}}{ldt} \tag{2}$$

Equation 2 expresses a positive correlation between flow and density growth, with roadway densities increasing as net traffic growth increases.

It is worth noting that there is also a feedback effect of traffic density on roadway flow. The traffic volume on the mainline in the weaving area can be expressed as the difference between the traffic volumes at the two ends. At the same time, the upstream and downstream capacities are limited by the weaving area. As shown in *Figure 6*, $Q=V_f \rho_c$ is obtained by branching through the left side of the triangulation diagram, $Q=w(\rho_{jam}-\rho_c)$ through the right side of the branch and $Q=wV_f \rho_{jam}/(w+V_f)$by combining them to represent the capacity of the weaving area when the traffic state enters the dissipative structure. Based on the principle of minimum entropy generation, the traffic flow in the interweaving area forms a non-equilibrium steady state. The increment of vehicles in the road section tends to be close to zero, so the net traffic increment of the main line can be expressed as a result of the weaving area traffic dissipation structure state. Taking the first-in-last-out weaving area as an example, the increase in traffic volume on the main line is shown in *Equation 3*.

$$\Delta Q = \frac{wV_f \rho_{jam} t}{w + V_f} = vt\rho \tag{3}$$

Where: V_f is the free flow speed [*km/h*], ρ_{jam} is the blockage density [*pcu/h*], w is reverse wave speed in blocked condition [*km/h*].

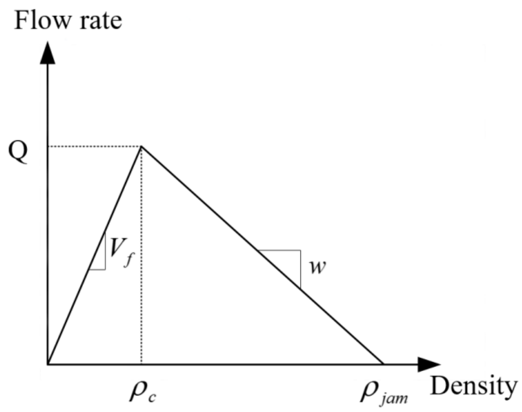
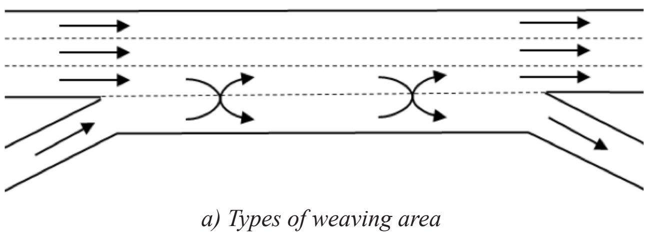


Figure 6 – Traffic flow fundamental diagram

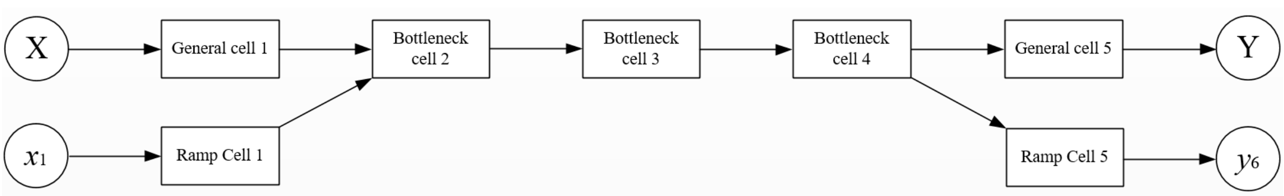
After considering the growth effect of net flow increment on density and the inhibition effect of density on flow increment, we obtain a model of the traffic dissipation structure in the urban expressway weaving area, as shown in *Equation 4*. The first equation represents the reflection of roadway traffic density on changes in roadway net gain, and the second equation represents the relationship between roadway net gain and traffic parameters when the roadway is at near-maximum capacity. *Equation 4* can calibrate the relevant range of traffic parameters by substituting traffic data. In addition, it can be observed from the second equation that the time variable t is not explicitly included in the equation, which indicates that the weaving area system is self-organising.

