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Exploring Lane Changing Dynamics: A Comprehensive Review of Modeling Approaches, Traffic Impacts, and Future Directions in Traffic Engineering Research

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ABSTRACT: Lane changing behavior, a pivotal aspect of vehicular dynamics, significantly influences traffic flow, safety, and overall road network efficiency. This review article synthesizes the current body of knowledge surrounding lane changing behavior, encompassing both mandatory and discretionary lane changes. The intricate interplay between various factors, including speed differentials, driver characteristics, road geometry, and external stimuli, shape the decision-making processes underlying lane changes. The article explores the underlying psychological, cognitive, and socio-demographic influences on lane changing behavior, highlighting the role of emerging technologies such as advanced driver assistance systems (ADAS) and vehicle-to-vehicle (V2V) communication. Furthermore, the review delves into existing models and methodologies employed to analyze lane changing behavior, addressing their limitations and potential for advancement. Real-world applications, such as work zones and incident management, are examined to underline the practical implications of understanding and predicting lane changing behavior. By presenting a comprehensive overview of the subject, this review aims to deepen the understanding of the complexities inherent in lane changing behavior, facilitating informed decision-making for traffic management, safety enhancement, and future research endeavors.

KEYWORDS: Lane changing behavior; Vehicular dynamics; Driver characteristics; Road safety; Road geometry

1. INTRODUCTION

Patterns of changing lanes by each driver is different, and for the same driver at different traffic conditions also varies. Again, the lane changing behaviour not only depends on the driver, but also the type of vehicle he/she is driving. Thus, it becomes a very important aspect on roads to understand the lane changing dynamics of the road user at different conditions. Further, as roads have become increasingly congested and transportation systems more complex, understanding the underlying factors that drive lane changing decisions has become essential for optimizing traffic management strategies and enhancing roadway safety. Lane-changing behavior is inherently intricate due to its involvement with three key elements: the need for lane changing, the feasibility of executing the act of changing lanes, and the trajectory taken during the lane-changing maneuver (Huang, 2002; Arai and Sentinuwo, 2012; Feng et al., 2015; Golbabaei et al., 2014; Li et al., 2015) Upon a driver's action is compelled to depart from the existing lane while adhering to a predetermined path, it leads to what is known as Mandatory Lane Changing (MLC). Conversely, Discretionary Lane Changing (DLC) aims to enhance driving conditions, such as attaining a optimal velocity, evading trailing behind trucks, or navigating merging traffic. However, in the case of DLC, the decision to perform lane changes is not an absolute necessity (Ali et al., 2018; Vechione et al., 2018; Pan et al., 2016; Kang, and Chang, 2004). Lane changes within work zones encompass merging segments that necessitate MLC. This particular type of lane change stands as the principal driver behind a substantial proportion involving clashes and interplay between vehicles within these merging segments (Pan et al., 2016). One emerging technological advancement, known as the Drivers' Smart Advisory System (DSAS), aims to improve the interaction among vehicles and temporary traffic control devices in work zones. This innovation is designed to enhance safety measures and promote better air quality within such environments (Li et al., 2015). However, the execution of a single lane change may encompass several seconds. These maneuvers offer insights into the driver's cognitive processes, where individual driver characteristics substantially influence factors such as the degree of acceptance for a specific DLC, the range of adopted acceleration or deceleration (Laval, and Daganzo, 2005). The driving performance is significantly influenced by individual socio-demographic factors of drivers, including but not limited to gender, age, educational history, and driving experience (Li et al., 2015; Kesting et al., 2007; Golbabaei et al., 2014).

Lane changing, a maneuver where a vehicle transitions from one lane to another, occurs in response to a variety of factors such as speed differentials, congestion levels, road geometry, driver characteristics, and external stimuli. These factors interplay in intricate ways, leading to diverse lane changing behaviors that can impact traffic flow stability, capacity, and safety. The study of lane changing behavior is inherently multidisciplinary, involving aspects of traffic engineering, psychology, human factors, and data analysis. It holds implications not only for transportation planners and engineers but also for researchers aiming to model and predict traffic patterns, manufacturers designing advanced driver assistance systems, and policymakers implementing traffic management strategies.

This review article concentrated on lane changing behavior, examining its theoretical foundations, empirical findings, methodologies for analysis, and its influence on traffic

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dynamics. By synthesizing existing research and shedding light on the complexities of this behavior, this article strives to provide an in-depth grasp of lane changing phenomena, facilitating the development of more accurate traffic models, advanced driver assistance systems, and effective traffic management policies. Through this exploration, the article endeavor to contribute to safer and more efficient road networks in an ever-evolving urban landscape.

The act of lane changing, where a vehicle moves from one lane to another, is influenced by a range of factors like speed variations, congestion, road layout, driver traits, and external stimuli. These elements interact intricately, resulting in diverse lane changing behaviors that impact traffic stability, capacity, and safety. The study of lane changing spans disciplines such as traffic engineering, psychology, human factors, and data analysis. Its significance extends to transportation planning, engineering, advanced driver assistance systems design, and policymaking for traffic management. This review article focuses on delving into lane changing behavior, covering theoretical foundations, empirical discoveries, analysis methodologies, and its repercussions on traffic dynamics. By amalgamating existing research, the article aims to unravel the intricacies of this behavior, providing a comprehensive understanding. The goal is to contribute to the development of more precise traffic models, advanced driver assistance systems, and effective traffic management policies. The overarching aim is to enhance the safety and efficiency of road networks in the urban environment.

2. RESEARCH METHODOLOGY

Prominent journals and conferences within the domain of traffic engineering, listed in databases such as Scopus, Web of Science, Google Scholar, and Science Citation Index, were meticulously selected for investigating the repercussions of lane changing behavior. Following keyword searches were done to collect various literature relevant to the present study.

1. Lane Changing Behavior
2. Intelligent Traffic Systems (ITS)
3. Modeling
4. Driving Behavior/Characteristics
5. Vehicular Dynamics
6. Human Factors
7. Driver Psychology
8. Road Safety
9. Road Geometry
10. Microscopic Lane-Changing Models
11. Risk Assessment
12. Environmental Factors
13. Traffic Flow Dynamics
14. Traffic Simulation
15. Traffic Management

Subsequently, the papers were selected based on accessibility, relevance, indexing (only scopus and SCI were selected), and subject matter coming down from 210 to 52 articles. Figure 1 shows the systematic selection process that was employed to curate articles for the literature review.

3. REVIEW OF LITERATURE

The literature review on lane-changing dynamics has been precisely presented, incorporating innovative techniques such as Intelligent Traffic Systems and simulation. The structure offers a coherent flow for the review article, systematically delving into various facets of lane-changing dynamics. In the pursuit of uncovering novel insights into lane-changing dynamics and their functionalities, the current review is organized into three distinct sections as outlined below.

- Lane changing phenomena and Intelligent Traffic Systems
- Driving behaviour during lane changing
- Simulation and modelling

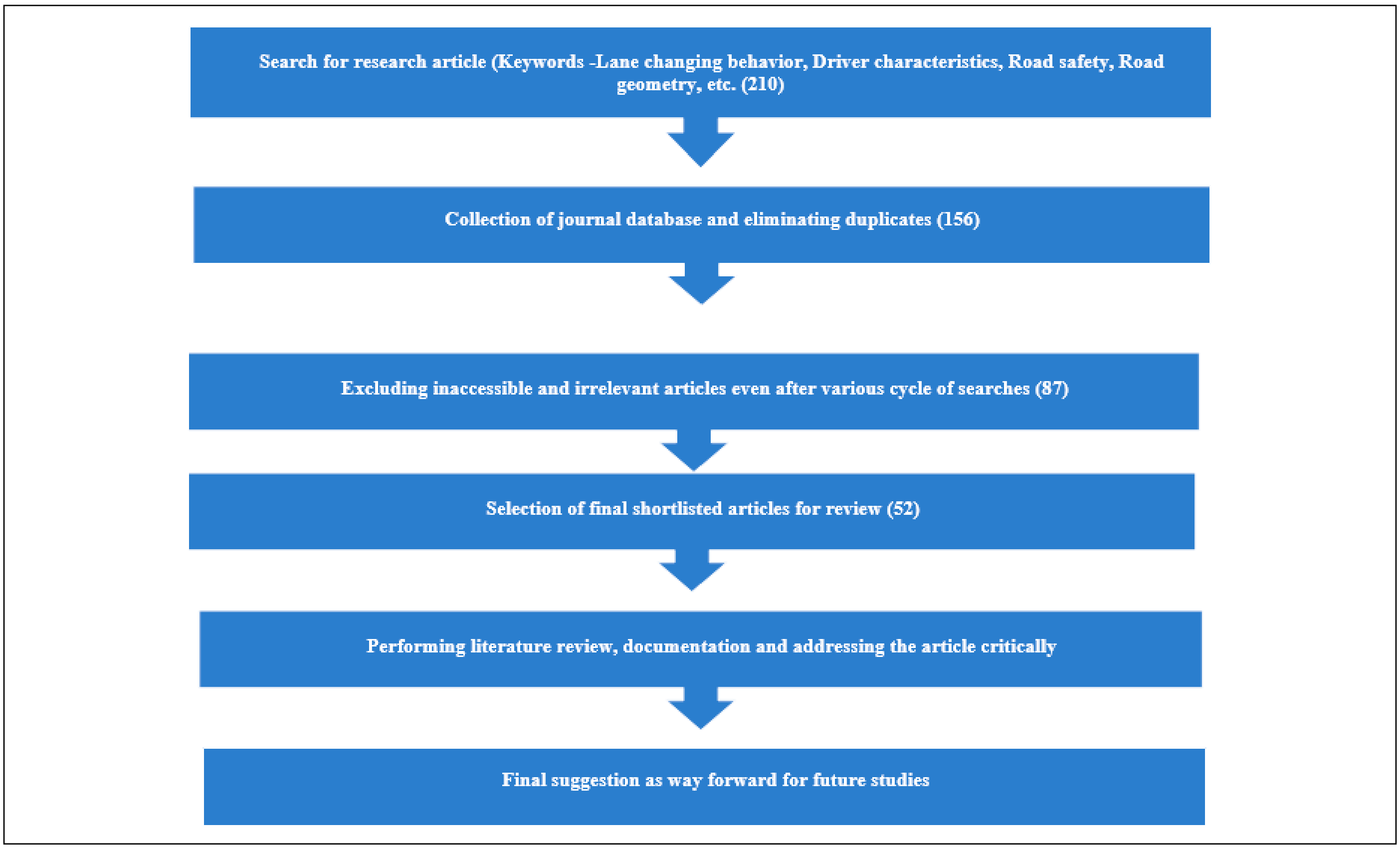

Fig. 1 Flowchart depicting the methodology

Lane changing phenomena and Intelligent Traffic Systems

Lane changing is a dynamic maneuver performed by drivers on roadways. Understanding lane-changing behavior is crucial for traffic flow modeling, road safety, and transportation planning. ITS involves the integration of advanced technologies to enhance transportation efficiency, safety, and management. In the context of lane changing, ITS can provide real-time traffic information, optimize signal timings, and facilitate communication between vehicles. The implementation of ITS contributes to improved traffic flow, reduced congestion, and enhanced overall road network efficiency.

