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From lane-less to lane-free: Implications in the era of automated vehicles

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ABSTRACT

Advances in autonomous vehicle (AV) technology and research into connected autonomous vehicle (CAV) technology have renewed interest in lane-free traffic. The present study reviews a large body of scientific literature to explore the potential impacts of lane-less and lane-free traffic streams and examines the control strategies and trends of lane-free traffic through the lens of future transport. The findings indicate that lane-free traffic has the potential to positively impact road traffic, including an increase in traffic performance and a rise in road infrastructure capacity due to efficient space use and the seepage behavior of small-sized vehicles (e.g., motorized two-wheelers) in mixed traffic scenarios. Furthermore, studies on lane-less traffic with human-driven vehicles can provide essential insights into the potential behavior of lane-free AV traffic and how AVs might be programmed and designed to operate safely and effectively in complex settings. For instance, a lane-free traffic setting could be a better option for improving traffic flow when AVs vary in size, and seepage behavior can be incorporated into the driving characteristics of AVs.

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1. Introduction

In developing nations, where lane markings are often absent or lane enforcement is weak, non-lane-based movement is widely observed in traffic streams. This traffic phenomenon, known as lane-less traffic, has been extensively studied in recent years. Similarly, pedestrian and bicycle traffic commonly operates without lanes. Further insights can be drawn from the concept of shared space, an approach that promotes equal street use by all users. The idea of lane-free traffic, inspired by the early stages of urban transport when vehicles moved freely without restrictions, emerged with the advent of autonomous vehicles (AVs).

The goal of understanding lane-free traffic is to actively design control strategies for AVs or connected autonomous vehicles (CAVs) operating on roads without lanes, while the study of lane-less traffic mainly focuses on modeling the behavior of human drivers either ignoring lane markings or driving on roads without defined lanes (Sekeran et al., 2022). This paper includes studies on both topics, as we believe understanding the movement characteristics of human-driven vehicles (HVs) is instructive in designing motion strategies for AVs or CAVs in a less constrained traffic environment. Additionally, before autonomy becomes widespread, there will be a mixed traffic flow consisting of both human-driven and robotic vehicles (Mohajerpoor and Ramezani, 2019; Ramezani and Ye, 2019). Comparative research and cross-reference between lane-less and lane-free traffic studies is valuable for modeling mixed traffic flow.

Without lanes, vehicles can drive anywhere on the two-dimensional surface of the road (Papageorgiou et al., 2021). To maintain safe movement, models typically assume that each vehicle must follow all other vehicles in a 'visibility cone' and consider both the vehicles in front and on the sides that may suddenly move in Mulla et al. (2017). We expect lane-free roads will be gradually considered with the deployment of AVs, as AV technology should be able to detect and predict the movement of other vehicles in the stream efficiently. However, assessing the impact and modeling traffic flow in a heterogeneous and lane-free stream are challenging, especially when AVs are mixed with HVs.

Using conventional traffic management systems with AVs will limit their benefit (Manjunatha et al., 2022). Even though most papers on AVs are order-based and lane-based traffic systems, AVs may soon be able to move through traffic without keeping the lane center or following lane markings (Levy and Haddad, 2021). Recently, Sekeran et al. (2022) reviewed the emergence of this concept outlining its current developments. However, to the best of the authors' knowledge, understanding the potential impacts of non-lane based movement, the control strategies of lane-free traffic, as well as the insights of lane-less HV traffic on lane-free traffic are still in its early stages. The objectives of this paper are to synthesize the results of non-lane-based traffic to date, review simulations of lane-free traffic for AVs, and transfer knowledge between lane-less traffic and lane-free traffic. The current study aims to answer the following research questions:

- How do HVs operate in a non-lane-based environment?
- How might AVs operate in a lane-free environment?
- What are the potential impacts of lane-free traffic compared to its lane-based counterpart?
- How can the results of lane-less traffic be used to gain insights into lane-free traffic?

By addressing these questions, this study aims to shed light on the benefits and challenges of lane-free traffic systems for AVs and the broader implications of lane-free traffic for future transport. The remainder of the paper is organized as follows: Section 2 describes the methodological framework. The findings from the review on lane-less and lane-free are explored in Sections 3 and 4, respectively. Finally, Section 5 discusses the main findings of the review, while Section 6 draws conclusions from the study and outline the potential future research directions.

2. Methods

A comprehensive review of the extensive body of literature was conducted to map out the current knowledge and identify gaps related to lane-less and lane-free traffic systems. The applied methodology includes several steps, such as searching for potential papers and their inclusion criteria and synthesizing the findings of selected studies.

2.1. Search strategy and inclusion criteria

This study used the Web of Science and Scopus to retrieve scientific literature. The following code was used to extract papers from the Web of Science: ALL=((lane-free OR laneless OR lane-less OR non-lane) AND (vehicle OR car) NOT (aerial OR unmanned)). The code TITLE-ABS-KEY ((lane-free OR laneless OR lane-less OR non-lane) AND (vehicle OR car) AND NOT (aerial OR unmanned)) was also used to search for relevant papers in Scopus.

We conducted additional screening of the databases to include only papers written in English and published no earlier than 2012. Furthermore, review papers, editorial materials, and corrections were excluded. As a result, 182 and 150 papers were extracted from

Table 1
Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Articles provide sufficient detail on the study design and methods	Studies that are not original research
Articles include a clear description of the lane-free traffic or lane-less traffic system	Studies that are not accessible or not available in full text
Studies that report on traffic impact indicators	Studies that focus solely on technologies

the two respective databases. Finally, 216 papers were considered for further investigation after removing duplicates from the two databases. Inclusion and exclusion criteria were set, focusing on lane-free traffic and the analysis of its potential impacts, as shown in Table 1, which was used to extract the eligible articles included in the current review.

Furthermore, 15 relevant articles have been added using snowballing techniques. Following a comprehensive screening process that evaluated each article's title, abstract, and full text, a total of 85 relevant studies were included in the current review.

