A REVIEW ON TRAFFIC FLOW THEORIES FOR WATERWAY TRANSPORTATION: CONSTRAINTS AND THE WAY FORWARD

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ABSTRACT

Traffic flow theories, based on physical and empirical traffic system evidence, have evolved to explain the complex interaction among the system's components making it more efficient. The kinematic wave theory, among these, is the most prominent one to explain the macroscopic relationship. Fundamental diagram is such an essential relationship among flow, density, and speed parameters' representing the critical interdependency of the road traffic system. In recent years, many researchers have begun to exert efforts to apply traffic flow theory in developing the approaches to solve waterway transportation problems. The aim of this study is to review the progress and challenges encountered in applying traffic flow theory and developing fundamental diagram for waterway traffic flow. It is worth mentioning that there are several inherent differences in characteristics between the roadway and waterway transportation modes. Unlike road traffic, the waterway traffic are usually larger in size, requires longer perception-response times, moves with lower speeds, and faces congestion rarely. Furthermore, the road traffic follows a predefined lane, and uses the concept of Passenger Car Equivalent (PCE) which is crucial to develop the fundamental diagrams -those are not yet addressed for analyzing water traffic flow. Nonetheless, the findings of several contemporary studies suggest that the outcomes of traffic flow analysis for simple waterway traffic settings matches mostly with that of road traffic. Apart from revealing relationship among speed, flow and density- the three basic traffic variables, determining the capacity and Level of Service (LOS) of the corresponding waterway have also been performed by a number of studies. However, investigations over several intricate issues on waterway traffic such as vessels' movement in both directions and multifaceted scenarios at intersections have not been performed yet. In this context, the variations between the fundamental diagrams of roadway and waterway traffic merit more comprehensive investigation. Finally, this study concludes by highlighting the contemporary research gaps and proposing future directions for developing a robust theoretical basis for waterway traffic flow.

Keywords: *Traffic flow theory, Fundamental diagram, Waterway traffic, Traffic capacity, Level of Service*

1. INTRODUCTION

The Traffic flow theory investigates the dynamics of traffic flow to ensure safer and efficient transportation (Ni, 2015). It uses mathematical relationships between key traffic variables to model the traffic behavior with an aim to reducing congestion and improving safety. The steps of applying this theory includes the collection of vehicle movement data, selection of traffic lanes, generation of spatio-temporal trajectory diagram, computation of traffic flow characteristics, and plotting the fundamental diagram (Edie, 1963). The fundamental diagram is termed as the core component of the traffic flow theory. Its application mainly involves in determining the capacity of a transportation network, assessing congestion level and so on.

The traffic flow theory was developed in 1930s and then started to apply in road transportation extensively. Apart from analyzing behavior of motor-vehicle on roadway, this theory has also been successfully applied in other fields of transportation including railway traffic, airport surface traffic, bicycle and pedestrian flow (Diaz & Dick, 2021; Yang et al., 2017; Botma, 1995; Hughes, 2002). The key similarities and dissimilarities among different modes of transportation are illustrated in Table 1.

Table 1: Similarities and dissimilarities among different modes of transportation, reproduced from Zhuang et al. (2024c)

Traffic Classification	Traffic Organization Mode			
Cars	Self-organizing	Free competition	Driver takes control	Traffic rules
Bicycles	Self-organizing	Free competition	Driver takes control	Traffic rules
Pedestrians	Self-organizing	Free competition	Driver takes control	Traffic rules
Trains	Schedule/Management	No free competition	Center control	-
Aircraft	Schedule/Management	No free competition	Center control	-
Small Unmanned Aircraft	Self-organizing	Free competition	Driver takes control	-
Vessels	Hybrid	Hybrid	Hybrid	Traffic rules

Recently, researchers have started to apply the concept of this theory to waterway traffic due to growing challenges on solving congestion related problems, and improving efficiency of waterway transportation network (Seong et al., 2012; Tasseda & Shoji, 2015; Huang et al., 2019). However, some basic differences between the roadway and waterway traffic are posing some notable challenges. In waterway, there is no physical lane line, and the speeds of vessels are considerably slower than vehicles on road. Moreover, stopping and maneuvering a vessel to a certain direction cannot be performed instantaneously. In addition, developing a standard framework similar to the Passenger Car Equivalent (PCE) used in road traffic is still far away to be harnessed for the waterway traffic. These factors along with many other crucial issues had created constraints to develop fundamental diagram for waterway traffic. However, researchers have started to apply the traffic flow theory in waterway and have been achieving satisfactory results. Although, the scenarios of waterways under those investigations were simple and uncomplicated, hence, more comprehensive studies are required at busy channels and waterway intersections to have a better outcome. Nonetheless, the progress made so far on this research domain is still convincing.