Kang, and Chang (2004) examined the relationship between traffic flow characteristics and macroscopic non-mandatory lane-changing behavior within a section of freeway. Data were gathered from a central section of the Capital Beltway. The research was divided into two distinct categories: analyzing the rate of lane changes and assessing the proportion of vehicles engaged in lane-changing maneuvers. By employing Poisson regression and logistic regression methodologies, the investigation aimed to estimate different model specifications. This approach allowed for a comprehensive evaluation of how traffic conditions influenced macroscopic lane-changing patterns.

Laval, and Daganzo (2005) suggested a multi-lane hybrid theory that conceptualizes lane changing as momentary blockages. Their model depicted lane-changing vehicles as discrete entities with constrained acceleration abilities, fostering realistic interactions within the multi-lane continuous flow. Notably, this hybrid framework necessitated just a single additional parameter compared to the simpler kinematic wave model. The study successfully replicated two bottleneck phenomena: a decrease in freeway bottleneck discharge rate as congestion initiates and the relationship between a moving bottleneck's speed and its capacity. Future research avenues could delve into intricate lane changing behaviors within merge bottleneck scenarios.

Adelakun and Cherry (2009) focused on understanding the perspectives of long-haul truck drivers concerning urban traffic congestion and safety difficulties, particularly focusing on lane changing behavior, geometric configurations, and operational solutions. A comprehensive survey was conducted, involving 500 truck drivers, at the strategic junction of prominent interstate highways running north-south and east-west in Knoxville, Tennessee. The dataset was equally divided among owner-operators and drivers utilized by truck companies. The research highlighted key concerns among truck drivers on Knoxville's urban highways, which encompassed issues such as aggressive driving, congestion, car lane changing patterns, and the merging behavior of vehicles. The study's recommendation pointed towards enhanced truck management strategies, proposing the implementation of traditional truck lane restrictions or exclusive truck-only lanes to mitigate issues tied to car merging and lane changing

Huizhi et al. (2010) considered the effects of lane-changing to traffic capacity, based on the observation data. A correlation was established between lane-changing tendencies and traffic capacity, revealing that during high traffic conditions, the likelihood of lane-changing occurrences was diminished, while in moderate traffic scenarios, the likelihood of lane-changing actions was highest. To encapsulate this relationship, a model was formulated, anchored in the connection between traffic capacity and road space allocation. The calibration of model parameters was facilitated by incorporating a correction factor.

Jin (2010) introduced a straightforward model aimed at investigating the bottlenecks caused by lane-changing behavior within traffic and the cumulative dynamics of a road section featuring lane-changing segments. It was noted that a vehicle's lane change exerted an influence on traffic within both its current lane and the target lane. This study examined how lane-changing traffic impacted overall traffic flow through modifications to fundamental diagrams and the application of a basic kinematic wave model. The results indicated that lane changes indeed had considerable bottleneck effects on the wider traffic flow. The authors recommended that future research delve into various aspects, including studying lane-changing intensity across distinct road configurations, sites, on-ramp/off-ramp interactions, and varied traffic conditions.

Duret et al. (2011) estimated the lane changing behavior parameters using passing rate measurements. The findings were calibrated using vehicle paths from a pair of distinct freeway segments. The study revealed that relaxation occurred within approximately 15 seconds, with the shoulder lane exhibiting a longer relaxation period. Additionally, passing rate measurements were utilized to quantitatively assess the after-relaxation effect of multiple lane-changing maneuvers within platoons comprising 10 or more vehicles in a queued traffic flow. The results indicated that the lane-changing maneuvers did not have a lasting effect on traffic states, as traffic streams experienced temporary unsettled conditions due to these maneuvers, only to revert to their initial states after relaxation periods.

Hu et al. (2012) studied traffic flow that combines motorized vehicles and non-motorized vehicles in the motorized vehicle lane. Notably, the investigation considered the unauthorized lane-changing behavior of non-motorized vehicles, integrating factors like motivation for overtaking and awareness of traffic safety. A novel model designed to simulate mixed traffic flow was introduced, integrating a new set of regulations within the context of Kerner's three-phase theory. Through a sequence of simulations, the research aimed to comprehend the formation, progression, and impact of mixed traffic flow. The findings indicated that the suggested model was capable of not only elucidating the travel patterns of mixed traffic environment but also addressing intricate traffic issues including traffic breakdown and the emergence of synchronized flow patterns.

Du et al. (2013) focused on examining lane-changing behaviors on freeways featuring distinct high-occupancy vehicle (HOV) access configurations. Lane change data were collected and then associated with lane-by-lane flow, along with occupancy data gathered from the California Freeway Performance Measurement System. The findings highlighted that instances of vehicles exiting the HOV lane were associated with a higher density of lane changes per distance unit within a shorter time gap. The study concluded by suggesting that lane-changing maneuvers, when considered in conjunction with HOV facilities, could serve as valuable tools for analyzing traffic operations, simulating driver behavior models, and assessing lane configurations and access control strategies.

Marczak et al. (2014) conducted an empirical analysis of lane changing behavior, utilizing a trajectory dataset obtained from a weaving section in Grenoble, France. The primary focus was to investigate lane changing behaviors at a microscopic level within this context. The researchers undertook a descriptive empirical examination of lane changes occurring in weaving scenarios, specifically analyzing the positioning of lane changes and the accepted gaps. Notably, it was observed that vehicles engaged in weaving activities were inclined to change lanes promptly following the initiation of the weaving section, particularly evident during congested traffic conditions. Additionally, the positions of lane changes were more dispersed during the initial part of the weaving section when traffic was flowing freely.

Furthermore, the study indicated that vehicles originating from the main road exhibited a tendency to change lanes earlier than those emerging from auxiliary lanes. The findings highlighted the need for further research, particularly exploring the impact of weaving section length on the applicability of the model.

Qi et al. (2016) explored lane-changing maneuvers by means of a distinct dataset comprising aerial photos collected from a specific road segment, both before and after the conversion of a high occupancy vehicle (HOV) lane configuration. The data was meticulously validated using a Kalman filter smoothing algorithm. The findings illuminated substantial impacts induced by the HOV-lane configuration on various lane-changing behaviors, encompassing aspects like lane-changing intensity, highway facilities, maneuvers involving merging into the HOV lane, and statistics related to time gaps. The study's implications extended to aiding the design of HOV lanes and offering valuable input for the calibration of micro-simulation models focused on lane-changing behaviors.

He et al. (2016) concentrated on the frequent occurrence of lane changing and merging within work zones. The investigation encompassed discretionary lane changes, considering various conditions such as driver response to signage, speed reduction, driver aggressiveness, and interactions with entering and exiting the work zone area, as well as maneuvering around slower-moving and heavy vehicles. With the aim of enhancing work zone safety, the researchers formulated a logistic regression model to pinpoint factors influencing drivers' behaviors. The findings highlighted that several factors, including vehicle type, average speed in the original lane, and volume of the target lane, significantly influenced lane changes within work zones. The study underscored the significance of comprehending driver behaviors, particularly concerning lane changing within and near work zone areas, as a means to enhance the design and operation of safe work zones.

Shuaib (2016) introduced a novel approach by integrating decision-making capabilities as an intelligent component within crowd dynamics models to accurately replicate real-life pedestrian flow. To achieve this, the researchers extended the social force model to include pedestrians' cognitive abilities, particularly in bidirectional walkways. In this extended model, the layout of lanes served as a social network, enabling simulated pedestrians encountering challenges in their movement to identify pertinent factors influencing their lane-changing behavior. Quantitative measurements were then conducted to examine the impact of pedestrians' motion efficiency.

Chen et al. (2016) presented empirical insights into the behaviors of car-following and lane-changing, with a specific focus on heavy vehicles. The researchers utilized trajectory data extracted from the next generation simulation program to conduct their analysis. Their findings revealed that when heavier vehicles followed passenger cars, the existence of heavy vehicles led to a reduction in speed fluctuations caused by traffic disruptions, contributing to the mitigation of traffic oscillations. Conversely, passenger cars following heavy vehicles exhibited a tendency to worsen traffic disruption, albeit with a lower likelihood and degree compared to the dampening effect. It was observed that heavy vehicles often deterred lane-changing action, and the prevalence of larger gaps behind heavy vehicles led to a suboptimal utilization of road capacity. The study concluded that a reduction in lane changes could enhance traffic stability by averting or minimizing disturbances.

Yun et al. (2017) investigated the effects of in-vehicle navigation data on lane-changing behavior. The researchers assessed lane-changing characteristics using various key indicators. Their findings unveiled that the influence of in-vehicle navigation data on lane-changing action exhibited variability based on traffic flow density and the timing of the initial navigation guidance. Importantly, the study noted that the introduction of in-vehicle navigation had a favorable effect on safety, particularly under conditions of moderate to high traffic density. The research concluded that providing in-vehicle navigation information earlier could yield enhanced improvements in driving behavior.

Qi et al. (2017) delved into the lane-changing patterns and sought to quantify the inherent connection between a driver's heart rate and their lane-changing behavior amidst urban traffic congestion. The experimentation exclusively involved selected drivers and specific testing routes. The researchers introduced the concept of a "pressure–state–response" model, employing back propagation neural network theory, which utilized data linked to driver behavior. This model incorporated the driver's pressure and state were utilized as input parameters, ultimately predicting the driver's reaction as the output. The study concluded that this pressure–state–response model could serve as a valuable tool for issuing warnings regarding risky lane-changing maneuvers in the context of urban traffic congestion.

Ali et al. (2018) explored the behavior of mandatory lane-changing (MLC) using the CARRS-Q Advanced Driving Simulator. Participants from diverse backgrounds were selected to engage in randomized driving scenarios within the experiment. Utilizing statistical analyses such as ANOVA in the form of a linear mixed model and Generalized Estimation Equation (GEE), the researchers examined a range of performance metrics related to driving in the context of MLC events. The findings revealed that, in comparison to the baseline condition, drivers in the connected environment exhibited tendencies to wait for longer periods, accelerate initially, maintain increased spacing, and display a preference for fewer gap rejections along with a preference for larger gap sizes during the lane-changing process.

Zhang et al (2018) investigated the attributes of lane-changing behavior exhibited on a four-lane freeway segment across varying traffic conditions. Extending over an extended period, the research observed driver behaviors and identified a total of 433 lane-changing instances for analysis. Employing a logit model, the investigators dissected the selection of target lanes and conducted a likelihood analysis of lane-changing patterns across three distinct traffic conditions: free flow, medium flow, and heavy flow. The study concluded that lane-changing behavior among exiting vehicles was the result of a nuanced balance between route planning and an aspiration to enhance driving conditions. Furthermore, the research highlighted that lane-changing from slower lanes to faster lanes correlated with heightened speed variance values, implying an elevated risk of potential collisions.

Das and Ahmed (2019) offered valuable observations into lane-changing attributes rooted in driver behavior under varying weather conditions, specifically fog and clear weather, utilizing the Naturalistic Driving Study (NDS). While only a limited number of researchers have investigated lane-changing behavior categorized by driver type, this particular study delves into the influence of adverse weather situations on such behavior. Multiple hypotheses were tested across diverse traffic conditions to discern differences in the frequency of lane-changing events per mile and the duration of lane changes between foggy and clear weather. Employing the K-means cluster analysis technique, the drivers were categorized into two groups: conservative and aggressive. The findings unveiled that in situations of heterogeneous traffic, the mean duration of lane changes was notably longer during heavy fog when compared to clear weather conditions. The study concludes that, in the context of heavy fog, conservative drivers tend to exhibit longer durations for lane-changing maneuvers compared to their behavior in clear weather conditions.