$$\begin{cases} \frac{d\rho}{dt} = \frac{d\Delta Q}{ldt} + \frac{d\Delta Q^{'}}{ldt} \\ \frac{d\Delta Q}{dt} = \frac{wV_f \rho_{jam}}{w+V_f} - v\rho \end{cases} \tag{4}$$

After analysing and modelling the dissipative structure in the weaving area of expressways, a series of simulation experiments is necessary to validate and further explore the accuracy and practicality of the model. To analyse the dynamic characteristics of the dissipative structure, we will employ the Cell Transmission Model (CTM) proposed by Daganzo [25]. The CTM represents roads as a series of homogeneous cells and uses discrete time steps to simulate the propagation of traffic density between cells. This allows incorporation of boundary conditions, shock waves and dispersion effects into the model's traffic flow dynamics. The CTM provides a suitable theoretical framework for evaluating dissipative structure models in the context of complex traffic flow behaviour.



a) Types of weaving area



b) Simulation scene

Figure 7 – Schematic diagram of weaving area simulation scene

3. SIMULATION FRAMEWORK

3.1 Simulation scenario

According to the capacity of different expressway sections, the cell types are categorised into general cells, bottleneck cells and ramp cells, and the simulation scenario is shown in *Figure 7*. The model is validated using DNSE1 traffic flow data as the basis. The expressway simulation scenario [25] contains an entrance ramp cell and exit ramp cell. The weaving area is divided into three cells according to the length of a single cell, defining the expressway mainline as three lanes, the entrance and exit ramps as a single lane, the length of a single cell as 150 meters, the simulation time-step length as 10 seconds, and the initial flow share of entrance and exit ramps as 0.2.

Table 1 – Verification results of the simulation model in dissipative structure state

Study site	1	2	3	Mean
Measured speed（km/h）	51.16	53.07	52.83	52.35
Simulation speed（km/h）	52.57	54.49	50.72	52.59
Relative error（%）	2.76	2.68	3.99	3.14
Measured flow rate（veh/h）	5126	5024	5282	5144
Simulation flow（veh/h）	5265	5309	5388	5321
Relative error（%）	2.71	5.67	2.00	3.46

During the model validation process, we conducted a simulation of 720 time steps. In the first 360 time steps, we input off-peak traffic flow data to preheat the simulation model, allowing it to adapt to the model and initial parameter settings. Specifically, the model was considered stable when each cell's density variation between consecutive time steps was below 5 vehicles/km. This criterion indicated that the model had adapted to the initial conditions, and the traffic flow in the network reached equilibrium, enhancing the reliability of the simulation. In the subsequent 360 time steps, we input the processed data from the DNSE1 for simulation to replicate real traffic conditions. Throughout the simulation, we used MATLAB to establish functions for the dissipative structure model in the weaving area and functions for determining dissipative structure states. These functions were associated with the net traffic increment between bottleneck cells, calculating their impact on density. Subsequently, we substituted the calibrated traffic parameters into the model to calculate bottleneck cells' velocity and density values in a stable state. Through simulation, we obtained results for velocity and flow at various sections under different states, including those determined by the dissipative structure model and the dissipative structure density range. We conducted a relative error analysis by comparing the simulation results with the measured data.

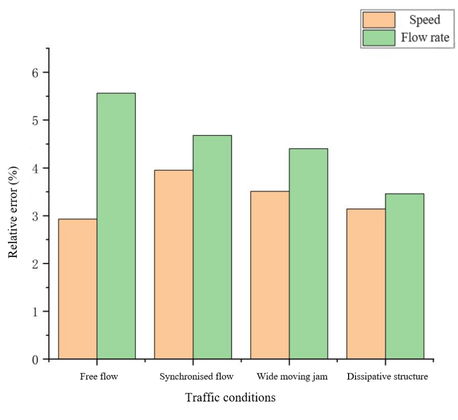


Figure 8 – Comparison of the average relative error of speed and flow in different traffic flow states

The simulation results for velocity and flow at various sections under different states are well-fitted to the measured data. Notably, the dissipative structure state determined by the dissipative structure model in the weaving area has a relative error with the measured data consistently below 5%, confirming the effectiveness of the dissipative structure model in delineating dissipative structures, as shown in *Table 1*. *Figure 8* compares the average relative errors in velocity and flow for each traffic state, all below 10%, further confirming that the CTM model can effectively simulate the actual traffic flow conditions and allow for detailed simulation analysis of dissipative structure characteristics in the weaving area.