Analysis of traffic flow on waterways is an evolving topic. This review study has incorporated all research articles identified by exploring the well-recognized scholarly databases. At first, the authors explored the research articles by searching through the keywords to select a number of relevant articles and extract their findings. Subsequently, the keywords from those articles are searched again to identify additional articles, and extract their findings. It is crucial to mention here that, primarily the authors had the intention to go for a systematic review for this study. However, due to the limited number of available studies on the topic, this approach was not feasible. Consequently, a hybrid review strategy was adopted, combining the approaches of narrative review and general review. Out of 38 reference documents cited in this study, 22 are specifically related to the waterway traffic flow. It is also revealed that most of the studies are being conducted on micro-level of traffic movement on waterway till now. Besides, almost all studies incorporated empirical method for unidirectional traffic setting on straight section of waterway. Furthermore, it was found that only one review paper is available on the waterway traffic flow theory. Though, there have been tremendous advances in application of traffic flow theory on waterways in the last couple of years, which were not included in any review study. Against this backdrop, the findings of these recent research papers have been incorporated in the current study. The main objective of this study is to investigate the key challenges of applying roadway traffic flow theory to waterways by reviewing the contemporary applications in waterways. In addition, identification of research gaps and recommendations for future research will also be outlined at the end of the study.

2. FUNDAMENTAL CONCEPT OF TRAFFIC FLOW THEORY

Traffic flow theory provides a rigorous mathematical and empirical framework to comprehend the phenomenon of traffic movement through transportation networks. The relationships among three basic traffic variables i.e. speed, density, and flow rate are illustrated in Figure 1. The Highway Capacity Manual (Highway Capacity Manual, 2022) defines speed as the distance per unit time, flow rate as the number of vehicles passing a fixed location per unit time, and density as the number of vehicles found in a specific segment of roadway at a particular moment. Bruce D. Greenshields is regarded as the pioneer in developing a traffic flow model by revealing these relationships in 1934 (Greenshields et al., 1934). Later on many other models were developed among which Greenberg's model (Greenberg, 1959), Underwood's model (Underwood, 1961), and Pipes' model (Pipes, 1967) are noteworthy. It is worth mentioning that these four models represent four distinct relationship (among the variables) patterns i.e linear, logarithmic, exponential, and power patterns respectively (Kang et al., 2018).

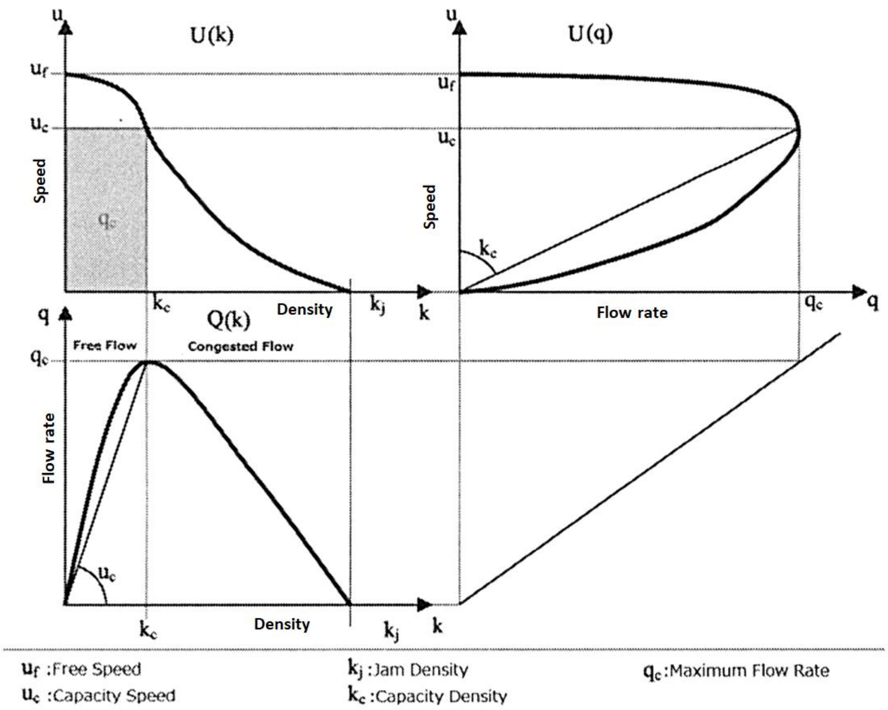


Figure 1: Fundamental Diagrams of Traffic flow, adapted from Tasseda & Shoji (2015)

Traffic flow models are generally categorized into three main categories, such as microscopic models, mesoscopic models and macroscopic models (van Wageningen-Kessels et al., 2014). Microscopic model investigate the individual behavior of each vehicle, including the lane-changing and following behaviors. This model includes a leading vehicle and a number of following vehicles. Each of the following vehicles will change or adjust its behavior according to that of the leading vehicle (Huang et al., 2019). On the other hand, the mesoscopic model represents traffic behavior in an aggregate form, i.e. probabilistic distributions like speed and density across the flow stream, and so on. In contrast, the macroscopic models consider traffic as a continuum flow by disregarding individual behavior of vehicles, and concentrate on aggregated variables such as average velocity and density (Huang et al., 2019). The kinematic wave theory is the most prominent macroscopic model applied to explain the complex relationship between the components of traffic system.