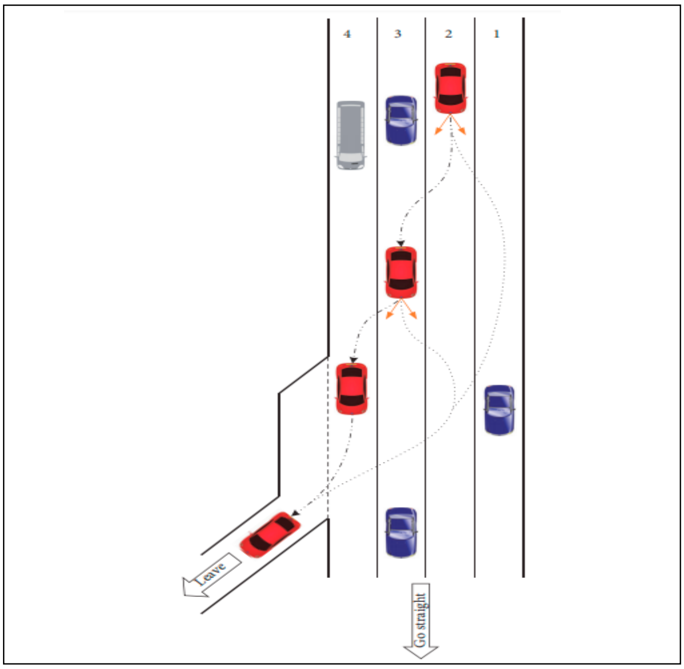

Fig. 2 Lane-changing behaviour at off ramp areas in freeways (Source Zhang et al (2018))

Wang et al. (2019) presented a comprehensive overview of prominent research endeavors concerning lane-changing models, algorithms, and traffic repercussions as per Connected and Automated Vehicles (CAVs). The analysis primarily concentrates on aspects like Vehicle-to-Vehicle (V2V) communication, decision-making and planning for lane-changing, as well as vehicle control algorithms. The review underscores the necessity for an in-depth exploration of real-world applications of CAV technologies to address prevailing gaps in the existing body of research.

Li et al. (2020) investigated how traffic jam impacts driver behavior on roads after congestion, specifically the roads traversed immediately after congestion. The study involved 25 participants who underwent simulation trials, conducting two separate trials—one under post-congestion conditions and the other under non-congestion conditions. By analyzing various parameters such as performance indicators related to driving, eye movement measurements, and electroencephalogram (EEG) measurements, a comparison was made between the two conditions. The researchers employed a hierarchical clustering method to identify distinct driver response patterns. The study's findings revealed that, following congestion, driver behavior tended to become more aggressive, with increased focus on the forward area but decreased focus on the dashboard area. The research concluded that traffic congestion had a detrimental impact on driver behavior in the context of post-congestion roads.

Mohanty, and Dey (2020) utilized Markov's process to examine the lane-changing behavior of approaching through vehicles influenced by the U-turns. To gather data, they employed video graphic techniques at seven median openings situated on six-lane divided roads. These selected locations were devoid of factors such as horizontal curvature, intersections, bus stops, parked vehicles, pedestrians, or other sources of side friction. Probability matrices were established for the initial 10 meters of the slowdown section, followed by transition matrices for each lane. By utilizing Markov's process, they assessed the lane-changing probabilities of vehicles and compared the results with actual field data. The study revealed that the likelihood of lane changing was higher when U-turning volumes were low, and this probability diminished as U-turn volumes increased. The research suggested that Markov's process could be effectively applied to enhance traffic management at median openings.

Driving behaviour during lane changing

Understanding driving behavior is essential for road safety initiatives, traffic management, and the development of intelligent transportation systems. It involves a complex interplay of cognitive, psychological, and external factors that contribute to the dynamics of vehicular movement on the road. Understanding the intricacies of driving behavior during lane changing is crucial for improving traffic safety, developing effective driver assistance systems, and optimizing traffic flow on roadways.

Cooper et al. (2008) explored the impact of naturalistic, hands-free, cell phone conversations on the driver's behavior regarding lane changes. The study involved 36 undergraduate psychology students who were placed within a simulated highway setting by three traffic density levels. Participants were directed to adhere to speed limits and signal lane changes. The findings revealed that, particularly in medium and high traffic density scenarios, engaging in cell phone conversations led to reduced lane changes, decreased average speed, and a notable rise in travel duration. Interestingly, drivers engaged in cell phone conversations exhibited a higher likelihood of trailing slower-moving lead vehicles compared to those solely focusing on driving tasks.

Moridpour et al. (2010) studied the traffic flow characteristics under congested traffic conditions due to the lane changing behavior of drivers operating heavy vehicles and passenger cars. The analysis encompassed 28 lane-changing maneuvers executed by heavy vehicles and an equal number by passenger cars. It was noted that when heavy vehicles exe-

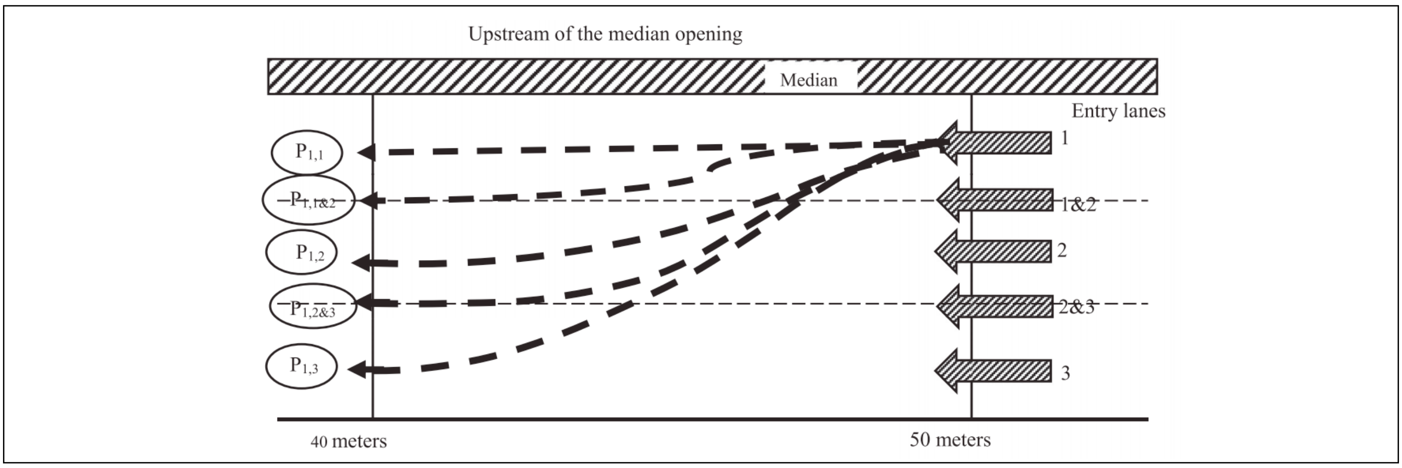

Fig. 3 Lane changing behaviour at median opening (Source Mohanty, and Dey (2020))

cuted lane changes, their speed exhibited minimal alteration. This was attributed to the heavy vehicle drivers' tendency to transition to slower lanes to avoid hindering faster-moving vehicles approaching from behind. In contrast, passenger car drivers adjusted their speed as per the lead and trailing vehicles' speeds within the intended lane. Consequently, passenger car drivers more frequently opted for lane changes into faster lanes in order to gain a speed advantage.

Aghabayk et al. (2011) explored the decision-making and execution of lane-changing maneuvers by drivers of heavy vehicles on both urban roads and highways. The researchers noted that, due to the distinctive attributes of heavy vehicles and associated driver behavior, lane changes by these vehicles could potentially have a more pronounced effect on traffic flow than those executed by passenger vehicles. They highlighted a significant gap in the literature concerning the investigation of lane-changing maneuvers involving heavy vehicles. By comparing the conduct of drivers operating heavy vehicles with that of passenger car drivers, the study uncovered nuances, particularly on arterial roads, where factors such as vehicle type and size influenced lane-changing behaviors. The researchers recommended that upcoming research ought to delve deeper into the incorporation of heavy vehicle characteristics into traffic dynamics with enhanced granularity.

Reimer et al. (2013) aimed to assess the impact of age and cognitive demand on both lane choice and lane changing behavior. Participants were categorized into three age groups: 20–29, 40–49, and 60–69. The findings revealed elderly individuals exhibited a more cautious driving approach in comparison to their younger counterparts. Specifically, individuals in their 60s were less inclined to travel in the leftmost lane compared to those in their 20s and 40s, and less prone to making lane changes than those in their 40s. Furthermore, the study noted that cognitive workload had a consistent effect across age groups, reducing the frequency of lane changes. The researchers concluded by suggesting that more investigation is required to comprehensively understand the influence of augmented cognitive demands on lane changing behavior.

Golbabaei et al. (2014) centered on examining the factors influencing aggressive overtaking maneuvers by road users. The Aimsun traffic simulator was employed to assess the effects of speed deviations on various performance metrics, including delay time, mean network speed, and travel time duration. The model was fine-tuned using data from a segment of urban highway in Tehran. Through comprehensive testing, the researchers elucidated the behavior of lane-changing maneuvers across various speed deviation scenarios. Notably, a significant reduction in the frequency of lane changes was observed when speed deviations were minimized, subsequently leading to improved network safety.

Li et al. (2015) focused on examining how driver lane-changing aggressiveness influences the stability of traffic flow within a two-lane system. To explore this phenomenon, a generalized lattice hydrodynamic model was employed, considering the individual lane-changing aggressiveness of drivers. Through a linear stability analysis, the study revealed that the level of driver lane-changing aggressiveness significantly effects the stability of traffic flow in the two-lane system. Notably, the findings indicated that higher lane-changing aggressiveness contributes to a traffic flow that is more stable.

Hill et al. (2015) focused on delving into the nuances of freeway lane changing as per the driver type executing the maneuver, instead of relying solely on external observation-based data. The study involved 46 participants who operated instrumented vehicles, collectively executing 726 freeway lane changes. Through cluster analysis, the participants were segmented into four distinct groups spanning from conservative to aggressive driving styles. Examination of the data enabled the identification of relationships between driver types and their lane changing attributes, notably regarding lane changing duration and gap acceptance behaviors. The findings unveiled that conservative driver displayed longer lane changing durations compared to their aggressive counterparts. Interestingly, no definitive correlation was observed between gap acceptance tendencies and driver types. The study concluded by highlighting the impact of driver type on freeway lane changing behavior and advocated for its consideration when designing or refining simulation-based lane changing models.

Keyvan-Ekbatani et al. (2016) explored the process of decision-making underlying lane-changing maneuvers across diverse drivers, employing a two-stage test-drive approach. In the initial stage, participants were directed to operate a camera-equipped vehicle on a Dutch freeway. Subsequently, in the second stage, drivers were prompted to analyze their choices concerning both lane selection and speed, drawing insights from recorded video footage. The investigation unveiled substantial variability in strategies adopted by different drivers when choosing lanes. It was also noted that decisions to change lanes were intricately linked with their speed preferences. An intriguing observation emerged: all drivers considered their chosen strategy as inherently logical and anticipated other drivers to adopt similar behaviors.