4. RESULTS

4.1 Relationship between dissipative structure and weaving length

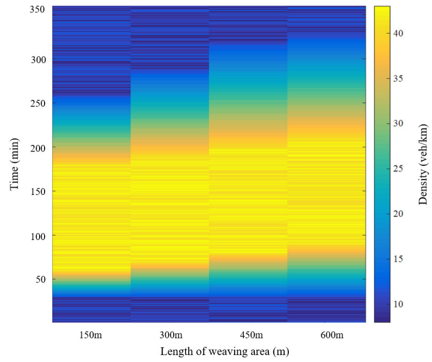


Figure 9 – Schematic diagram of congestion propagation in the weaving area under different weaving length

During the validation phase, the effectiveness of the CTM and dissipative structure models in the weaving area was confirmed. The weaving flow ratio in the weaving area rarely rises above the range of 0.4 [5], and we fix the weaving flow ratio to 0.15, ensuring equal flow at the exit and entrance ramps. The weaving flow ratio is the ratio of weaving flow to total flow, representing a crucial parameter describing the operation of traffic flow weaving. Combining the triangulation diagram considerations of classical simulation input of peak traffic demand [26], the formation and dissipation of dissipative structures were observed and estimated. Simultaneously, the variation of traffic dissipative structures under different lengths of weaving areas was studied. *Figure 9* illustrates the propagation of congestion in the weaving area under different lengths, where the vertical axis represents time steps, and the horizontal axis represents different lengths of the weaving area.

In *Figure 9*, the green area indicates that the density of the weaving area is in the dissipative structure interval. We can observe that congestion generation is significantly faster than evacuation in the weaving area environment with different lengths. The emergence time of dissipative structures is significantly longer than congestion evacuation in congestion generation. As the length of the weaving area increases, congestion generation and congestion evacuation become slower, and dissipative structures appear for a longer time. It is because the speed of traffic wave transmission becomes slower in longer weaving areas, which suggests that congestion is more difficult to generate in longer weaving areas and quickly returns to normal traffic flow once roadway congestion occurs. These observations emphasise the importance of the length of the weaving area on the congestion generation and evacuation process, as well as the emergence of dissipative structures.

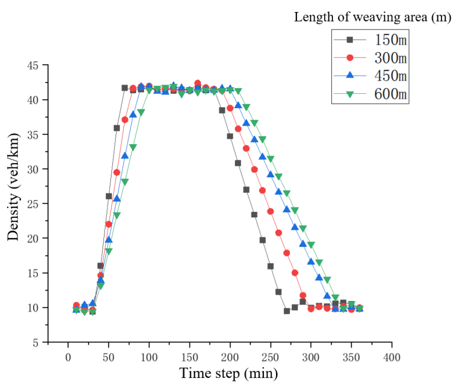


Figure 10 – Density variation at different weaving lengths

In order to study the relationship between the length of the weaving area and the traffic flow state more deeply, we created the density variation graphs under different lengths of the weaving area. Based on the observations in *Figure 10*, we can find a fundamental proportionality between the congestion generation and evacuation speeds of the weaving area and the length of the weaving area. All other things being equal, as the length of the weaving area increases, the time required for the change in the traffic flow state increases accordingly, which means that the speed of congestion formation and relief is proportionally delayed.

We further counted the length of time that the dissipative structures appear during congestion generation and evacuation and plotted the relationship with the length of the weaving area, as shown in *Figure 11*. As the length of the weaving area increases, the length of time for the generation of dissipative structures shows a significant upward trend, both for congestion generation and congestion evacuation. It is verified that there is a positive correlation between the length of the weaving area and the degree of health status of the traffic flow. This result emphasises the vital influence of the length of the weaving area on the congestion generation and evacuation processes and the emergence of dissipative structures.