3. APPLICATIONS OF TRAFFIC FLOW THEORY IN WATERWAYS

This section will discuss the attempts so far on applying traffic flow theory or developing the fundamental diagram to investigate the waterway traffic flow. Moreover, the challenges encountered in explaining the results in line with the traffic flow theory of roadway will be presented as well.

A study by Fujii & Tanaka (1971) was the first to provide the basic concept of waterway traffic capacity from the Highway Capacity Manual. They discussed elaborately about the factors affecting the determination of capacity of a waterway channel. However, the study could not investigate relationship between the variables of traffic flow. Fischer et al. (2014) presented a dynamic microscopic model by simulating two-way heterogeneous traffic flow near a bottleneck on inland waterway, and applied the model to estimate capacities, assessed required fairway widths and depths, and provided recommendations for maximum-sized vessels. It was revealed that the capacity of a bottleneck in inland waterway is highly dependent on the fleet composition and the proportion of vessels moving downstream. However, the major limitation of the study was failure to validate the obtained results by real-world traffic data. Tasseda & Shoji (2015) performed a macroscopic assessment of vessel streams in three zones of the Tokyo Bay, and investigated the existence of constraints related to the three basic variables based on the concept of fundamental diagrams. The results indicated that the zone in which free flow and congested flow occurs, the shapes of fundamental diagram are nearly similar to that of standard fundamental diagram. However, in other two zones where speed restriction is imposed, the regular patterns of fundamental diagrams are not obtained. Qi et al. (2017) applied a microscopic traffic flow model based on cellular automata called Spatial-Logical Mapping (SLM) model to investigate the relationship between the flow rate and density of vessels. The study concluded that number of ships in waterway decreases with the increment of proportion of large ships. Furthermore, with the introduction of high-speed large-scale vessels on waterway, this relationship would serve in assessing traffic capacity based on the SLM model (Qi et al., 2017).

Kang et al. (2018) analyzed the Automatic Identification System (AIS) data of vessels at the fifteen legs of the Singapore Strait to generate the speed-density relationships by applying four well-recognized models i.e. Greenshields' stream model (Greenshields et al., 1934), Greenberg's logarithmic model (Greenberg, 1959), Underwood's exponential model (Underwood, 1961) and Pipes' generalized model (Pipes, 1967). It is worth mentioning that, these typical models are representative in describing the linear, logarithmic, exponential and power patterns respectively. Furthermore, a new weighted least square approach was employed for formulate the vessel traffic speed-density relationships in a precise way. The analysis revealed that ship speed and density are inversely proportional to each other, as depicted in Figure 2. However, the major limitations of the study were not establishing the relationships between speed-flow rate and density-flow rate, and neglecting the overtaking behavior of the vessels in the strait.

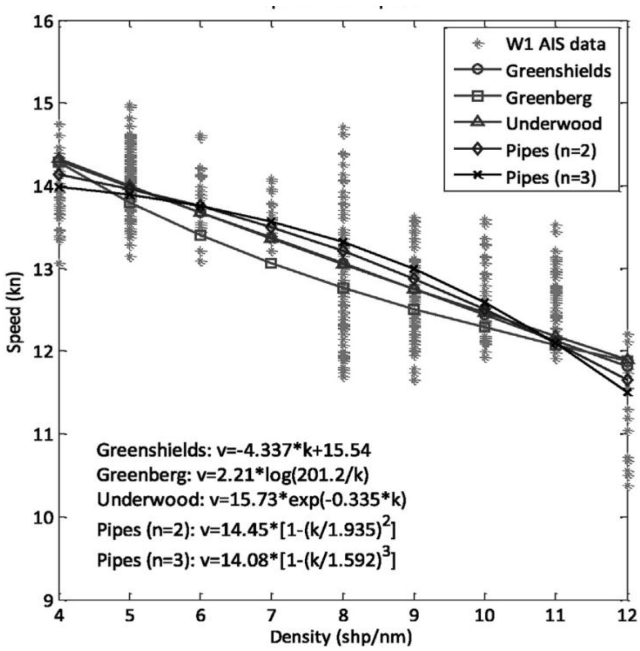


Figure 2: Speed-density relationship of vessels at leg W1 of Singapore strait, reproduced from Kang et al. (2018)

Liu et al. (2018) applied Edie's theory (Edie, 1963) of macroscopic traffic flow rate, density, and speed to propose a measurement technique of area-wide traffic flow characteristics of vessels in multi-directional maneuverable waterways with three-dimensional vessel trajectories. Moreover, the lower and upper bounds of the relation intervals are obtained by applying the modified Greenberg's logarithmic models- in which it is assumed that the speed-density relationship followed a particular constant in the free flow state. The results of the investigation showed that fundamental diagram obtained by considering area-wide vessel traffic exhibit almost similar configurations with the traffic on roadway, having a modification in interval instead of a robust curvilinear correlation- as depicted in Figure 3.