3. Lane-less traffic

3.1. Overview

(Un)signalized intersections, straight segments, urban road networks, and highways are among the investigated roadway elements. Most of the reviewed studies consider mixed traffic conditions that include motorized two-wheelers (MTW), motorized three-wheelers (MThW), passenger cars (PC), buses, light commercial vehicles (LCV), and heavy commercial vehicles (HCV). However, some papers consider homogeneous traffic comprising only PCs, as presented in Das and Chattaraj (2020), Das et al. (2019a) and Khansari et al. (2018).

Furthermore, studies typically used two main types of data sources: video-graphic (VG) and simulations (Sim). Additionally, Mahapatra and Maurya (2013) used GPS-based data, while Asaithambi and Shravani (2017) employed moving car observers and plate registration techniques.

The reviewed papers can also be classified into two primary categories: empirical studies and simulations, as shown in Section 3.2 and Section 3.3, respectively. The reviewed articles on HVs quantify various indicators, such as traffic flow, speed, stability, vehicle trajectory, or time to collision (TTC), and are then classified according to different types of roads, vehicles, data sources, and methodologies used.

3.2. Empirical

In this section, we present the empirical studies quantifying different traffic parameters, including flow, speed, distance between vehicles, headway time, TTC, and deceleration rate to avoid crash (DRAC), as outlined in Section 3.2.1, Section 3.2.2, and Section 3.2.3, respectively. Table 2 summarizes the synthesis of each study across considered indicators, study location, vehicle type, data source, and applied methodology, and presents the findings on the comparison of lane-less traffic with lane-based traffic.

3.2.1. Driving behavior analysis

Numerous studies explored drivers' micro decision and driving behavior in non-lane-based discipline to find the unique aspects of these behaviors compared to lane-based scenarios. They also made efforts to establish the relationship among different traffic parameters at the micro level and determine the empirical values and range of these parameters.

Ambarwati et al. (2014) estimated the smallest allowable space — known as a 'pore' — between vehicle corners in a lane-less traffic stream. The authors then expanded their research by evaluating essential pore sizes that are unique to each type of vehicle, establishing pore size density distributions, and developing fundamental traffic flow diagrams for MTW-MTW, MTW-PC, and PC-PC scenarios. The pore size in the traffic stream comprising the following vehicle n and a proceeding vehicle $n-1$ is calculated from the location of each vehicle. The following equations were used to estimate the pore size r_p of each vehicle with length L and Width W, and center of gravity (X, Y):

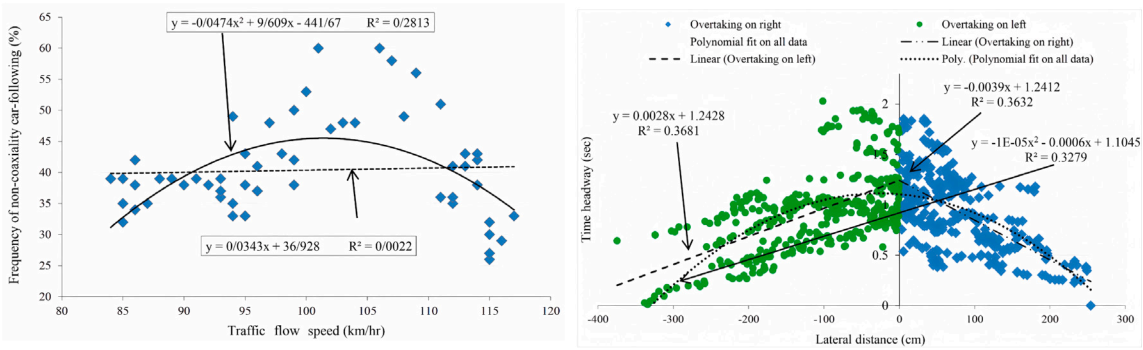
$$\Delta X = |X_n - X_{n-1}| - \left(\frac{L_n + L_{n-1}}{2}\right) \tag{1}$$

$$\Delta Y = |Y_n - Y_{n-1}| - \left(\frac{W_n + W_{n-1}}{2}\right) \tag{2}$$

$$r_p = \sqrt{\Delta X^2 + \Delta Y^2}. \tag{3}$$

According to Ambarwati et al. (2014), the pore size distribution is affected by the traffic composition. For example, the value can be as low as 2.9 m for MTW-MTW and 4.3 m for car-car configurations.

Madhu et al. (2022) reached similar conclusions by investigating the interactions of PC with MTW on a 250 m long and 10.5 m wide mid-block section of Indian roadway. Their statistical analysis showed that the MTW-MTW pair maintained the smallest lateral gap between the leader and follower, whereas the PC-PC pair maintained the highest and demonstrated that passenger



(a) (b)

Fig. 1. Non-coaxial car following behavior and overtaking behavior in lane-less traffic: (a) The relationship between the frequency of non-coaxial car-following behavior and traffic flow speed, (b) The relationship between time headway and lateral distance for left overtaking and right overtaking.
Source: Adopted from Khansari et al. (2018).

vehicles exhibit less lateral shifting tendencies as compared to MTW. The findings underlined that, when the lead vehicle is a PC as opposed to a MTW, the following vehicle is more attentive to avoid collisions. The authors signposted that while a PC changes its acceleration based on the relative position and speed of the leading vehicle, the MTW is solely impacted by the relative speed.

In order to determine how lateral distance and time headway relate to each other in lane-based and lane-less traffic situations, Khansari et al. (2020) researched this relationship on a rural freeway in Iran. They found a lateral gap of 0.50 to 2.20 m between two vehicles is required to be considered in 'lane-less' situations; it is deemed 'lane-based' and 'out of following' below and outside those limits, respectively. Based on their statistical analysis of video graphics data, in lane-less traffic, time headway and lateral distance were shown to be linearly related. They also highlighted that while lane-based traffic has an average headway time of 0.97 s, the lane-less scenario has a headway time of 0.81 s.