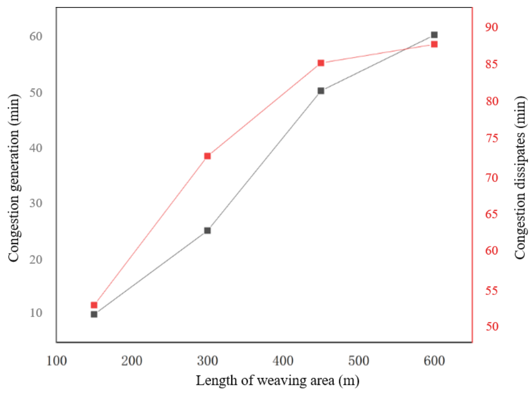


Figure 11 – Relationship between the time of dissipative structure and the length of a weaving area

4.2 Relationship between dissipative structure and weaving flow ratio characteristics

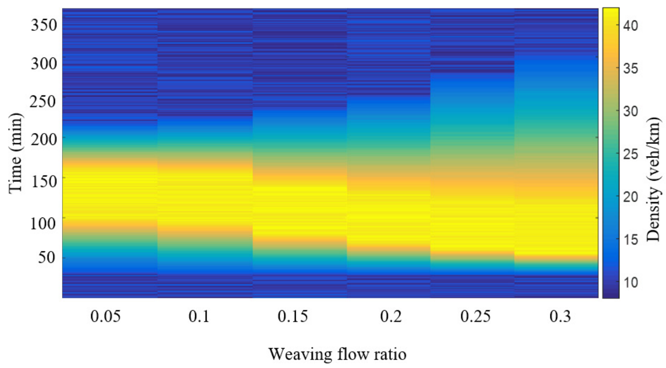


Figure 12 – Schematic diagram of congestion propagation in the weaving area under different volume ratios

To explore the relationship between the dissipative structure and the weaving flow ratio and to get the congestion of the weaving area with different weaving flow ratios, as shown in *Figure 12*, the length of the weaving area is limited to a universal average length of 450 m, the weaving flow ratio is respectively set to 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, and the default entrance and exit ramps have the same flow rate. The horizontal coordinate indicates the length of the time step, and the vertical coordinate indicates the weaving area with different lengths.

It is clear from *Figure 12* that higher weaving flow ratios will result in faster congestion formation and slower congestion dissipation. This is because as the ramp inflow flow ratio increases, the impact on the mainline traffic flow rises as well. Interestingly, unlike the previous section, dissipative structures may not appear more during congestion dissipation than during congestion generation. For example, when the weaving flow ratio is 0.05, the time for dissipative structures to appear during congestion generation and dissipation is essentially the same, mainly because, in this case, the weaving behaviour has a tiny perturbation on the traffic state.

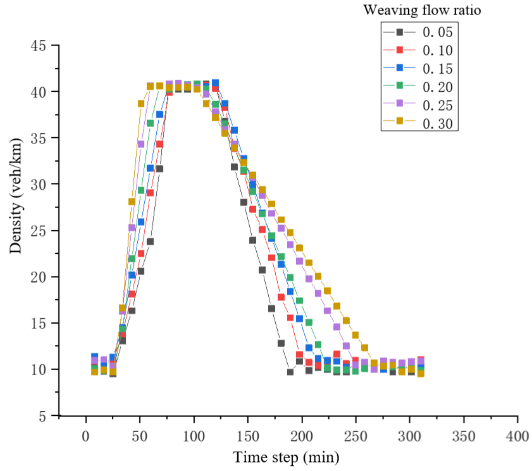


Figure 13 – Density variation at a different volume ratios

Figure 13 shows the relationship between the traffic flow state in the weaving area and the weaving flow ratio. Unlike the case of the length of the weaving area, the density grows relatively slowly when the weaving flow ratio is low. As the weaving flow ratio gradually increases, the density grows gradually faster and not in equal proportions. This suggests that the weaving flow ratio has a greater impact on the capacity of the weaving area, and its increase leads to a significant increase in the density growth rate.

Figure 14 counts the traffic dissipative structure state durations for congestion generation and evacuation. As the weaving flow ratio increases, the dissipative structure state duration decreases continuously during congestion generation, while the exact opposite is true during congestion evacuation. This is because the traffic flow state changes faster in congestion generation, and the dissipative structure state keeps appearing and disappearing, so the duration is relatively short. While in congestion evacuation, the traffic flow state changes more slowly, so the traffic flow stays in the dissipative structure state for a longer time.