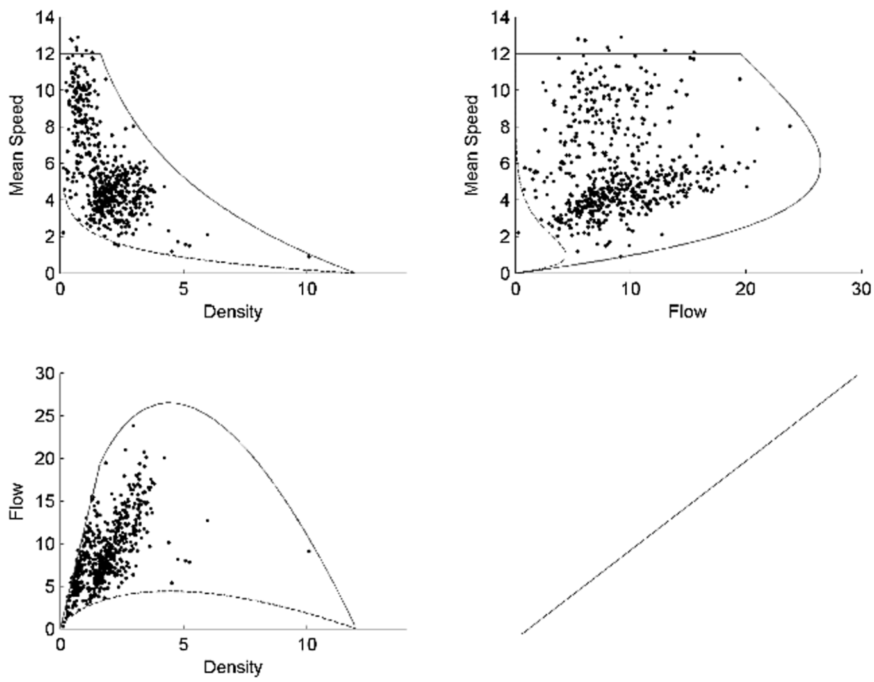


Figure 3: Depiction of relation models over fundamental diagrams, reproduced from Liu et al. (2018)

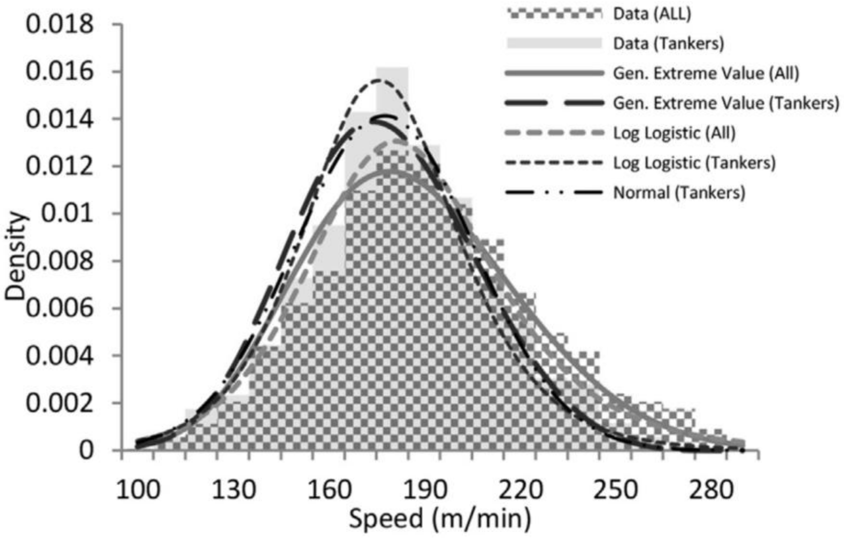
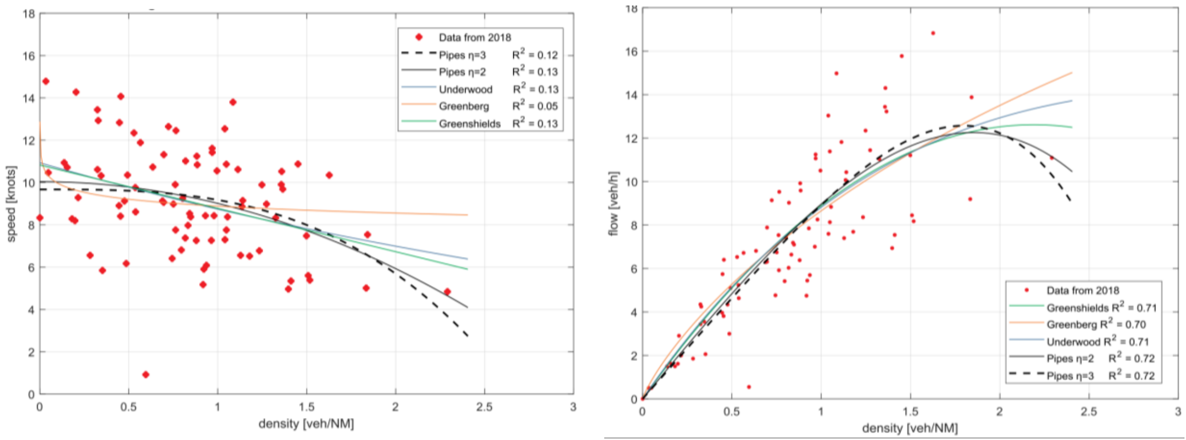