Pal and Sreenivasulu (2019) studied the relationship of lateral position of vehicles with their corresponding speed on a lane-less straight section of a road in India. The studied road segment has mixed traffic comprising MTW, MThW, PC, LCV, and HCV, and their findings pointed out that small-sized vehicles (MTW and MThW) showed more maneuverability and tended to travel close to the shoulder lane. They also found that when the vehicles are positioned close to the median, their distance from the center is linearly related to their speed. However, when the lateral position is far from the center, there is a quadratic relationship between the two variables. Mahapatra and Maurya (2013) investigated the relationship between longitudinal speed, heading angle, and lateral acceleration for traffic comprised of cars and MThW on a straight roadway with weak lane discipline. Using GPS-based data, the authors concluded that heading angle and lateral acceleration values are small at low speeds and quickly rise as speed increases until the maximum desired acceleration.

Madhu et al. (2020) studied different vehicles following dynamics and maneuvers of mixed traffic on lane-less Indian roadways, which accommodate different vehicle categories such as MTW, MThW, PC, buses, LCV, and HCV. The authors analyzed the lateral shift and trajectory of vehicles based on video-graphic data. Their results indicated that the vehicles shift laterally proportionally with the increase in volume to the capacity ratio of the roadway, which also shows that lateral shift is greater for small vehicles like MTW than for heavy vehicles like buses. The shift of the vehicles is computed as the inverse tangent of the ratio of lateral to longitudinal position over consecutive time steps (from the prior to the present time), and the results showed that an MTW has the highest shift (1.935°) followed by MThW (1.835°), whereas HCV has the lowest shift for the studied roadway (1.635°).

Furthermore, Chauhan et al. (2021) explored the driving behaviors of mixed and lane-less traffic in three isolated signalized intersections in Indian cities. The traffic is composed of MTW, MThW, PC, bus, and LCV. Like previous studies, small-size vehicles such as MTW and MThW vehicle classes exhibit the greatest lateral velocity, lateral movement, and aggressiveness. The findings indicate that lateral movement is proportional to traffic density in the section up to a certain point; beyond that point, lateral movement decreases because of a lack of available space. Additionally, it is noted that drivers traverse diagonally to cross over the dense section to achieve a longitudinally advantageous position while joining a queue, resulting in higher lateral movement during stopped conditions, whereas, for unaffected traffic flow conditions, vehicles are moving at their desired position; lateral movement of the vehicle significantly reduced.

In their study, Khansari et al. (2018) considered the notion of 'non-coaxial,' which refers to a considerable lateral gap (ranging from 50 centimeters to 220 centimeters) between the leader and following vehicles in a lane-less traffic stream, to investigate driving behavior. The behavior of overtaking was investigated on the Iranian freeway by considering a recording of traffic flow, and their results revealed that as the traffic flow speed increases, the frequency of non-coaxial car-following first increases and then decreases. The relationship between these two variables can be fitted by a parabola, as shown in Fig. 1(a). In comparison to overtaking on the left, overtaking on the right had a 33%, 28%, and 15% lower steering angle, final lateral distance, and lateral speed difference between the follower and leader, respectively, as shown in Fig. 1(b).

Asaithambi and Shravani (2017) identified two types of overtaking in a lane-less and heterogeneous traffic stream: flying overtaking and accelerative overtaking. The first occurs in free-flow conditions, while the second occurs when the following fast-moving vehicle approaches the slow-moving vehicle and decelerates to the same speed as the lead vehicle for a short period of time before accelerating to overtake. They employed the registration plate method and the moving car observer method. According to their findings, 62% of drivers perform flying overtaking, compared to 38% who use accelerative. Nonetheless, in the case of homogeneous and lane-based traffic streams on comparable routes, flying overtaking was found to be 20%.

Das et al. (2019b) examined the implications of center-line separation in lane-less traffic based on real-time data collected from two GPS-equipped vehicles on a rural, straight roadway in India. Their findings pointed out that a larger center-line separation resulted in a reduction in the longitudinal gap as the vehicles tend to follow the leading vehicles closely. Besides, they showed that the speed of the following vehicle rises as the center line separation exceeds 2 m. With the same experimental setting, Das et al. (2019a) demonstrated that when speed decreases and center-line separation rises, the likelihood of sustaining smaller gaps increases. Additionally, their finding highlighted that, for speeds above 60 km/h, for instance, a staggered car-following scenario led to a 15%–20% decrease in longitudinal gaps compared to orderly traffic flows. Furthermore, using the copulas approach, Das and Maurya (2018) showed that the following headway in lane-less situations is significantly lower (about 69%) than in lane-based situations as, at large center-line separations, the following vehicles experience less obstruction from the lead vehicle, and can better predict the lead vehicle's driving behavior. The authors indicated that the time headway increases with an increase in center-line separation.

In summary, this section explores various studies on driving behavior and vehicle interactions in lane-less traffic conditions, highlighting key factors such as lateral and longitudinal gaps, time headways, and vehicle maneuverability. The research indicates that vehicle interactions in lane-less systems are distinct from lane-based systems, with small vehicles exhibiting more lateral movement and flexibility. Additionally, traffic composition, lateral and longitudinal gaps, as well as vehicle speeds, are shown to influence driving behavior, such as overtaking and following dynamics. These findings emphasize the unique nature of traffic flow in non-lane-based environments.

3.2.2. Traffic performance

In addition to researching on the driving behavior of individual drivers, some research explores the impact of lane-less traffic on traffic performance from a macro-level perspective. The most common topic is to study the relationship between saturation flow and the proportion of different vehicle types in heterogeneous traffic.

Gaddam and Rao (2020) devised a two-sided continuum model to capture the complex behavior of lane-less mixed traffic comprising PC, MTW, MThW, and HCV. They demonstrated their model on a 10.5 m wide Indian urban arterial roadway, and it has been noted that traffic flow and density increase as the MTW share increases as they can percolate through small gaps in the stream due to their smaller physical dimensions and shorter space headway. Maximum flow values were found to be four times higher in MTW-only conditions than in PC-only scenarios, but if the MTW share is less than 0.4, it has no significant effect on traffic flow. In contrast, when the proportion of HCV in the traffic stream rises, the values of the traffic flow are reduced.