Wang et al. (2017) introduced a multi-lane changing model considering the influence of drivers' psychology and behavior, with a distinction between aggressive and conservative drivers. The study found that this model effectively describes traffic flow characterized by frequent lane changing, particularly aligning with driving behavior in China. The model demonstrated substantial impacts on density, flow, speed, and the risk factor. Notably, a positive correlation between the risk factor and traffic flow efficiency was observed at lower traffic demand. However, under higher traffic demand, frequent lane changing exhibited a detrimental effect on traffic efficiency. In summary, the proposed model proves suitable for representing traffic flow with a high proportion of lane changes, aligning well with drivers' prevalent behavior of frequent lane changes.

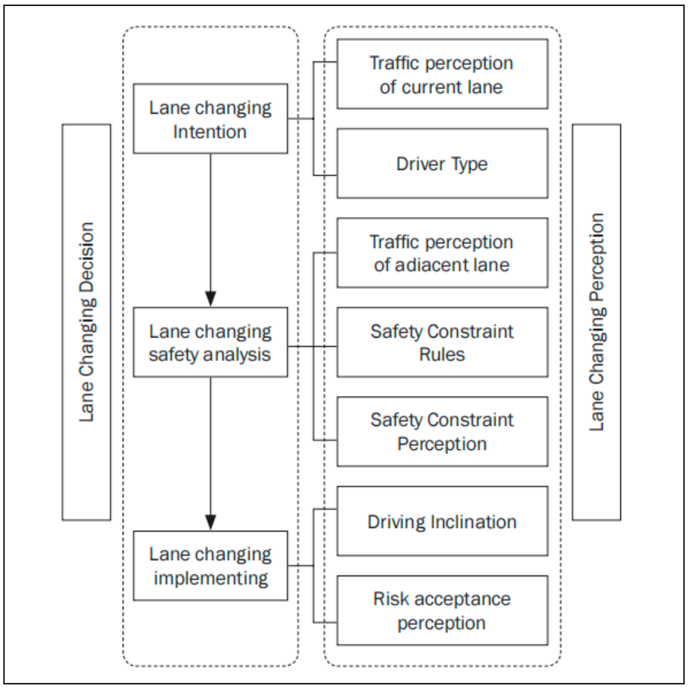

Fig. 4 – Lane changing decision-making and influencing factors (Source Wang et al.(2017)

Guo et al. (2018) focused on examining lane-changing behavior on Chinese freeways, particularly in areas characterized by relatively aggressive driving conditions. Video graphic data were gathered from both urban expressways and an intercity highway to investigate various aspects of lane-changing, including the rate, motivations, target lane preferences, and its influence on traffic. The research revealed that lane-changing constituted a transient behavior, occurring randomly and frequently, which was a hallmark of aggressive driving tendencies. It was observed that this frequent lane-changing behavior heightened the risk associated with high-speed car-following scenarios.

Vechione et al. (2018) scrutinized drivers' behavior in the contexts of both mandatory and discretionary lane changes. The researchers gathered descriptive statistical data from both types of lane changes and subsequently performed hypothesis tests for comparisons. Their observations indicated that the sole variable showing statistically significant that exhibited notable variations in averages and distributions was the space between the subject vehicle and the preceding vehicle in the initial lane. The study underscores the need for further extensive research to deepen our understanding of both mandatory and discretionary lane-changing behaviors.

Shi, and Liu (2019) explored drivers' lane-changing behavior within the context of distinct per-lane speed limits. Three separate test scenarios encompassing varying speed limit configurations were utilized, and driving behavior as well as workload characteristic parameters were meticulously collected. The research devised task workload indexes to assess the qualities of drivers' experiences. Notably, the investigation revealed that the designated per-lane speed limits exerted a substantial influence on both lane-changing behavior and the associated levels of driving workload. The study proposes that employing a differentiated per-lane speed limits approach holds potential for enhancing traffic safety management.

Simulation and modeling

Simulation and modeling play a crucial role in understanding and predicting lane-changing behavior. These tools offer insights into traffic dynamics, contribute to road safety assessments, and aid in the development of intelligent transportation systems.Simulation and modeling provide valuable insights into the complex dynamics of traffic systems, allowing researchers, engineers, and policymakers to make informed decisions for improving transportation efficiency, safety, and overall urban mobility.

Sheu, and Ritchie (2001) employed an approach based on stochastic system modeling to predict fluctuating lane-changing proportions and queue lengths over time aiding real-time incident management in traffic. The approach utilized a stochastic model operating in discrete time intervals, incorporating recursive and quantification identification alongside boundary restrictions to define variables describing the traffic conditions within lanes and between lanes. To evaluate these variables, methods such as Kalman filtering, truncation, standardization, and a queue update process were applied. The input data for the model relied solely on lane traffic counts gathered from traditional point detectors. The model underwent calibration using video-derived data and validation through simulated data generated by the TRAF-NETSIM Version 5.0 simulation model.

Huang (2002) studied modeling of lane-changing behavior in a multi-lane highway using cellular automaton techniques. The researcher examined the impact of factors such as speed limits and stochastic noise. Notably, it was observed that the rate of lane-changing becomes negligible when the highway is in a stationary state without stochastic noise. Conversely, the presence of stochastic noise led to frequent lane changes, even in the absence of slower vehicles to overtake. Furthermore, the study identified a subset of vehicles displaying aggressive behavior, changing lanes opportunistically. Surprisingly, these aggressive vehicles maintained only a slightly higher speed than their counterparts.

Choudhury (2005) developed a refined lane-changing model, which was a versatile framework capable of encompassing lane-changing behavior in various scenarios, even in the presence of unlimited access exclusive lanes. The researcher introduced a novel lane-changing model, distinguished by its clear selection of a destination lane. Notably, this model depicted lane changes following the direction indicated by the selected target lane, contingent upon the availability of sufficient gaps. Model parameters were collectively estimated utilizing comprehensive data regarding vehicle paths and subsequently adjusted for a context involving an unrestricted access High Occupancy Vehicle (HOV) lane. To validate the model's performance, a comparison was drawn against a preexisting lane-changing model through a microscopic traffic simulator within an HOV lane context. The study revealed that the choice of target lane is influenced based on lane-specific characteristics, like average speed and traffic density, as well as variables linked to path planning and the intricate interactions between the subject vehicle and its neighboring vehicles.

Coifman et al. (2006) introduced within this study is the notion of delay attributed to lane-change maneuvers, accompanied by a method designed to assess these delays within a specific lane. This assessment is relative to scenarios devoid of any lane-change maneuvers. The researchers explored the impact of lane-change actions on delays in traffic, leveraging vehicle trajectory data containing precise temporal and positional information for each vehicle. The study postulated that the devised methodologies offer an effective means to estimate delays stemming from lane-change maneuvers, particularly on congested freeway segments.

Kesting et al. (2007) suggested a comprehensive model called as minimizing overall braking induced by lane changes (MOBIL). This model aimed not only to evaluate the desirability of a particular lane but also to consider the risks inherent in executing lane changes. The study established both general safety criteria, preventing hazardous lane changes and collisions, and incentive criteria that incorporated the mutual pros and cons of lane changes for other drivers, factoring in a politeness factor. Employing the MOBIL model, simulations were conducted involving cars and trucks, utilizing the intelligent driver model as the foundational car-following model. The study recommended an exploration of the lane-changing rate, accounting for its variation concerning both spatial coordinates and traffic density.

Sun, and Kondyli (2010) have quantified the interactions between vehicles while executing a lane-changing action, utilizing video data captured on a bustling arterial street in Gainesville, Florida. Through this data, distinctions were drawn among three categories of lane changes: voluntary, compelled, and collaborative/competitive. A specific model was formulated, focusing particularly on competitive/cooperative lane changes. This model enabled the examination of whether following vehicles cooperated with the primary vehicle during lane changes. To validate the model's efficacy, it was implemented within the CORSIM microsimulator package. The study findings demonstrated that this novel model exhibited improved accuracy in emulating observed traffic patterns across varying congestion levels.

Arai, and Sentinuwo (2012) presented a new Cellular Automation model designed to explain the occurrences of sudden-braking actions and lane-changing maneuvers in traffic flow. Additionally, the study delved into the ramifications of lane-changing maneuvers on traffic congestion arising from spontaneous braking actions. Investigating the effects within a two-lane, one-way traffic scenario, the researchers examined the influence of factors like spontaneous braking probability and lane-changing maneuvers. Their findings suggested that traffic congestion could stem from not only road capacity limitations but also driver behaviors. While the study highlighted the substantial impact of spontaneous braking on local vehicle speeds, it did not encompass the broader systemic implications. As a result, future endeavors should encompass a holistic consideration of all traffic-related facets to provide a more comprehensive perspective.

Sun, and Elefteriadou (2012) contended that most prevailing models had been developed and validated using vehicle trajectories, lacking the incorporation of driver-specific attributes. To address this, an experiment was orchestrated utilizing instrumented vehicles, observing drivers' behaviors across diverse situations involving lane changes in urban environments. The gathered data, derived from lane-changing maneuvers executed within an urban street setting, were employed to categorize 40 drivers into four distinct groups. The study's ultimate deduction was that to enhance the precision of lane-change behavior models, it is imperative to account for driver behaviors within urban street networks.

Rahman et al. (2013) conducted a comprehensive review of current microscopic lane-changing models, which are commonly applied in roadway traffic simulation. The objective was to enhance understanding regarding the specific attributes, strengths, and limitations of these models. One notable observation was that the existing models insufficiently accounted for driver distractions, environmental conditions, and geometric features (such as curves) of roadways. This complexity becomes more pronounced within real-time traffic scenarios. The study's recommendation underscored the necessity for detailed microscopic vehicle trajectory datasets. These datasets are essential for the development of new lane-changing models that accurately capture the complexities of real-time traffic. Furthermore, such datasets are crucial for calibrating and validating lane-changing models to ensure their fidelity in representing real-world traffic dynamics.

Ding et al. (2013) evaluated the efficacy of utilizing Back-Propagation (BP) neural networks to predict lane-changing trajectories using historical vehicle data. The comparison encompassed training time and prediction accuracy, contrasting the results between the Back-Propagation (BP) neural network model and the Elman Network model. To validate the model's performance, driving simulator data was employed. The findings concluded that the Back-Propagation (BP) neural network proved to be a precise method for predicting driver lane-changing behavior within urban traffic flow.

Zheng et al. (2014) utilized a neural network (NN) model to effectively capture the intricate nature of lane changing behavior. Vehicle trajectory data were used for estimating and validating the model.A multinomial logit (MNL) model was also incorporated for comparison purposes. The findings revealed that both models performed adequately for non-lane-changing instances. However, when it came to lane-changing samples, the neural network (NN) model outperformed the MNL model. Specifically, the NN model accurately predicted 94.58% of left lane-changing instances and 73.33% of right lane-changing instances, while the MNL model exhibited significantly lower accuracy, correctly predicting only 13.25% and 3.33% of lane-changing instances to the left and right respectively.

Zheng (2014) conducted a comprehensive review of recent advancements in modeling lane-changing behavior. The researcher organized the lane-changing behavior models into two distinct categories: those designed to comprehend the decision-making process behind lane changing, and those aimed at assessing the repercussions of lane changing actions by neighboring vehicles. The review delved into the methodologies and essential attributes of various models within these categories. Ultimately, the study underscored the need for future research endeavors in this domain to further enhance the understanding and outcomes in the field of lane-changing behavior modeling.