Figure 4: Speed-density relationship of vessels (histograms of the data and fitted distribution curves), reproduced from Wu et al. (2018)

Wu et al. (2018) investigated the microscopic travel behavior of vessels based on trips, rather than straightforward use of AIS reported data in narrow waterways. The analysis revealed an uncommon pattern of speed-density relationship- quite different from the typical inverse relationship, as outlined in Figure 4. It is evident that the speed is almost independent from the density indicating that the waterway does not experience severe congestion.

Huang et al. (2019) investigated the AIS traffic data of vessels in the Shanghai port area to compare the obtained results with that of traditional traffic flow models. It is revealed that the speed-density relationship did not exactly follow the similar pattern of conventional models, although, the flow rate-density relationship demonstrated a closed pattern - as illustrated in Figure 5. The potential reasons of these discrepancies as mentioned by the study are the absence of physical boundary of lanes, and frequent incidence of overtaking in waterway. However, the major limitation of the study was not considering the impact of variation of ship sizes.

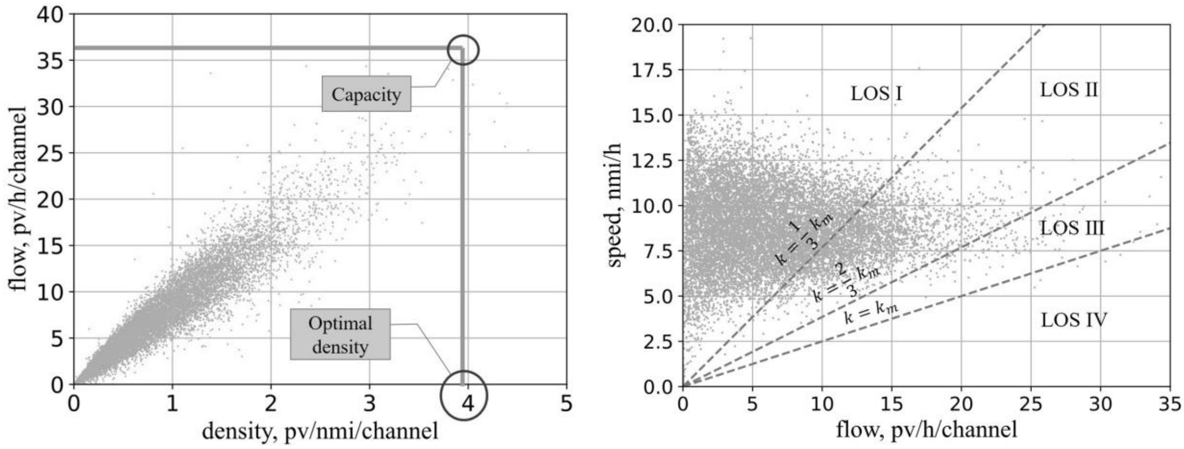


(a) (b)

Figure 5: (a) Speed-density relationships of the Shanghai port area; (b) flow rate-density relationships of the Shanghai port area, reproduced from Huang et al. (2019)

Tian et al. (2020) analyzed the traffic flow of a sea channel and compared the results with the models established by Greenshields, Greenberg, and Underwood. The investigation claimed that traffic flow in waterway is different from that of roadway, even in the areas of low density. It is also stated that vessels will not gain significant acceleration, but maintain a reasonably stable and economic speed.

On the other hand, Liu et al. (2022, 2023a, 2024) proposed a method to evaluate the Level of Service (LOS) in estuary of the Yangtze River in China- based on of the concept of traffic flow of roadway. For the purpose of analysis, the water area was considered to be consisted of four LOS i.e. LOS I, LOS II, LOS III and LOS IV; where LOS I indicates the best level of service and vice versa. The analysis identified the capacity of the estuary from the flow rate-density relationship-as outlined in Figure 6 (a). It was also found that speed- flow rate diagram skipped the congested regime (LOS IV), signifying that the existing flow condition do not reach at capacity-as outlined in Figure 6 (b). However, the limitations of the investigation were that it was applied to a linear waterway, and could not take into consideration the effect of vessel overtaking on the fundamental diagram.