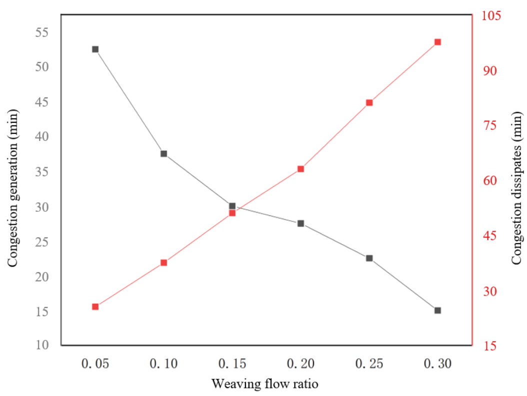


Figure 14 – Relationship between the time of dissipative structure and the volume ratio

5. DISCUSSION

The traffic flow in the weaving area exhibits characteristics of dissipative structures. By studying the dissipative structure states in the weaving area and constructing a dissipative structure model, a deeper understanding of the dynamic balance relationships among traffic parameters can be gained. Additionally, insights into the relationship between dissipative structures and static traffic parameters can be obtained. This conceptual understanding provides a new perspective on traffic congestion and theoretical guidance for engineering applications in the static configuration of weaving areas.

The WMD data validates the characteristics of the three-phase theory in the traffic flow in the weaving area, accurately capturing the congestion formation and dissipation processes. It confirms that the three-phase traffic flow theory provides an appropriate analytical granularity for studying the dissipative structure properties of traffic flow near critical points. When the traffic flow reaches the critical value of 2000 vehicles per hour, oscillations and fluctuations begin to appear, indicating the presence of fluctuations in the weaving area. Beyond a specific density threshold, the fluctuation effect triggers the self-organisation of vehicles, driving the system toward a critical state. This explanation aligns with the conclusions of the literature [22] from the perspective of dissipative structures.

The length of the weaving area and the weaving flow ratio are critical factors influencing traffic states. As the length of the weaving area increases, its self-organisation ability improves, and the duration of the dissipative structure state also increases. This finding aligns with prior research, which considers the weaving length a key determinant of service levels [7]. Increasing the length of the weaving area proves to be an effective strategy for alleviating traffic congestion, resulting in higher vehicle speeds and throughput [27]. It is worth noting a distinction from [6, 7], as our study goes beyond exploring the impact of interweaving length on the capacity to evaluate the dynamic characteristics of the weaving area. We uncover how different lengths exhibit varying resistance to traffic fluctuations and disturbances, providing new insights into the dynamic management of weaving areas.

Simulation results indicate that when the length of the weaving area exceeds 300 meters, the dissipative state during congestion generation and dissipation can be sustained for at least 30 minutes, demonstrating sufficient recovery capacity. As the length surpasses 450 meters, the growth rate of the duration of the dissipative structure state gradually diminishes, aligning closely with the conclusions in [6]. When the length falls below 300 meters, the duration of the state decreases to less than 25 minutes, implying a susceptibility to bottlenecks [28]. Urban traffic networks, irrespective of congestion scale in time and space, exhibit similarities in duration and relief processes, showcasing resilience against disturbances of varying magnitudes [15]. Therefore, to resist disruptions in traffic flow, the minimum weaving area length should fall within 300–600 meters. Considering that only 60% of the weaving segment length is utilised for weaving under free-flow conditions [29], and longer weaving lengths induce more lane-changing behaviours, making vehicle behaviour more complex [4], a length of 450 meters is considered optimal.