Sushmitha and Ravishankar (2020) analyzed the effects of vehicle composition on the saturation flow at eight signalized intersections in Indian cities. The studied intersections have a mix of MTW, MThW, PC, LCV, and HCV, with MTW having the highest market penetration (34%–60%). The author developed a linear regression model using the field data collected through video recording to estimate the saturation flow of the intersections while considering the geometric features, cycle time, green time, percentage of right-turning vehicles, and the market penetration rates of MTW, PC, and HCV as parameters. They found the saturation flow rate is positively correlated with the market penetration of MTW and green time, while it is inversely correlated with the market penetration of HCV and the number of right-turning vehicles.

Gaddam and Rao (2019) analyzed the lane-less heterogeneous traffic comprising MTW, MThW, PC, LCV, and HCV on a straight section of road in India. They found that the safe longitudinal headway maintained by vehicles decreases due to their off-centered behavior of lane-less traffic flow. This behavior decreases the critical gaps for vehicles. The authors also noted that vehicles maintain a shorter headway with MTWs compared to larger-sized vehicles; therefore, a large percentage of MTWs enhance the density and capacity of the traffic stream. Nevertheless, HCVs have the effect of a moving bottleneck, resulting in a decrease in traffic performance.

Padinjarapat and Mathew (2021) estimated saturation flow considering passenger car units for signalized intersections in India with heterogeneous traffic comprised of MTW, MThW, PC, and HCV, showing that the width of the road affects the saturation flow — vehicles tend to pack more closely together on narrower roads in the absence of lane markings, and consequently, the saturation flow rate per unit width decreases as the roadway width increases.

Farabi (2019) estimated the number of vehicle stops at signalized intersections with no significant disturbance from pedestrians and other roadside activities. The authors examined the Canadian capacity guide's application for determining the number of vehicle stops using real-world data collected in Bangladesh with video recording, and their findings revealed that lane-less traffic has a higher number of stops during a red period and a lower number of stops during a green period of the cycle.

Shokry et al. (2020) compares the traffic performance of signalized intersections located in Cairo, Egypt. Their findings indicated that, in congested roadways, in particular, lane-less traffic can result in slower, more unpredictable traffic flow and longer travel time; in the specific cases studied, the travel time was greater by 12.07% to 16.23% in comparison to the lane-based scenario.

Asaithambi and Anuroop (2016) proposed a method called the 'additive conflict flow' that is suitable to estimate the capacity of two unsignalized intersections (one is uncontrolled and the other is semi-controlled) in lane-less and heterogeneous traffic comprised of MTW, MThW, and PC. Occupation time is considered as the key parameter in this method, and traffic flow data were collected using a video graphic technique. The findings indicated that occupation time rises as conflicting traffic increases and is higher at an uncontrolled intersection than at a semi-controlled intersection.

To summarize, this section examines the impact of lane-less traffic on overall traffic performance. Research shows that vehicles like MTWs can enhance traffic flow due to their ability to maneuver through small gaps, while larger vehicles like HCVs reduce flow and act as bottlenecks. The findings highlight how vehicle composition, road width, and intersection control can significantly influence traffic density, flow rates, and travel time in heterogeneous lane-less traffic environments.

3.2.3. Traffic safety

Lane-less vehicular flow adversely influences traffic safety. Recently, Shahana and Perumal (2022) analyzed the safety impacts of lane-less heterogeneous traffic on two signalized intersections in India using two surrogate safety measures: TTC and DRAC (Eqs. (4) and (5)), for different vehicle types comprised of MTW, MThW, PC, bus, LCV, and HCV.

$$\mathrm{TTC} = \frac{X_1 - X_2 - l_1}{V_2 - V_1} \quad \text{if} \quad V_2 > V_1 \tag{4}$$

$$\mathrm{DRAC} = \frac{(V_2 - V_1)^2}{2(X_1 - X_2 - l_1)} \tag{5}$$

where X_1 and X_2 are the leader's and follower's longitudinal positions, respectively; V_1 and V_2 are the leader's and follower's speeds, respectively; l_1 is the length of the lead vehicle. The authors considered varying thresholds from 1 to 5 s and from 6 to 0 $\mathrm{m/s^2}$ for TTC and DRAC, respectively. Their findings revealed that MTWs on the curbside portion of the roadway commonly percolate laterally in the free space between other vehicles, mainly during the red signal period, to occupy a suitable position closer to the stop line, which accounts for 40% to 69% of the conflicts at the studied intersection. Apart from edge side lanes, nonetheless, PCs are responsible for the majority of conflicts (57% to 85%).

Das and Maurya (2020) studied the safety of lane-less traffic based on the interactions of TTC, center line separation, and leader-follower vehicles in a heterogeneous traffic setting, considering vehicle trajectory data from Indian urban roads. The study considers the interactions of drivers with the leading MTW, MThW, PC, and HCV on a straight roadway. Their results revealed that TTC follows a decreasing trend with increasing center-line separation and a decrease in the size of the vehicle in front. More importantly, compared to lane-based traffic, car drivers can maintain a smaller longitudinal spacing at larger center line separations in lane-less traffic settings which results in lower TTC values. For center-line separation of less than 0.34 m, for example, the percentage reduction in TTC thresholds for PC-MTW and PC-MThW following-lead scenarios with respect to a critical value of 3 s was 47.3% and 29.3%, respectively, whereas the value was raised by 25.7% when PC followed HCV.

In brief, this section highlights the impact of lane-less traffic on safety. The research shows that smaller vehicles like MTWs contribute significantly to conflicts, especially at intersections, while PCs dominate conflicts in the main traffic lanes. Additionally, TTC values tend to decrease as center-line separation increases.

3.3. Simulation

This section reviews simulation-based studies related to micro driving behavior modeling (Section 3.3.1), as well as traffic performance and fundamental diagram (Section 3.3.2). Table 3 summarizes the research across: type of roadway, study location, vehicle type, simulators, and applied methodology, and also presents the findings on the comparison of lane-less traffic with lane-based traffic.