(a) (b)

Figure 6: (a) Capacity of the Yangtze River estuary illustrated on Flow rate-density diagram; (b) Level of Service (LOS) of the estuary, reproduced from Liu et al. (2022)

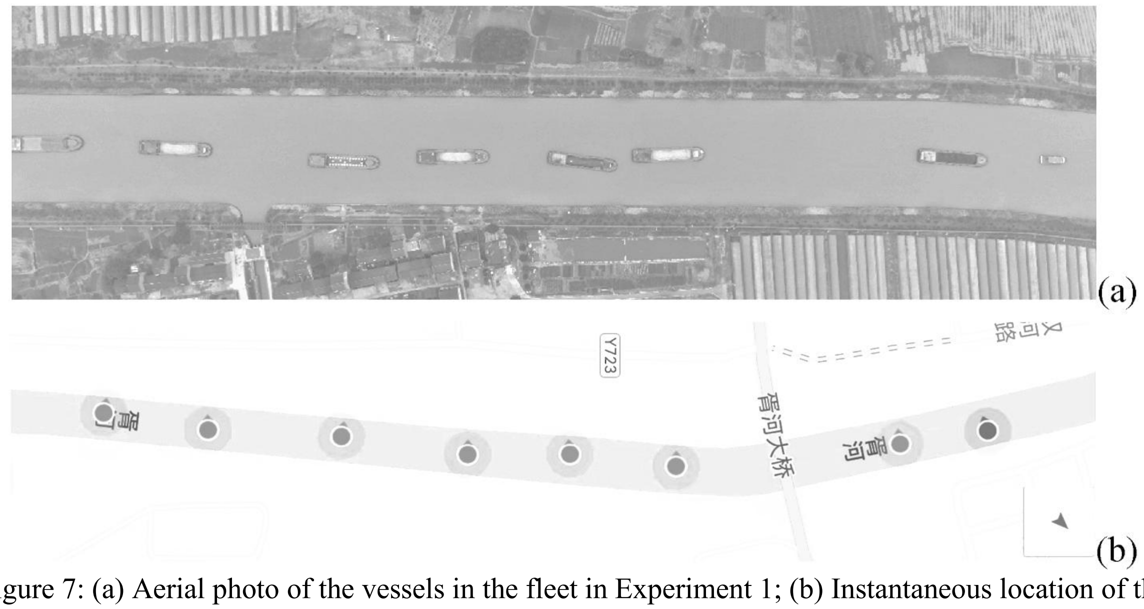


Figure 7: (a) Aerial photo of the vessels in the fleet in Experiment 1; (b) Instantaneous location of the fleet of Experiment no. 3 obtained from Global Navigation Satellite System (GNSS), reproduced from Yang et al. (2023)

Most of the researches on application of traffic flow theory on waterway were conducted by using AIS data. However, it has some limitations like discontinuity and incompleteness of data, and many other issues. To evade this difficulty, Yang et al. (2023) carried out three vessel-following experiments- similar to the car-following experiments on roadway, with the purpose of obtaining the vessel-following behavior data in microscopic level at several restricted inland waterways of Yangtze Delta in China -as outlined in Figure 7. Six well-recognized car-following models were applied by recalibrating their parameters to verify their suitability to vessel-following behavior. It was revealed that the improved Newell model (Newell, 1961), General Motor (GM) model (Chandler et al., 1958; Gazis et al., 1961), Intelligent Driver Model (IDM) (Treiber et al., 2000), and Longitudinal Control Model (LCM) (Ni, 2015) were found as valid to elucidate the vessel-following behavior. However, the major limitation of the investigation was carrying out the experiment in a very restricted inland waterway, which could not be taken as a representative of a busy and operationally complex waterway.

Liu et al. (2023b) claimed that following the procedure of defining the traffic flow parameters on the basis of quantity used in road traffic flow is unsuitable to explain the traffic flow on waterway. The analysis, therefore, attempted to provide a comprehensive description of the inland water traffic flow conditions by redefining parameters and using a novel approach for ship area and ship length respectively. Although the results showed that by refining the definition considering ship scale the quality of fundamental diagram was improved, however, it still became unsuccessful to illustrate the congestion part on that diagram. On the other hand, Zhuang et al. (2024a) proposed a macroscopic approach to subdivide the shipping lane to plot the fundamental diagram of waterway traffic flow, and revealed the presence of hysteresis in the flow rate - density diagram that corresponds to the characteristics of the road traffic flow. It is worth mentioning that the left side of that hysteresis specifies the free-flow condition and the right side designates the congested or block-flow condition. However, the analysis could not investigate the blockage density of the shipping lane by applying fundamental diagram's equilibrium model.