One of the core tasks in managing congestion on expressways is establishing a resilient traffic system in the weaving area. This system should adapt to various traffic disturbances, aiming to avoid congestion as much as possible or recover quickly from congestion. Some weaving area models primarily investigate the relationship between static and dynamic parameters of the weaving area as independent variables and capacities [4, 5, 30]. In contrast, the dissipative structure model of the weaving area can more profoundly characterise the positive and negative feedback interactions between traffic volume changes and density. Most controls are adjusted through empirical parameters. The dissipative structure model can be integrated with detection systems to predict impending flow bottlenecks near state boundaries for different scenarios and take proactive control measures. With an increase in the weaving flow ratio, the duration of the dissipative structure state during congestion generation continuously decreases, while it behaves oppositely during congestion dissipation. Consistent with the results of the HCM2016 study, when the weaving flow ratio is between 0.15 and 0.2, the dissipative structure state can sustain for more than 25 minutes during the formation and dissipation of congestion, effectively resisting the impact of peak hours. This implies that effective control strategies should be adopted to maintain traffic within the ideal dissipative structure state range and enhance the resilience of the weaving area.

6. CONCLUSION

In this study, we employed the three-phase traffic flow theory and the self-organised dissipative structure theory to investigate the characteristics of dissipative structure states in weaving areas. We constructed a dissipative structure model for weaving areas and explored the relationships between the duration of dissipative structure states, weaving area length and the weaving flow ratio. The results indicate that the three-phase traffic flow theory can conceptually analyse the dissipative structure characteristics of weaving areas on expressways. We define the dissipative structure state as the density interval $[\rho_{th}, \rho_{\min})$ with high-speed, low-density flow occurring before the phase transition of free flow. Simulation results from the dissipative structure model of weaving areas revealed that with an increase in weaving area length, the speed of congestion generation and dissipation slows down, and the duration of dissipative structure appearance becomes longer. When the weaving area length is set between 300 and 600 meters, the congestion generation and dissipation times are consistent. They can be maintained for at least 30 minutes, demonstrating good resistance to peak periods. Furthermore, as the weaving flow ratio increases, the duration of dissipative structure states during congestion generation decreases, while during congestion dissipation, it exhibits the opposite trend. Controlling the weaving flow ratio between 0.15 and 0.2 effectively maintains the traffic state in weaving areas. These findings contribute to a deeper understanding of the dynamic characteristics of weaving areas and offer insights for formulating effective traffic management strategies.

This study defines the unstable high-flow state before congestion in the weaving area from the perspective of dissipative structures, providing new insight into analysing weaving area flow bottlenecks. The weaving area dissipative structure model elucidates the feedback mechanisms behind phase transitions, expanding the theoretical foundation of traffic flow behaviour and contributing to improving the stability and robustness of prediction and control systems. The relationship between geometric structure and dissipative structure states can guide the design of weaving area lengths for different requirements in traffic engineering construction. In the future, incorporating the dissipative structure model into active traffic control systems can predict impending flow bottlenecks near state boundaries and take proactive control measures, providing theoretical guidance for constructing a flexible weaving area traffic control framework.

Indeed, this study has some limitations. Using a simplified triangular fundamental diagram to describe the relationship between traffic parameters during dissipative structure states may only capture some of the complexities of real-world situations. Future research could consider employing more sophisticated models for a more comprehensive analysis. Additionally, the geographical variations and limited time span of the data could impact the generalisability of the findings. Future studies should aim for extensive, long-term data collection to address these limitations.

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快速路交织区交通流的耗散结构特性

摘要：
快速路交织区满足耗散结构特性，当交织区交通状态达到一定范围时，会表现出自组织临界性，轻微的变化可能会引发突然而不可预测的交通拥堵。研究探讨了交织区的耗散结构和关键交通参数之间的相关性。通过自组织理论的耗散结构概念与三相交通流理论，结合真实交通数据定义了交织区耗散结构状态范围。基于三角基本图和实测交通数据，构建并验证了表征交织区耗散结构状态时交通量变化关系的交织区耗散结构模型。最后，通过仿真实验的方法，使用了元胞传输模型和交织区耗散结构模型考察了交织区耗散结构状态的形成和消散时长与交织区长度和交织流量比这两个关键参数之间的特性关系。结果表明，交通流自组织为自由流状态与拥堵状态时保持的耗散结构状态时长与交织区长度呈正相关，较高的交织流量比导致耗散结构状态时长在拥堵形成时更短，拥堵疏散时则完全相反。本研究对于采用新范式理解交通拥堵的原因以及交通工程建设制定控制策略具有重要的实际意义。

关键词：城市快速路;耗散结构;交织区;交织区长度;交织流量比;拥堵持续时间