Li et al. (2015) employed lane-changing models based on fuzzy logic, incorporating both drivers' socio-demographic characteristics and their lane-changing behaviors within work zones. The research focused on socio-demographic factors of drivers as independent variables and Lane-Changing Response Time (LCRT) and Distance (LCRD) as the resultant output variables. Notably, the implementation of the Drivers' Smart Advisory System (DSAS) effectively provided instructions to all drivers, encouraging earlier lane-changing preparations and subsequently reducing the time required for lane changes. The study highlighted the significance of further research in prioritizing aspects such as drivers' educational background, age, and gender within the context of lane-changing maneuvers.

Park et al. (2015) provided insights into the attributes of Discretionary Lane changes (DLC). By employing trajectory data from the Next Generation Simulation, the study analyzed traffic conditions surrounding DLC actions on a mesoscopic scale, allowing for a detailed examination. The findings underscored the considerable impact of speed and density differences on the rate of lane changes. Notably, the research identified that drivers exhibited a propensity to change lanes more frequently when aiming for increased speed and greater space in the target lane. It was concluded that the connections between lane-changing behavior, speed disparities, and traffic density differences exhibited statistical significance and a non-linear relationship.

Feng et al. (2015) conducted a simulation on an actual road segment, employing a novel cellular automaton model to validate the outcomes. The simulation aimed to assess alterations in overall traffic flow dynamics resulting from unconstrained lane-changing behavior within typical urban environment. In evaluating the effect of lane-changing, the study focused on two pivotal aspects: time and space. These dimensions were respectively quantified through average delay and transitable flow rates. To construct these parameters, the researchers employed dual independent variables: the probability of vehicle arrivals and the green signal ratio. The culmination of this investigation involved comparing two surfaces—namely, those arising from free lane-changing and uninterrupted forward progression—while also addressing the horizontal projection of their intersecting lines.

Pan et al. (2016) introduced a novel mesoscopic multi-lane model designed to effectively simulate both mandatory and discretionary lane-changing behaviors. The focus was on capturing the complex dynamics of multi-lane traffic, particularly within expressway contexts. By integrating lane-specific fundamental diagrams, the model could replicate dynamic and diverse lane flow distributions with heterogeneity.Additionally, various priority levels were assigned to distinct lane-changing motivations, reflecting varying levels of urgency. Calibration and validation of this mesoscopic multi-lane cell transmission model were carried out on a complex merging segment of California's State Route 241 freeway.The study not only highlighted the advantages and disadvantages of lane-changing maneuvers but also positioned the model as a tool for predicting the repercussions of traffic incidents and informing lane control strategies.

Li and Sun (2017) introduced an integrated model that combined vehicle lane-changing with microscopic dynamic car-following within the context of a road bottleneck. The researchers explored the impact of lane-changing on various aspects including traffic effectiveness, safety, and fuel usage. The investigation considered a range of variables such as the distance from the emergency sign. preceding the lane closure, speed limits, and traffic density. By conducting comprehensive simulations across various scenarios, the study revealed instances where lane-changing proved advantageous, shedding light on conditions under which this maneuver could offer benefits to the overall traffic system.

Huang et al. (2019) investigated the correlation between lane-changing spacing intervals facilitated by off-ramp provisions and prevailing traffic flow situations. By examining various lane-changing behaviors in off-ramp areas, the researchers investigated the subject. Employing VISSIM-based micro simulations in off-ramp scenarios, they captured traffic flow scenarios associated with diverse lane-changing spacing intervals and relevant model parameters like traffic volume and off-ramp vehicle ratio. Their findings indicated a direct relationship between lane-changing spacing intervals and both traffic volume and off-ramp vehicle ratio, with increased intervals observed under higher traffic volume and off-ramp vehicle ratios. The study underscores the potential for enhancing traffic capacity by optimizing lane-changing spacing intervals and related behaviors.

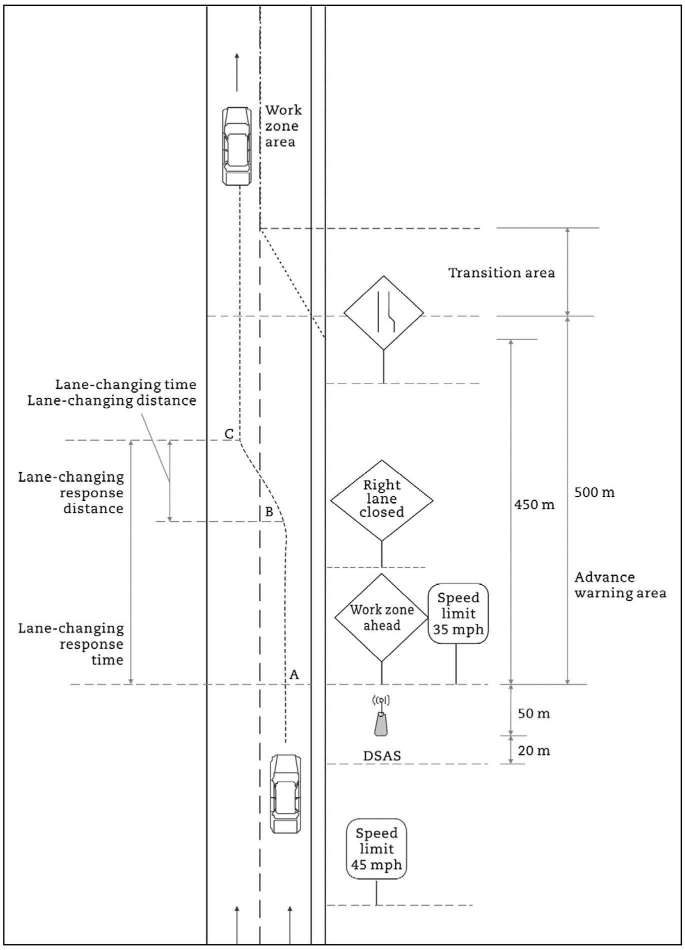

Fig. 5 Diagram illustrating lane-changing behavior using Drivers' Smart Advisory System (Source Li et al. (2015)

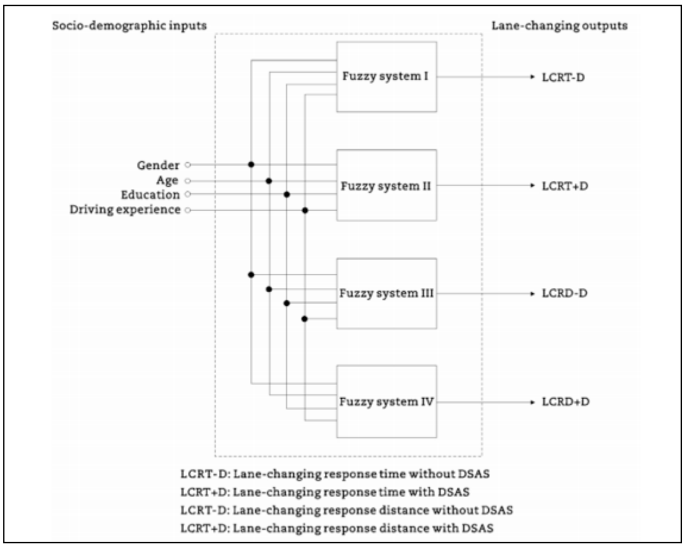

Fig. 6 Mapping of socio-demographic factors with lane-change decision time and distance. (Source Li et al. (2015)

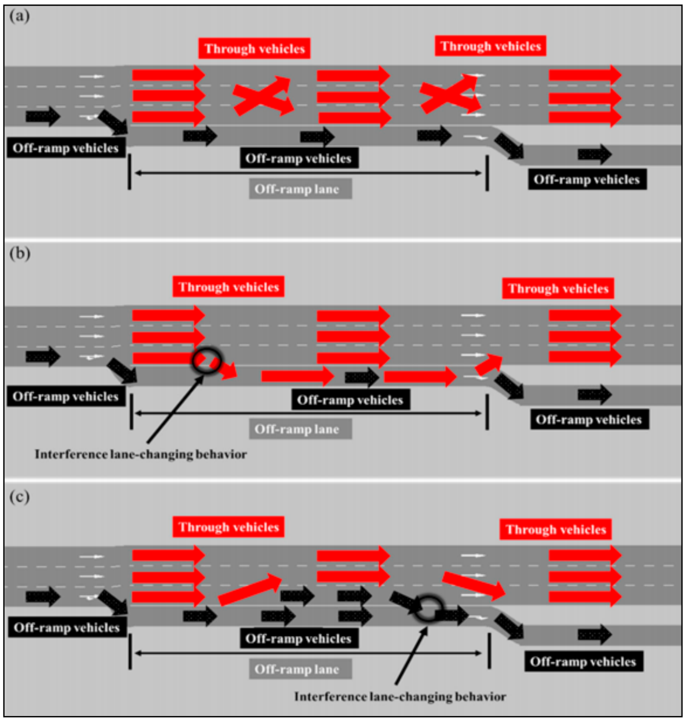

Fig. 7 Lane-changing behaviors exhibited by primary through vehicles in various traffic conditions: (a) no congestion; (b) due to traffic flow saturation or exceeding saturation and (c) off ramp traffic flow saturation or over-saturation. (Source Huang et al. (2019)

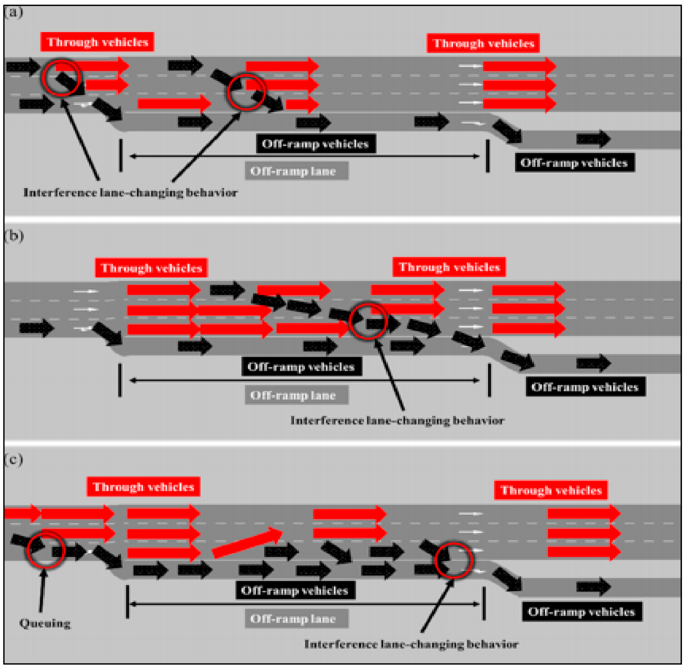

Fig. 8 Lane-changing behaviors of off ramp vehicles under different traffic conditions: (a) no traffic jam; (b) through through traffic flow saturation or over-saturation and (c) off ramp traffic flow saturation or over-saturation. (Source Huang et al. (2019)