3.3.1. Driving behavior modeling

Sarkar et al. (2020) simulated the microscopic characteristics of traffic in the lane-less stream, considering two stages of the modeling: vehicle movement and region selection. Stage 1 determines the lane-less movement direction of the subject vehicle by using a multinomial logit model. The subject vehicle's alternative space is divided into several realistic radial cones that serve as its decision-making options. The alternatives are described in terms of spacing, relative speed, and angular departure from the flow direction to account for the potential movement directions of the subject vehicle in the following simulation time step. The second stage involves simulating the subject vehicle's subsequent position using a modified intelligent driving model. The proposed model was calibrated and validated using actual data for PC and MTW, and the results revealed that it outperformed conventional lane-based model scenarios.

Nguyen et al. (2012) formulated a microscopic model to describe the dynamics of lane-less movements by focusing on two behaviors — the oblique following behavior and the swerving behavior under congested traffic situations — and introduced the concept of 'safety space' to explain the behavior of MTW under congested traffic conditions. The area around a single subject MTW that roughly resembles a half-ellipse and whose limits are equipotential lines, where all vehicles on the line are assumed to have the same degree of safety as the subject vehicle, is known as a 'safety space' for MTW.

Li et al. (2015b) conducted a thorough investigation of the impact of lateral gaps under non-lane discipline on the energy consumption of electric vehicles (EVs) considering three types of car-following models: full velocity difference, non-lane-based full velocity difference car-following, as well as two-sided lateral gaps with full velocity difference. Their findings reveal that, even though the EVs can recover more energy back to the battery, they use more energy while operating on lane-less roadways. When considering the acceleration scenario as an example, the two-side lateral gap car-following scenario has a greater energy consumption than the one-sided lateral gap and lane-based car-following scenarios, respectively, by around 7% and 23%. The major factor is that EVs are more responsive, which causes early acceleration and aggressive driving behavior in a lane-less traffic setting.

To summarize, this section reviews models of driving behavior in lane-less traffic. Studies highlight the use of multinomial logit models and modified intelligent driving models to simulate vehicle movement and decision-making, particularly for PC and MTW.

Table 2
Summary of reviewed empirical literature: human-driven vehicles.

Indicator	Location	Vehicle	Method/ Approach	Effect*	Remarks on the findings	Study
Flow	India	M	Continuum model	↑	MTW-only conditions increase traffic flow while higher proportions of HCV reduce flow. Maintaining a higher mean speed in lane-less traffic than lane-based traffic.	Gaddam and Rao (2020)
	India	M	Linear regression model	—	Flow and share of MTW are positively correlated, whereas the share of heavy vehicles is negatively correlated.	Sushmitha and Ravishankar (2020)
	India	M	Optimization model	—	Increasing the width of the roadway leads to a decrease in the unit saturation flow.	Padinjarapat and Mathew (2021)
Speed	India	H	Image-based traffic analysis	—	Speed increases with center line separation exceeding 2 meters, but decreases with lower center line separation.	Das et al. (2019b)
Capacity	India	M	Statistical models	—	Increasing the share of small-sized vehicles enhance the density and capacity of the traffic stream.	Gaddam and Rao (2019)
Number of stops	Bangladesh	M	Regression analysis	—	Lane-less traffic has more stops during a red period and fewer stops during a green cycle period compared to the predictions made by the capacity guides.	Farabi (2019)
Occupation time	India	M	Additive conflict flow	—	Occupation time increases with conflicting traffic and is higher at uncontrolled intersections than at semi-controlled ones.	Asaithambi and Anuroop (2016)
Overtaking	India	M	Mathematical model	↑	42% increase in flying overtake in lane-less traffic than lane-based traffic.	Asaithambi and Shravani (2017)
Pore-size	Indonesia	M	Porous flow approach	—	Traffic composition affects pore size distribution, ranging from 2.9 m for MTW-MTW to 4.3 m for car-car interactions.	Ambarwati et al. (2014)
Time headway	Iran	H	Regression analysis	↑	16.5% reduction in time headway in lane-less traffic than lane-based traffic.	Khansari et al. (2020)
	India	M	Copulas approach	↑	About 69% decrease in time headway in lane-less traffic than lane-based traffic.	Das and Maurya (2018)
Lateral movement	India	M	Statistical models	—	Larger vehicles have a preference for the center lane, while MTWs and MThWs show a tendency to use the shoulder lane.	Pal and Sreenivasulu (2019)
	India	M	Descriptive analysis in VBOX	—	Heading angle and lateral acceleration are small at low speeds and increase as speed increases but remain minimal at higher speeds.	Mahapatra and Maurya (2013)
	Iran	M	Statistical analysis	—	Left-lane overtaking resulted in a 33% lower steering angle, a 28% shorter lateral distance, and a 15% lower lateral speed difference than right-lane overtaking.	Khansari et al. (2018)
	India	H	Copulas approach	↑	15%–20% reduction in longitudinal gap in lane-less traffic than lane-based traffic.	Das et al. (2019a)
	India	M	Statistical analysis	—	Small-sized vehicles show high lateral velocity, movement, and aggression, as well as a tendency to occupy curbside lanes.	Chauhan et al. (2021)
	India	M	Statistical analysis	—	The smaller the vehicle size, the higher the tendency for lateral shift.	Madhu et al. (2020)

(continued on next page)

Table 2 (*continued*).

Indicator	Location	Vehicle	Method/ Approach	Effect*	Remarks on the findings	Study
Safety	India	M	Statistical analysis	—	When the lead vehicle is a PC, the following vehicle tends to be more attentive to avoid collisions than when the lead vehicle is an MTW.	Madhu et al. (2022)
	India	M	Copula approach	↓	PC-MTW and PC-MThW following scenarios reduce TTC by 47.3% and 29.3%, respectively, while following an HCV increases it by 25.7%. A smaller longitudinal spacing and TTC can be maintained in lane-less traffic than in lane-based traffic.	Das and Maurya (2020)
	India	M	Surrogate safety measures	—	MTWs move laterally in curbside lanes during red signals, causing 40%–69% of conflicts, while PCs account for 57%–85% of conflicts in other lanes.	Shahana and Perumal (2022)

TTC: Time to Collision; MTW: Motorized Two Wheeler; MThW: Motorized Three Wheeler; HCV: Heavy Commercial Vehicle; PC: Passenger Car; M:Mixed; H:Homogenous; *:Effect of lane-less traffic compared with lane-based traffic; ↑: Increasing; ↓: Decreasing —: Not specified.