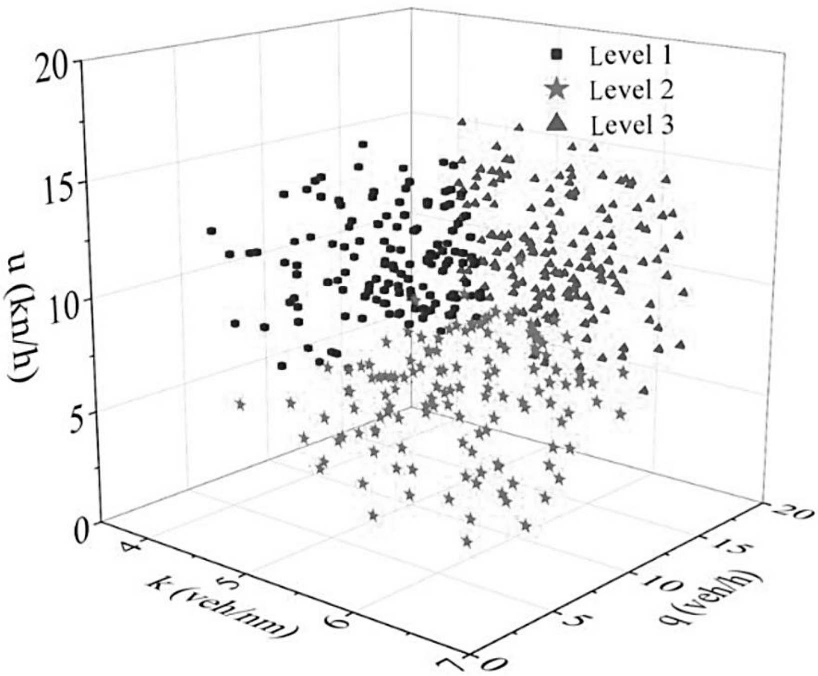
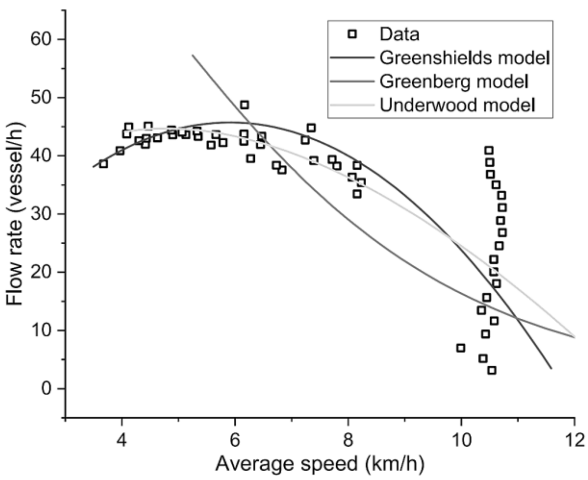


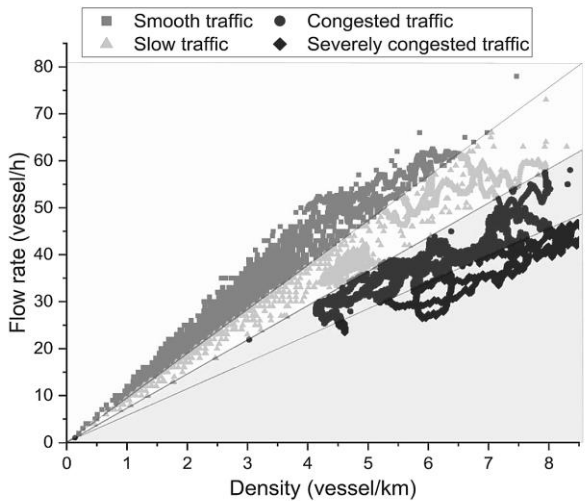
Figure 8: Relationship between three fundamental variables of traffic flow, reproduced from Sui et al. (2024)

In another study Zhuang et al. (2024b) proposed a method to define the fundamental characteristics of traffic flow in waterway by considering three-dimensional size i.e. displacement of vessel. This novel approach is claimed to evade the difficulties of choosing 'standard vessels' as well as determining traffic conversion factors, and demonstrate the real waterway traffic condition in a more accurate way. However, the major limitation of the study was applying the investigation on an inland waterway where the vessels move in only one direction. Hence, the result of the analysis is not applicable to the seaways and navigable waterway intersections where the traffic flow pattern is more complex. On the other hand, Sui et al. (2024) proposed a framework to analyze the multi-state traffic flow based on AIS data, where the Visibility Graph (VG) method was applied to investigate the dynamic properties of ship traffic flow time series network. Figure 8 illustrates the perspective view of the obtained relationship between the variables of traffic flow in a three-dimensional plane. Although, a case study is provided in the analysis, additional case-based investigations are needed to further validate the study for addressing scenarios in different categories of waterway.