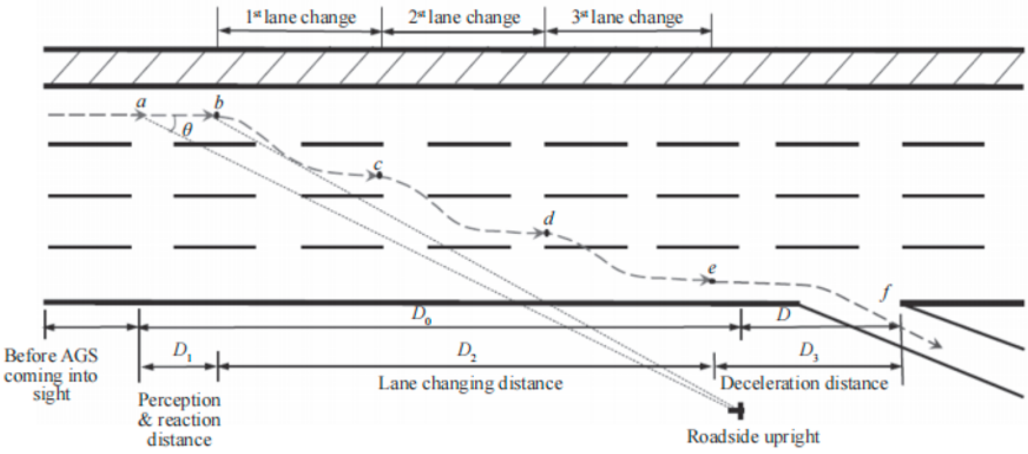

Fig. 9 Analysis of AGS distance and schematic calculation diagram for the innermost lane on a two-way eight-lane expressway (Su et al. (2022)

Su et al. (2022) involved the modification of advance guide signs (AGSs) to align with the lane change traversal time in free flow conditions in China. Utilizing VISSIM simulation, the researchers observed a slight variance between the eight-lane changing distance calculated through the modified theoretical approach and the VISSIM simulation in free flow conditions. The study recommended placement distances for all-level AGSs at 3 km, 2 km, 1.2 km, and 0.8 km, taking into consideration the formula for the attenuation of driver's short-term memory. Additionally, the proposed modified lane change distance formula incorporated factors such as the driver's waiting, reaction, and execution periods.

4. SUMMARY AND DISCUSSION

Lane changing behavior is a crucial aspect of traffic dynamics that plays a important role in influencing traffic flow, congestion, safety, and overall road efficiency. Researchers have extensively studied various aspects of lane changing behavior, seeking to understand the factors that drive drivers to change lanes, the patterns of lane changing under different conditions, and the impacts of these maneuvers on the surrounding traffic environment. Studies have explored both discretionary and mandatory lane changes, considering factors such as speed differentials, traffic density, driver characteristics, road geometry, weather conditions, and the presence of other vehicles.

Lane changing behavior can be analyzed by considering various elements like road user characteristics, vehicle attributes, pavement conditions, spatial availability, and location specifics. Among these factors, driver behavior and vehicle trajectories are frequently employed by researchers to investigate lane changing tendencies. Recent advancements in the field have introduced innovative techniques like Back-Propagation neural network models, Cellular Automation models, fuzzy logic-based lane-changing models, Kalman filter methods, car-following models incorporating road bottlenecks, vehicle-to-vehicle (V2V) communication, VISSIM based micro simulations, queuing analysis, and Markov's process. These diverse approaches collectively contribute to a comprehensive understanding of lane changing behavior in urban networks. These methods address different facets of the phenomenon, revealing insights into how drivers make lane-changing decisions and how vehicles interact within the traffic flow. By utilizing a range of methodologies and considering various influencing factors, researchers aim to uncover the underlying dynamics and intricacies of lane changing behavior in urban settings.

Sheu, and Ritchie (2001) and Qi et al. (2016) have adopted Kalman filter techniques to validate the lane changing behavior parameters and to suggest the better understanding of the lane changing phenomena. Sheu, and Ritchie (2001) focused mainly on the traffic characteristics related to incidents within lanes and between lanes based on queue length analysis, whereas Qi et al. (2016) focused on the lane-changing maneuvers of high occupancy vehicle (HOV) based on aerial photo. Huang (2002), Arai, and Sentinuwo (2012), and Feng et al. (2015) have utilized the cellular automation model to study the lane-changing behavior of the urban road network. Huang (2002) has not given the sufficient information regarding the driver and vehicle behavior, whereas Arai, and Sentinuwo (2012) investigated the effect of spontaneous-braking behavior and lane-changing maneuver in traffic flow. In other hand Feng et al. (2015) have used cellular automaton to validate the result. The study seems to be accurate as it covered the effect of lane-changing behavior with respect to time and space.

Most of the research (Kesting et al. 2007; Golbabaei et al., 2014; Li et al., 2015; Hill et al., 2015; He et al. ,2016; Qi et al., 2017; Zhang et al, 2018; Vechione et al., 2018; Shi, and Liu, 2019; Das, and Ahmed, 2019; and Li et al., 2020) have explored the lane-changing characteristics based on driver behavior. More ever Kesting et al. (2007) have taken the pros and cons of the drivers linked to a lane change through the politeness factor. Golbabaei et al. (2014) focused on the parameters which affects the road users' aggressive overtaking maneuvers. Li et al. (2015) considered drivers socio-demographic characteristics and lane-changing maneuvers in work zones based on fuzzy logic. Hill et al. (2015) have analyzed driver categories, lane changing attributes, lane changing timeframes, and gap acceptance traits. He et al. (2016) focused on lane changing and merging in work zones with respect to signs, speed reduction, driver aggressiveness, entry, and exit from the work zone area. Qi et al. (2017) established the correlation between a driver's heart rate and their lane-changing behavior in the context of urban traffic congestion. Zhang et al (2018) analyzed the analysis of lane-changing behavior concerning three traffic situations: free flow, medium flow, and heavy flow. Vechione et al. (2018) analyzed drivers' behavior during mandatory and discretionary lane changes. Shi, and Liu (2019) have collected driving behavior and driving workload characteristic parameters in different speed limit configurations. Das, and Ahmed (2019) has taken the influence of adverse weather environments on lane-changing behavior. Li et al. (2020) investigated how traffic congestion influenced driver behavior on roads immediately following congestion, known as post-congestion roads. However, most of the researcher have not included the effect of season and days in the behavior of lane changing maneuver, except Das, and Ahmed (2019), where they have taken the influence of adverse weather environments on lane-changing action He et al. (2016), where they observed that under heterogeneous traffic conditions the mean duration of lane changes was notably longer in heavy fog as compared to clear weather.

Jin (2010) and Li, and Sun (2017) have discussed about car following models with road bottleneck. Jin (2010) studied the impact of lane-changing maneuvers on the overall traffic flow with the help of advanced fundamental diagrams and simple kinematic wave model. The study was a good study, but they could have included the lane change frequencies in various road configurations, positions, on-ramp/off-ramp volumes, and traffic scenarios for better understanding. However, Li, & Sun (2017) have explored how lane changes impact both traffic efficiency and safety, speed limit, traffic density and fuel consumption. The study sounds to be the good one as it covered all the possible impacts of illegal lane changing behavior.

Moridpour et al. (2010), Aghabayk et al. (2011), and Chen et al. (2016) have considered the lane-changing behavior involving heavy vehicles. Moridpour et al. (2010) observed that during the lane changing maneuver, there is little change in speed of heavy vehicles. They have not considered the driver behavior. Aghabayk et al. (2011) explored the decision-making and execution of lane-changing maneuvers by drivers of heavy vehicles on both arterial roads and freeways. The result presented in the study in not having proper justification. Chen et al. (2016) observed that heavy vehicles discourage lane changing behavior and large gaps behind the heavy vehicles contributed to underutilization of road capacity. The study was a good to be considered as it covered all the parameters related to the lane changing behavior of the heavy vehicles and passenger cars. Cooper et al. (2008) and Rahman et al. (2013) have analyzed the lane changing behavior based on cell phone conversation. Cooper et al. (2008) explored how cell phone conversations impact a driver's lane-changing behavior. Whereas Rahman et al. (2013) took into account real-time traffic conditions monitoring based on the driver distraction, environmental factors, and geometric features of the roadway. The study found to be more realistic as it considered all the aspects of the lane-changing behavior within the context of real-time traffic conditions.

Some of the researchers (Choudhury, 2005); Duret et al., 2011; Sun, and Elefteriadou, 2012; Zheng et al., 2014; Marczak et al., 2014; and Chen et al., 2016) have studied the lane-changing characteristics based on vehicle trajectory. However, none of them have considered the driver behavior except Marczak et al. (2014), where the study has considered the lane changes within weaving areas, their locations, and the gaps they accept. The result was satisfactory and is practically applicable to the urban road network system. The researcher like Ding et al. (2013), Zheng et al. (2014), and Qi et al. (2017) have taken back propagation neural network model to analyze the lane changing behavior. Ding et al. (2013), Zheng et al. (2014) have taken vehicle trajectory data for the model, whereas Qi et al. (2017) have taken the vehicle trajectory as well as driver behavior to validate the result obtained from the model, which was a good study considering the lane changing behavior. Wang et al. (2019) and Mohanty, and Dey (2020) have adopted some new technology to study the impact of lane changing behavior. Wang et al. (2019) have adopted vehicle-to-vehicle (V2V) communication technology to know the lane-changing decision and planning with respect to the real time traffic scenario. The study found to be a good one as it covers the whole factors influencing the lane changing behavior. On other hand Mohanty, and Dey (2020) have analyzed the lane changing behavior of approaching through vehicles with the help of Markov's process. They have evaluated the lane changing probabilities of the vehicles and compared with the lane changing probabilities derived from real-world field data. The result of the study was very appreciable and considered to be the best study. The research work could be used for the better traffic management in the urban road network.

These investigations have employed diverse methodologies, ranging from field observations and video data collection to driving simulators and computational models. Many studies have highlighted the complex interplay between factors like driver aggressiveness, traffic conditions, lane-specific attributes, and the presence of different vehicle types. Researchers have developed mathematical models, cellular automaton approaches, neural network models, and statistical analyses to illustrate the essence of lane changing behavior accurately. The findings of these studies have underscored the importance of understanding and predicting lane changing behavior for traffic management, safety enhancements, road design, and the advancement of intelligent transportation systems. Moreover, research in this domain has identified the need for incorporating real-world driver characteristics, cognitive load, environmental factors, and emerging technologies like connected and automated vehicles into comprehensive models that accurately simulate and predict lane changing behavior. By shedding light on the intricacies of this behavior, these studies contribute to creating safer and more efficient roadways for the benefit of both drivers and society at large.

Authors (Year of publication)	**Approaches adopted for analysis**
Sheu, and Ritchie (2001)	A modeling approach based on stochastic methods to estimate lane-changing fractions and queue lengths in real-time to manage traffic incidents.
Huang (2002)	Speed limit effects and stochastic noise analysis using cellular automaton techniques.
Kang, and Chang (2004)	Correlations between lane-changing action and traffic flow attributes during both peak and off-peak periods.
Laval, and Daganzo (2005)	Lane changing behaviour during congested traffic.
Choudhury (2005)	Lane changing behaviour considering High Occupancy Vehicle (HOV) lane.
Coifman et al. (2006)	Assessing the impact of lane-change maneuvers on traffic delays using vehicle trajectory data.
Kesting et al. (2007)	Risk associated with lane changes based on car following theory.
Cooper et al. (2008)	Influence of cell phone conversations on driver's lane-changing behavior.
Adelakun, and Cherry (2009)	Perceptions of urban congestion and safety challenges among truck drivers with respect to the lane changing behavior.
Huizhi et al. (2010)	Impact of lane-changing behaviour on traffic capacity.