3.3.2. *Traffic performance and fundamental diagram*

Li et al. (2015a) studied the traffic flow stability of a lane-less traffic stream; according to the results of a numerical experiment, the lane-less car-following model has a wider stable zone than its lane-disciplined equivalent. It can also disperse perturbations more quickly, such as a rapid stimulus from a leading vehicle.

Using distributed control law, Mulla et al. (2017) found that the roadway's density influences lane-less traffic dynamics; for example, with less congested traffic, vehicles may move into and out of each other's influence cones. Additionally, they emphasized how longitudinal vehicle dynamics affect lateral movement. Considering 12 identical vehicles in their simulation, for instance, a decrease in longitudinal velocity was noted during the lateral movement of the vehicles. Their model also demonstrated that, in dense traffic, a layered formation with space headway based on vehicle velocities is observed, but for a changing influence topology, the space headway can oscillate while remaining uniformly bound and safe.

To reduce the control delay and queue length of an isolated and signalized lane-less intersection, Patel et al. (2016) developed an optimization model for a mixed traffic stream and compared it with a vehicle actuator and a real-time reinforcement learning model. According to their research, it is possible to reduce the average control delay and queue length by up to 77.6% and 78.6%, respectively.

Kumaravel and Ayyagari (2020) investigated decentralized area occupancy-based back pressure controllers (DAOBPC) on two adjacent four-leg signalized intersections to study the possibilities of enhancing the performance of a traffic network with heterogeneous driving behavior. Their study comprises a vehicle composition of MTW, MThW, PC, buses, HCV, and bikes, with a respective market share of 50%, 24%, 20%, 3%, 2%, and 1%. They considered a time-varying demand and conducted a simulation study using an external model of VISSIM and evaluated the performance of vehicle actuators (base scenario), aggregated-queue based with back pressure (AQ-BP), and spatial and temporal area occupancy with back pressure (SAO-BP and TAO-BP) control algorithms in terms of average delay, average queue length, and average travel time. Their findings revealed that SAO-BP and TAO-BP are appropriate for lane-less, heterogeneous traffic conditions. In comparison with the base scenario at higher demand, for example, the average delay was reduced by 18.13%, 22.47%, and 34.34% by the AQ-BP, SAO-BP, and TAO-BP control strategies, respectively. The respective control strategies reduced average queue lengths by 17.94%, 22.56%, and 38.38%, and average travel time by 10.12%, 13.24%, and 20.14%. The authors also highlighted that TAO-BP is the algorithm that works best for lane-less signalized junctions with mixed traffic.

Raju et al. (2021) developed a method to model the driving behaviors of different types of vehicles (MTW, MThW, PC, LCV, and HCV) in mixed and weakly lane-disciplined urban roads. They used VISSIM to model the traffic flow and calibrated Wiedemann's car-following parameters for the respective vehicle type using traffic data collected via videography survey from road segments in India. To accurately represent the lane-less nature of the traffic, the road space was simulated as a single unit with lateral staggering behavior incorporated within the same lane, and their findings outlined that leader-follower combinations of vehicles in the mixed traffic scenarios impact the fundamental diagram of the traffic stream. Similarly, Nguyen et al. (2012) analyzed the fundamental traffic flow diagram of motorcycles using a simulation that mimicked the real data collected by videography and found that lane-less movement reduces traffic flow compared to its lane-based counterpart. For instance, if the driver's reaction time is 0.5 s on a 5.4 m wide congested road with 700 veh/km of density, the flow drops by around 18%, from roughly 11,000 to 9000 veh/h. Furthermore, in a cellular automata-based simulation study, Das and Chattaraj (2020) evaluated the effects of changes in driving behaviors on the capacity of roads with or without lane discipline. The authors took into account homogeneous traffic, and their findings showed that a stream of lane-less traffic led to a reduction in capacity by approximately 30% because of the simultaneous interaction of vehicles both longitudinally and laterally in the driving process.

In addition, Singh and Ramachandra Rao (2022) investigated the impact of small-sized vehicles on lane-less signalized intersections with traffic comprising MTW, PC, and buses in their simulation-based using a cellular automata approach, and obtained an interesting conclusion that is slightly different from previous studies. According to their findings, vehicle size has little effect on fundamental diagrams, except when conditions like seepage and different maximum speeds for different vehicles apply. The authors also underlined that open boundary conditions are preferred over closed boundary conditions for lane-less intersections.

To conclude, this section reviews studies that explore traffic performance in lane-less environments through simulation experiments, highlighting that lane-less models tend to have greater stability and faster dispersion of traffic perturbations compared to lane-based models. Simulations show that optimization models and control strategies can significantly improve traffic performance, particularly at signalized intersections.

4. Lane-free traffic

4.1. Overview

Lane-free traffic in a completely automated traffic environment requires different approaches to analyze and manage the dynamics of vehicular traffic. Vehicle models for AVs can range from simple, like the kinematic bicycle model with a negligible slip angle, to complicated, accounting for tire forces, friction, and slip angles (Collares Pereira et al., 2023). As the majority of the literature is simulation-based, the vehicle model and parameters significantly influence the design and analysis of AVs control strategies since the simulation output depends on the assumptions made and could lead to a different conclusion. It is worth mentioning that different roadway configurations have received attention in recent studies, including straight sections (Li et al., 2017; Karafyllis et al., 2022; Deshpande et al., 2020), unsignalized intersections (Li et al., 2018c, 2021), bidirectional highway segments (Malekzadeh et al., 2021b), roundabouts (Naderi et al., 2023), and roadways with curves (Papageorgiou et al., 2021; Levy and Haddad, 2021, 2022; Yanumula et al., 2021), for studying the potential impacts of lane-free traffic.