In a review study, Zhuang et al. (2024c) investigated the aspect of application of traffic flow theory of roadway with regard to traffic flow on waterway by investigating the dissimilarities among different transportation modes. Based on the identified differences, the existing definitions of traffic flow characteristics, fundamental diagram, and traffic flow simulation models were analyzed as well. In addition, the major constraints those have been encountered in applying the road traffic flow theory to the context of waterway traffic flow, and several potential recommendations for future investigations were also discussed in the study. Chen et al. (2025) conducted a bibliometric analysis to investigate the critical factors that influence vessel traffic flow, including the fundamental parameters of traffic flow, vessel trajectories, and traffic flow patterns. On the other hand, Liu et al. (2025) presented a fundamental diagram of traffic in Xiazhimen waterway of China, and analyzed the capacity by using the Pipes-Forbes model. However, the results of the analysis were limited to the application in unidirectional waterway channel. With a view to achieving a holistic and comprehensive understanding of traffic flow in inland waterways, Yang et al. (2025) analyzed the vessel traffic flow characteristics by integrating multi-source data i.e. macroscopic data from video surveillance footage, and microscopic data from vessel-following experiments in waterways of Jiangsu province of China. The flow rate - average speed relationship obtained from the study is depicted in Figure 9 (a). In addition, the K-means clustering algorithm was used for categorizing the traffic flow into 4 levels i.e. smooth, slow, congested, and severely congested traffic- as illustrated in Figure 9 (b). Nevertheless, the waterway under the analysis has a limitation of having minimal impact on navigation by the geological factors.



(a)



(b)

Figure 9: (a) Flow rate - average speed diagram; (b) four states of vessel traffic classified by K-means clustering approach, reproduced form Yang et al. (2025)

4. RECOMMENDATIONS FOR FUTURE RESEARCH

Recently, the application of traffic flow theories to waterway transportation has emerged as an innovative research direction aimed at extending conventional traffic modeling frameworks beyond roadway systems. The outcomes of studies discussed in the previous section suggest that the development of fundamental diagrams considering the multifaceted scenarios of waterways remains as an ongoing challenge requiring further investigation. Therefore, this section will present a number of areas of potential future investigation based on the research gaps of those studies.

The conventional car-following models do not consider the lane-changing of vehicles, although vessels in waterways overtake (Kang et al., 2018). Therefore, future investigations should consider these distinctions. In addition, future studies could also explore multi-scale modeling frameworks that integrate microscopic vessel interactions with macroscopic flow patterns to achieve a more comprehensive depiction of actual traffic conditions on waterway routes. Moreover, the vessel's movements in both directions of waterway and complex scenarios at intersections have not been analyzed in the past studies that lay a vast ground for future research.

Due to the absence of any physical lanes on waterway, the researchers have been struggling a lot to deciding whether the full width of waterway be considered as a lane or be divided into a number of lanes. Therefore, future researches should explore the techniques for dividing or separating lanes. Furthermore, the modeling for heterogeneous waterway traffic i.e. vessels of different sizes and categories to develop the concept of a standard sized vessel - similar to the PCE concept of road traffic, could be a vital domain of future research. Most importantly, the relationship between gap distance and speed among the vessels in motion is also a crucial area that is relevant to traffic flow theory. However, the limited existing researches on this topic have not considered these intricate scenarios encountered by waterway traffic. Therefore, extensive research on this relationship would also reveal more comprehensive findings related to waterway transportation.

5. CONCLUSIONS

Traffic flow theory provides a quantitative framework for comprehending the dynamic interactions among vehicles within a transportation system, with the ultimate aim of enhancing safety and operability. Fundamental diagram characterizes the relationship among key traffic parameters i.e. speed, density and flow. Application of this diagram is pivotal in estimating capacity, assessing congestion, and thereby improving traffic performance across transport networks through appropriate interventions. For the last couple of years, the traffic flow theory developed for roadway has begun to be applied extensively in waterway. Unlike roadway traffic, the traffic in waterway move in slower speeds, have longer reaction times, faces congestion rarely, possess bigger size, move on without physical lane. Moreover, there is no standard sized vessel for unit conversion framework like PCE. Nonetheless, researchers have attempted to identify the shape of fundamental diagram for the waterway traffic.

This study has focused on the applications of traffic flow theory in waterway so far. The main aim of this study is to review the progress and challenges encountered in developing fundamental diagram for waterway traffic flow. The results of the reviewed studies indicate that there have been limited studies to investigate the fundamental diagram of waterway. Although, some of those studies have claimed that the results fit well with the well-established pattern of roadway traffic. However, most of those are constrained by a number of crucial limitations like poor data related to congestion, absence of traffic flow in both directions of waterways and so on. Hence, future research should emphasize on eradicating these constraints.

In a nutshell, analyzing waterway traffic flow with a view to ensure safer, efficient and sustainable transportation in waterways is turning out to be highly imperative. More comprehensive studies are needed to mitigate the existing challenges and constraints in this domain. Nonetheless, it is highly anticipated that the outcome of this study will open new avenues for such investigations in the research community.

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