Jin (2010)	Examination of the effects of lane-changing traffic on overall traffic flow utilizing advanced fundamental diagrams and a simple kinematic wave model.
Sun, and Kondyli (2010)	Lane-changing maneuver observation under different levels of congestion.
Moridpour et al. (2010)	Study on lane changing action of heavy vehicle and passenger car drivers in congested traffic conditions.
Aghabayk et al. (2011)	Examined the actions of heavy vehicle drivers when deciding to change lanes on arterial roads.
Duret et al. (2011)	Lane changing behavior assessment based on vehicle trajectories.
Arai, and Sentinuwo (2012)	Impact of lane-changing action on congestion caused by spontaneous-braking phenomena.
Sun, and Elefteriadou (2012)	Analysis of drivers' behavior under various urban lane-changing scenarios.
Hu et al. (2012)	Mechanism of non-motorized vehicle illegal lane-changing behavior taking into overtaking motivation and traffic safety.
Reimer et al. (2013)	Assessed the impact of age and cognitive demand on lane selection and lane changing maneuver.
Du et al. (2013)	Study of lane-changing maneuver on highways with various high-occupancy vehicle (HOV) access setups.
Rahman et al. (2013)	Microscopic lane-changing model based on driver distraction, environment and geometric factors of the roadway.
Ding et al. (2013)	The efficacy of Back-Propagation (BP) neural networks in predicting lane-changing trajectories using historical vehicle data.
Golbabaei et al. (2014)	Analysis of lane-changing maneuvers during aggressive overtaking at varied speed deviations.
Zheng et al. (2014)	Utilized a neural network model to comprehend the intricacies of lane-changing behavior using vehicle trajectory data.
Marczak et al. (2014)	Empirical examination of lane-changing behavior in a weaving segment.
Zheng (2014)	Lane-changing behavior modeling based on the lane changing decision-making process and the effect of surrounding vehicles on lane changing behavior.
Li et al. (2015)	Adopted fuzzy logic-based lane-changing models considering drivers socio-demographic characteristics and lane-changing behaviour in work zones.
Li et al. (2015)	Studied the influence of driver's lane-changing aggressiveness on two-lane traffic flow stability using a generalized lattice hydrodynamic model.
Park et al. (2015)	Discretionary lane changes actions based on speed difference and density difference.
Hill et al. (2015)	Examined the physical aspects of freeway lane changing by analyzing lane changing duration and gap acceptance attributes.
Feng et al. (2015)	Studied alterations in global traffic flow patterns during unrestricted lane-changing behavior in typical urban traffic environments.
Keyvan-Ekbatani et al. (2016)	Examined the decision-making process of lane-changing maneuvers across various driver profiles.
Qi et al. (2016)	Studied lane-changing maneuvers utilizing aerial photo data pre and post high occupancy vehicle lane configuration conversion.
Pan et al. (2016)	Utilized lane-specific fundamental diagrams to model dynamic lane flow distributions with heterogeneity in a mesoscopic multi-lane model.
He et al. (2016)	Focused on frequently lane changing and merging in work zones.
Shuaib (2016)	Incorporated decision-making capability of pedestrians influencing the lane changing behavior.
Chen et al. (2016)	Shared empirical insights into car-following and lane-changing behaviors, focusing on heavy vehicles.
Yun et al. (2017)	Examined lane-changing characteristics considering parameters such as lane-changing merging gap, lane-changing position, lane change delay, lane-changing steering angle, lane-changing deceleration, and safe lane-changing distance.
Li, and Sun (2017)	Explored the impact of lane-changing on traffic effectiveness, safety, and fuel usage.
Qi et al. (2017)	Correlation between driver's heart rate and lane-changing behavior during traffic jam.
Guo et al. (2018)	Explored lane-changing behavior in aggressive driving scenarios.
Zhang et al (2018)	Studied lane-changing behavior across free flow, medium flow, and heavy flow traffic conditions.
Ali et al. (2018)	Analyze various driving performance indicators during mandatory lane-changing behavior through a driving simulator.
Vechione et al. (2018)	Studied driver behavior in mandatory and discretionary lane changes.
Shi, and Liu (2019)	Examined driver lane changing behavior in relation to different speed limits and corresponding driving workload levels.
Das, and Ahmed (2019)	Impact of adverse weather environments on lane-changing behavior under heterogeneous traffic condition.
Wang et al. (2019)	Lane changing models based on vehicle-to-vehicle communication and lane-changing decision.
Huang et al. (2019)	Explored the relationship between lane-changing spacing intervals at off-ramp facilities and traffic flow situations.
Li et al. (2020)	Investigated the effect of traffic jam on driver behavior on post-congestion roads.
Mohanty, and Dey (2020)	Utilized markov's process to analyze lane changing behavior of approaching through vehicles at u-turns amid mixed traffic conditions.

TABLE 1 Summary of studies on lane changing behavior

5. CONCLUSIONS

The study of lane changing behavior is a multidimensional endeavor that encompasses a multitude of factors influencing driver decisions and interactions within traffic flow. Through a wide array of research methodologies, ranging from empirical data collection to advanced modeling techniques, researchers have gained valuable insights into the complexities of lane changing behavior. Lane changing behavior has emerged as a pressing concern within urban road networks, particularly in developing nations like India, where the complexities of mixed traffic conditions amplify the issue. The impacts of lane changing dynamics have far-reaching consequences, negatively impacting both the safety of neighboring vehicles and the overall traffic flow. The intricate nature of these challenges underscores the need for researchers to address them comprehensively and consider recent advancements.

Finding effective solutions to mitigate the adverse effects of lane changing is of utmost importance for the betterment of society and the environment. The urgency to develop innovative approaches arises from the need to improve road safety and streamline traffic management in urban settings. As researchers work to navigate these intricate dynamics, it is imperative to focus on current developments that can provide sustainable solutions to these pressing challenges.

The review delves into the multifaceted aspects of lane changing behavior, encompassing its causes, impacts, prediction techniques, and overarching implications for traffic safety. Despite the considerable body of research dedicated to studying lane changing behavior, numerous countries continue to grapple with unresolved challenges in this domain. Researchers from various corners of the world have endeavored to contextualize lane changing behavior within the urban road networks of their respective regions, taking into account diverse parameters that align with unique traffic characteristics. A prevailing theme among these studies is the common utilization of driver behavior and vehicle trajectory analysis as fundamental methods for investigating lane changing behavior. Researchers have probed into crucial factors such as target lane preferences, gap availability, politeness factors, the effect of cell phone conversations, impact of spontaneous braking, impacts of age and cognitive demands on lane choice, as well as environmental and geometric factors like pavement conditions, lighting, and roadway curvature. Furthermore, aggressive overtaking maneuvers, drivers' socio-demographic characteristics, educational background, age, and gender have been scrutinized as contributors to lane changing behavior.The analysis of lane changing behavior has revealed that it is influenced by numerous factors, encompassing driver characteristics, vehicle attributes, road conditions, and traffic density. Driver behavior and vehicle trajectory data have been particularly instrumental in understanding the patterns and motivations behind lane changes. The introduction of innovative models, such as Back-Propagation neural networks, Cellular Automation models, and fuzzy logic-based approaches, has allowed for a more nuanced understanding of how drivers navigate lane changes in diverse scenarios. Additionally, studies have delved into the impacts of specific conditions on lane changing behavior, such as adverse weather conditions, congestion, and connected vehicle technologies. This has provided valuable insights into how external factors can influence driver decisions and the overall flow of traffic.

Overall, the comprehensive investigation of lane changing behavior contributes not only to our understanding of individual driver choices but also to the broader realm of traffic management, road safety, and infrastructure design. As road networks continue to evolve, the findings from these studies will be crucial in developing effective strategies for optimizing traffic flow, reducing congestion, enhancing safety, and shaping the future of transportation systems. Further research in this field is essential to continually refine our understanding and improve our ability to predict and manage lane changing behavior in various urban scenarios. Notably, a significant portion of research has not yet incorporated weather-related factors incorporating the examination of lane changing behavior, with only a few exceptions. While road user and vehicular characteristics have often been harnessed to understand the impacts of lane changing behavior, and in some cases, location and space availability have been explored, the influence of pavement characteristics remains largely unexplored. Lane changing behavior is intricately intertwined with the broader realm of traffic safety, encompassing the well-being of drivers, vehicles, pedestrians, and effective traffic management. This dynamic nexus prompts the emergence of numerous avenues for future exploration in this field of research. While prior studies predominantly centered around driver behavior and vehicle trajectory analysis, these approaches are now facing limitations due to their age and diminishing relevancy. In response, innovative methodologies such as back propagation neural network models, Cellular Automation models, fuzzy logic-based lane-changing models, Kalman filter techniques, car-following models integrated with road bottleneck considerations, vehicle-to-vehicle (V2V) communication paradigms, VISSIM based micro simulations, queuing analyses, diverse clustering techniques, and the insightful application of Markov's process offer promising alternatives. These progressive methodologies promise heightened accuracy, enhanced usability, and contemporary relevance. It is paramount that lane changing behavior remains aligned with established traffic rules and regulations while prioritizing traffic safety. Safeguarding the well-being of all road users and ensuring seamless traffic management converge as critical considerations in shaping and optimizing lane changing behaviors. As the study of lane changing behavior advances, it stands poised to play an instrumental role in cultivating safer and more efficient road networks. The present review consolidates a substantial body of significant scientific studies delving into the lane-changing behaviors exhibited by various vehicles. However, several articles were inaccessible, preventing their review and assessment of their relevance to the current context. Additionally, some articles presented only abstracts that piqued interest, but the complete articles were not accessible. Notably, in the studies conducted by various authors, it was observed that the majority of lane-changing investigations have been carried out exclusively in developed countries with established lane discipline. Few articles explore lane-changing patterns in developing countries, and there is a scarcity of studies focused on underdeveloped countries, where the actual challenges related to lane-changing patterns, safety, and congestion are prevalent. Lastly, the lane-changing behaviors of two-wheelers and cars are frequently examined, while the lane-changing dynamics of three-wheelers (prevalent in developing countries) and heavy vehicles (though infrequently observed, capable of causing significant traffic issues) receive limited attention in the literature. The review underscores the global scope of lane changing behavior research, emphasizing the prevalent focus on driver behavior and vehicle trajectory analysis. Despite the breadth of investigations, challenges persist in addressing lane changing behavior issues comprehensively, with potential opportunities for future studies to encompass weather-related effects and explore the less explored area of pavement characteristics' impact on lane changing dynamics. The future research should involve investigating the effectiveness of Intelligent Transportation Systems (ITS) in optimizing traffic flow and reducing congestion, employing advanced lane-changing algorithms. Future studies should also include experiments or simulations to understand how different personality types and psychological states impact lane-changing behavior. Machine learning algorithms should be explored for enhancing simulation models to predict lane-changing patterns. The interaction between drivers in the context of lane changing, risk assessment models for collisions, and the impact of environmental factors can be considered for future studies. Additionally, more research should delve into the adaptation of lane-changing decisions in adverse weather conditions, cultural influences on lane changing behavior, societal norms and regulations, and the interaction between human drivers and autonomous vehicles during lane changes.