4.2. Vehicle control and traffic modeling

New modeling approaches have recently evolved to handle the design and analysis of lane-free traffic for AVs and CAVs, as also shown in Table 4.

Broadly, optimization is the most common approach to control lane-free traffic. It has a unified problem-solving framework and a solid theoretical foundation, and is also the basis of many other methods, such as path planning (Yanumula et al., 2021), model predictive control (MPC) (Naderi et al., 2024), linear quadratic regulators (LQR) (Malekzadeh et al., 2021b, 2024a), and centralized optimal control (COC) (Li et al., 2021, 2018a).

Amouzadi et al. (2022) designed a centralized multi-objective optimal controller for a four-leg lane-free cross-intersection. They introduced a separating hyperplane based on the dual representation of the distance to keep the vehicles at a certain distance from neighboring vehicles when moving laterally, as shown in Fig. 2. The bicycle model they employed consisted of two degree-of-freedom and included the lateral and rotational motion of vehicles. They also used polynomials to represent vehicle and road boundaries for collision avoidance. The simulation results indicate that the crossing time of the algorithm proposed is shorter by an average of 40% compared to the state-of-the-art reservation-based method in lane-based traffic.

Li et al. (2018b) modeled the motion planning of CAVs at signal-free, lane-free intersections as a nonlinear optimal control problem with a two-stage strategy. In the first stage, vehicles are aligned into a predetermined formation at the entrance of intersection by a pre-calculated standardized movement strategy. In the second stage, the motion planning process is discretized using the Orthogonal Collocation on Finite Elements method and solved using the Interior Point Method. The objective function aims to minimize the total traversal time and maximize safety, while the constraints are related to vehicle dynamics and traffic safety, such as speed limits, acceleration limits, and safe distances between vehicles.

Levy and Haddad (2021) developed a controller for AVs' movement considering a nonlinear MPC to improve traffic flow performance in their simulation-based study. The main idea is, without the restriction of lanes, vehicles can increase their turning radius to increase their speed of turning. They designed a ring road in simulation environment that included three scenarios of lane-free vs. two-lane, three vehicles, and heterogeneous vehicles. Subsequently, in their recent study, they demonstrated with a laboratory experiment using reduced-sized mobile robots (Levy and Haddad, 2022).

Yanumula et al. (2023) modeled the movement strategy of CAVs in lane-free traffic as a nonlinear optimal control problem. They built the constraints based on a discrete-time vehicle model, the longitudinal acceleration limitation, and road boundaries. The objective function is composed by three sub-objectives including fuel consumption and passenger comfort, desired longitudinal and lateral speed, and obstacle avoidance. They also established an MPC framework and used the feasible direction algorithm to get the numerical solution for finite time-horizons in real-time.

Without lanes on road, vehicles can move freely in a two-dimensional plane, so Yanumula et al. (2021) thought of employing the path planning method for AVs control, and modeled it as a nonlinear constrained optimal control problem (OCP) for effective AV movement on a lane-free roadway.

Some studies simulate repulsive forces between CAVs to operate them. Berahman et al. (2022) introduced artificial force, including repulsive force and nudging force, to control CAVs laterally, while used a deep deterministic policy gradient (DDPG) to maintain a constant time gap between two consecutive vehicles to avoid a longitudinal collision. Rostami-Shahrbabaki et al. (2023) introduced the concept of vehicle flocking and regarded it as the unit of repulsive force effect, as shown in Fig. 3. They first assigned CAVs into different clusters and then simulated the repulsive forces between them. The two types of agents considered respectively represent the potential flock mates and the virtual leader with collective objectives. They used an energy function to

Table 3
Summary of reviewed simulation-based literature: human-driven vehicles.

Indicator	Location	Vehicle	Simulator/ Approach	Effect*	Remarks on the findings	Study
Delay	India	M	VISSIM	—	A reduction of average delay by up to 77.6% in optimization-based approaches compared to vehicle-actuated and real-time reinforcement models.	Patel et al. (2016)
	—	M	VISSIM	—	Advanced control strategies like temporal area occupancy with back pressure can achieve up to 34.3% reductions in delay compared to vehicle-actuated systems.	Kumaravel and Ayyagari (2020)
Travel time	Egypt	M	VISSIM	↑	Lane-less traffic resulted in unpredictable vehicle movement and resulted in a travel times increase by 12.07%–16.23% compared to lane-based traffic.	Shokry et al. (2020)
	—	M	VISSIM	—	Advanced control strategies like temporal area occupancy with back pressure can achieve up to 20.14% reductions in travel time compared to vehicle-actuated systems.	Kumaravel and Ayyagari (2020)
Queue length	India	M	VISSIM	—	A reduction of queue length by up to 78.6% in optimization-based approaches compared to vehicle-actuated and real-time reinforcement models.	Patel et al. (2016)
	—	M	VISSIM	—	Temporal area occupancy with back pressure can achieve up to 38.4% reductions in queue length compared to vehicle-actuated systems.	Kumaravel and Ayyagari (2020)
Distance traveled	India	M	IDM	—	The use of area-based traffic models improves the prediction of the dynamics of lane-less traffic.	Sarkar et al. (2020)
Self-organization	–	H	Graph-based	—	Vehicles form layered formations with space headway, but this space headway can oscillate while remaining safe from changing influence topology.	Mulla et al. (2017)
Capacity	—	H	CA simulation	↓	Traffic without lanes led to a reduction in capacity by approximately 30%.	Das and Chattaraj (2020)
Stability	—	H	Numerical simulation	↑	The car-following model for lane-less traffic that includes two-sided lateral gaps leads to a larger stability region and improved perturbation dissipation.	Li et al. (2015a)
Fundamental diagram	India	M	VISSIM	↓	Mixed traffic flow in the lane-less roadway is less stable and has wider speed-density curves than homogeneous and orderly-oriented traffic.	Raju et al. (2021)
	—	M	CA simulation	—	Vehicle size has no significant impact on fundamental diagrams.	Singh and Ramachandra Rao (2022)
	Vietnam	H	C++	↓	Lane-less traffic resulted in a more significant decrease in traffic volume under congested conditions, while its lane-based counterpart exhibited higher speed, traffic flow, and density.	Nguyen et al. (2012)
Energy consumption	—	H	Numerical simulation	↑	Energy consumption of the two-sided lateral gap option is approximately 7% and 23% higher than the one-sided lateral gap and lane-based options, respectively.	Li et al. (2015b)

IDM: Intelligent Driving Model; CA: Cellular Automata; M:Mixed; H:Homogenous; *:Effect of lane-less traffic compared with lane-based traffic; ↑: Increasing; ↓: Decreasing —: Not specified.