REFERENCES

Adelakun, A., & Cherry, C. R. (2009). *Exploring truck driver perceptions and preferences: Congestion and conflict, managed lanes, and tolls* 88 th Annual Meeting of the Transportation Research Board, Washington, D.C. Conference CD Paper No. 09-1324.

Aghabayk, K., Moridpour, S., Young, W., Sarvi, M., & Wang, Y. B. (2011). Comparing heavy vehicle and passenger car lane-changing maneuvers on arterial roads and freeways. *Transportation research record*, *2260* (1), 94-101

Ali, Y., Zheng, Z., & Haque, M. M. (2018). Connectivity's impact on mandatory lane-changing behaviour: Evidences from a driving simulator study. *Transportation Research Part C: Emerging Technologies*, *93*, 292-309.

Arai, K., & Sentinuwo, S. R. (2012). Spontaneous-braking and lane-changing effect on traffic congestion using cellular automata model applied to the two-lane traffic. *IJACSA) International Journal of Advanced Computer Science and Applications*, *3* (8).

Chen, D., Ahn, S., Bang, S., & Noyce, D. (2016). Car-following and lane-changing behavior involving heavy vehicles. *Transportation Research Record*, *2561* (1), 89-97.

Choudhury, C. F. (2005). *Modeling lane-changing behavior in presence of exclusive lanes* (Doctoral dissertation, Massachusetts Institute of Technology).

Coifman, B., Mishalani, R., Wang, C., & Krishnamurthy, S. (2006). Impact of lane-change maneuvers on congested freeway segment delays: Pilot study. *Transportation Research Record*, *1965* (1), 152-159.

Cooper, J. M., Vladisavljevic, I., Strayer, D. L., & Martin, P. T. (2008, January). Drivers' lane changing behavior while conversing on a cell phone in a variable density simulated highway environment. In *Proceedings of the 87th Annual Meeting of Transportation Research Board*.

Das, A., & Ahmed, M. M. (2019). Exploring the effect of fog on lane-changing characteristics utilizing the SHRP2 naturalistic driving study data. *Journal of Transportation Safety & Security*, 1-26.

Ding, C., Wang, W., Wang, X., & Baumann, M. (2013). A neural network model for driver's lane-changing trajectory prediction in urban traffic flow. *Mathematical Problems in Engineering*, *2013*.

Du, Y., Wu, G., Boriboonsomsin, K., & Chan, C. Y. (2013). Empirical study of lane-changing behavior along different types of high-occupancy vehicle facilities in California. *Transportation research record*, *2396* (1), 143-150.

Duret, A., Ahn, S., & Buisson, C. (2011). Passing rates to measure relaxation and impact of lane-changing in congestion. *Computer-Aided Civil and Infrastructure Engineering*, *26* (4), 285-297.

Feng, S., Li, J., Ding, N., & Nie, C. (2015). Traffic paradox on a road segment based on a cellular automaton: Impact of lane-changing behavior. *Physica A: Statistical Mechanics and its Applications*, *428*, 90-102.

Golbabaei, F., Nejad, F. M., & Noory, A. R. (2014). A microscopic analysis of speed deviation impacts on lane-changing behavior. *Transportation Planning and Technology*, *37* (4), 391-407.

Guo, M., Wu, Z., & Zhu, H. (2018). Empirical study of lane-changing behavior on three Chinese freeways. *PloS one*, *13* (1), e0191466.

He, Y., Shu, Z., Ge, Y., & Daniel, J. (2016). Drivers' lane change maneuver and speed behavior in freeway work zones. In *Proceedings of SAE-China Congress 2015: Selected Papers* (pp. 229-241). Springer, Singapore.

Hill, C., Elefteriadou, L., & Kondyli, A. (2015). Exploratory analysis of lane changing on freeways based on driver behavior. *Journal of transportation engineering*, *141* (4), 04014090.

Hu, X., Wang, W., & Yang, H. (2012). Mixed traffic flow model considering illegal lane-changing behavior: Simulations in the framework of Kerner's three-phase theory. *Physica A: Statistical Mechanics and its Applications*, *391* (21), 5102-5111.

Huang, D. W. (2002). Lane-changing behavior on highways. *Physical Review E*, *66* (2), 026124.

Huang, Z., Zhang, Z., Li, H., Qin, L., & Rong, J. (2019). Determining appropriate lane-changing spacing for off-ramp areas of urban expressways. *Sustainability*, *11* (7), 2087.

Huizhi, X., Guozhu, C., & Yulong, P. (2010). Study on effect of lane-changing behavioral characteristic to capacity. *Sciencepaper Online*, *5* (10), 749-753.

Jin, W. L. (2010). A kinematic wave theory of lane-changing traffic flow. *Transportation research part B: methodological*, *44* (8-9), 1001-1021.

Kang, K. P., & Chang, G. L. (2004, October). Observations of macroscopic non-mandatory lane-changing behaviors on the Capital Beltway. In *Proceedings. The 7th International IEEE Conference on Intelligent Transportation Systems (IEEE Cat. No. 04TH8749)* (pp. 441-446). IEEE.

Kesting, A., Treiber, M., & Helbing, D. (2007). General lane-changing model MOBIL for car-following models. *Transportation Research Record*, *1999* (1), 86-94.

Keyvan-Ekbatani, M., Knoop, V. L., & Daamen, W. (2016). Categorization of the lane change decision process on freeways. *Transportation research part C: emerging technologies*, *69*, 515-526.

Laval, J. A., & Daganzo, C. F. (2005). Multi-lane hybrid traffic flow model: a theory on the impacts of lane-changing maneuvers. In *84th transportation research board's annual meeting, Washington, DC*.

Li, G., Lai, W., Sui, X., Li, X., Qu, X., Zhang, T., & Li, Y. (2020). Influence of traffic congestion on driver behavior in post-congestion driving. *Accident Analysis & Prevention*, *141*, 105508.

Li, Q., Qiao, F., & Yu, L. (2015). Socio-demographic impacts on lane-changing response time and distance in work zone with Drivers' Smart Advisory System. *Journal of traffic and transportation engineering (English edition)*, *2* (5), 313-326.

Li, X., & Sun, J. Q. (2017). Studies of vehicle lane-changing dynamics and its effect on traffic efficiency, safety and environmental impact. *Physica A: Statistical Mechanics and its Applications*, *467*, 41-58.

Li, Z., Zhang, R., Xu, S., & Qian, Y. (2015). Study on the effects of driver's lane-changing aggressiveness on traffic stability from an extended two-lane lattice model. *Communications in Nonlinear Science and Numerical Simulation*, *24* (1-3), 52-63.

Marczak, F., Daamen, W., & Buisson, C. (2014, January). Empirical analysis of lane changing behavior at a freeway weaving section. In *93rd Annual Meeting of the Transportation Research Board, Washington, DC*.

Mohanty, M., & Dey, P. P. (2020). Modelling the lane changing behavior of major stream traffic due to U-turns. *Transportation Engineering*, 100012.

Moridpour, S., Rose, G., & Sarvi, M. (2010). Effect of surrounding traffic characteristics on lane changing behavior. *Journal of Transportation Engineering*, *136* (11), 973-985.

Pan, T. L., Lam, W. H., Sumalee, A., & Zhong, R. X. (2016). Modeling the impacts of mandatory and discretionary lane-changing maneuvers. *Transportation research part C: emerging technologies*, *68*, 403-424.

Park, M., Jang, K., Lee, J., & Yeo, H. (2015). Logistic regression model for discretionary lane changing under congested traffic. *Transportmetrica A: transport science*, *11* (4), 333-344.

Qi, W., Wen, H., Wu, Y., & Qin, L. (2017). Effect model of urban traffic congestion on driver's lane-changing behavior. *Advances in Mechanical Engineering*, *9* (9), 1687814017724087.

Qi, X., Wu, G., Boriboonsomsin, K., & Barth, M. J. (2016). Empirical study of lane-changing characteristics on high-occupancy-vehicle facilities with different types of access control based on aerial survey data. *Journal of Transportation Engineering*, *142* (1), 04015034.

Rahman, M., Chowdhury, M., Xie, Y., & He, Y. (2013). Review of microscopic lane-changing models and future research opportunities. *IEEE transactions on intelligent transportation systems*, *14* (4), 1942-1956.

Reimer, B., Donmez, B., Lavallière, M., Mehler, B., Coughlin, J. F., & Teasdale, N. (2013). Impact of age and cognitive demand on lane choice and changing under actual highway conditions. *Accident Analysis & Prevention*, *52*, 125-132.

Sheu, J. B., & Ritchie, S. G. (2001). Stochastic modeling and real-time prediction of vehicular lane-changing behavior. *Transportation Research Part B: Methodological*, *35* (7), 695-716.

Shi, J., & Liu, M. (2019). Impacts of differentiated per-lane speed limit on lane changing behaviour: A driving simulator-based study. *Transportation research part F: traffic psychology and behaviour*, *60*, 93-104.

Shuaib, M. M. (2016). Modeling the Pedestrian Ability of Detecting Lanes and Lane Changing Behavior. *Modern Applied Science*, *10* (7), 1-9.

Su, X., Ma, Y., Li, R., Sun, X., & Han, Y. (2022). Placement Distance of Exit Advance Guide Sign on an Eight-Lane Expressway Considering Lane Changing Behaviour in China. *Promet-Traffic&Transportation*, *34*(2), 285-295.

Sun, D., & Elefteriadou, L. (2012). Lane-changing behavior on urban streets: An "in-vehicle" field experiment-based study. *Computer-Aided Civil and Infrastructure Engineering*, *27* (7), 525-542.

Sun, D., & Kondyli, A. (2010). Modeling vehicle interactions during lane-changing behavior on arterial streets. *Computer-Aided Civil and Infrastructure Engineering*, *25* (8), 557-571.

Vechione, M., Balal, E., & Cheu, R. L. (2018). Comparisons of mandatory and discretionary lane changing behavior on freeways. *International journal of transportation science and technology*, *7* (2), 124-136.

Wang, J., Gao, C., Zhu, Z., & Yan, X. (2017). Multi-lane changing model with coupling driving intention and inclination. *Promet-Traffic&Transportation*, *29*(2), 185-192.

Wang, Z., Shi, X., & Li, X. (2019). Review of lane-changing maneuvers of connected and automated vehicles: models, algorithms and traffic impact analyses. *Journal of the Indian Institute of Science*, 1-11.

Yun, M., Zhao, J., Zhao, J., Weng, X., & Yang, X. (2017). Impact of in-vehicle navigation information on lane-change behavior in urban expressway diverge segments. *Accident Analysis & Prevention*, *106*, 53-66.

Zhang, L., Chen, C., Zhang, J., Fang, S., You, J., & Guo, J. (2018). Modeling lane-changing behavior in freeway off-ramp areas from the shanghai naturalistic driving study. *Journal of Advanced Transportation*, *2018*.

Zheng, J., Suzuki, K., & Fujita, M. (2014). Predicting driver's lane-changing decisions using a neural network model. *Simulation Modelling Practice and Theory*, *42*, 73-83.

Zheng, Z. (2014). Recent developments and research needs in modeling lane changing. *Transportation research part B: methodological*, *60*, 16-32.