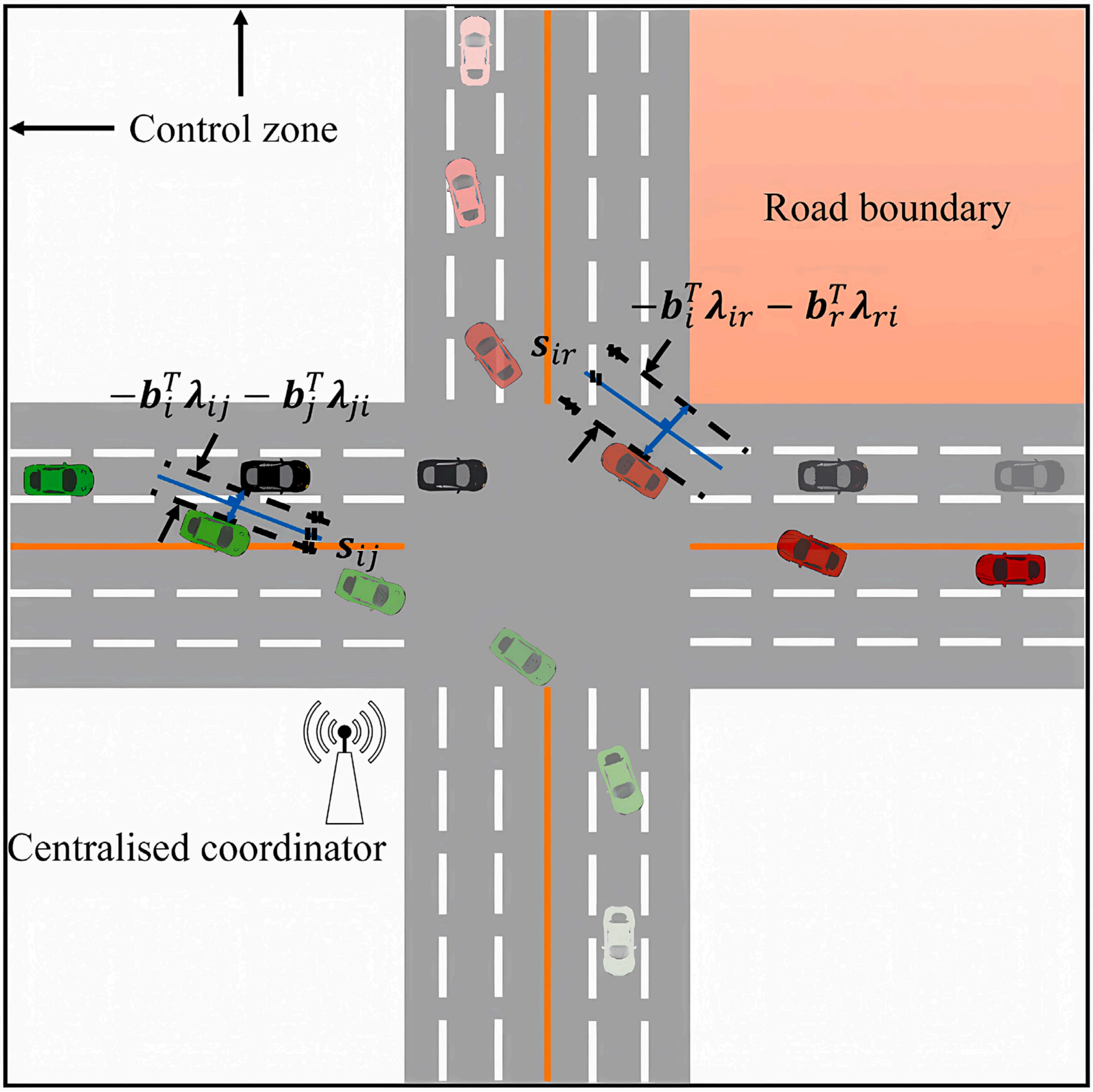


Fig. 2. The separating hyperplane among vehicles for collision avoidance.

simulate the repelling force to avoid the collision of flock members and a consensus algorithm for velocity matching. They also implemented a virtual leader for the navigational feedback. In addition, they added additional lateral acceleration constraints to confine the CAVs to the road boundaries.

Chavoshi and Kouvelas (2021) also adopted the clustering approach. They defined a neighbor for each CAV according to its speed, the communication delay, and the maximum speed and deceleration. Within that neighbor, the CAVs were considered a threat to each other. Furthermore, they clustered the CAVs into threat groups and used nonlinear MPC to minimize the amount of threat between CAVs in a period of time in the future.

The approach based on artificial force is intuitive, but the assumption of using repulsive forces to model interactions between vehicles is simplistic and may not be compatible with the vehicle's motion characteristics.

A proportional–integral–derivative (PID) controller is a classic feedback control system that adjusts the behavior of a system through a combination of proportional, integral, and derivative components, which enables the system to achieve desired states in a stable and accurate manner. It is widely used in autonomous driving, and has been used to control lane-free traffic. Deshpande et al. (2020) investigated the problem of tracking trajectories in heterogeneous and lane-free urban traffic, considering attributes such as the surrounding vehicles, including their location, speed, type, and roadway factors like curb presence and speed limit, as inputs to the model in a PID controller proposed. The output is a subject vehicle trajectory that avoids collisions while traveling

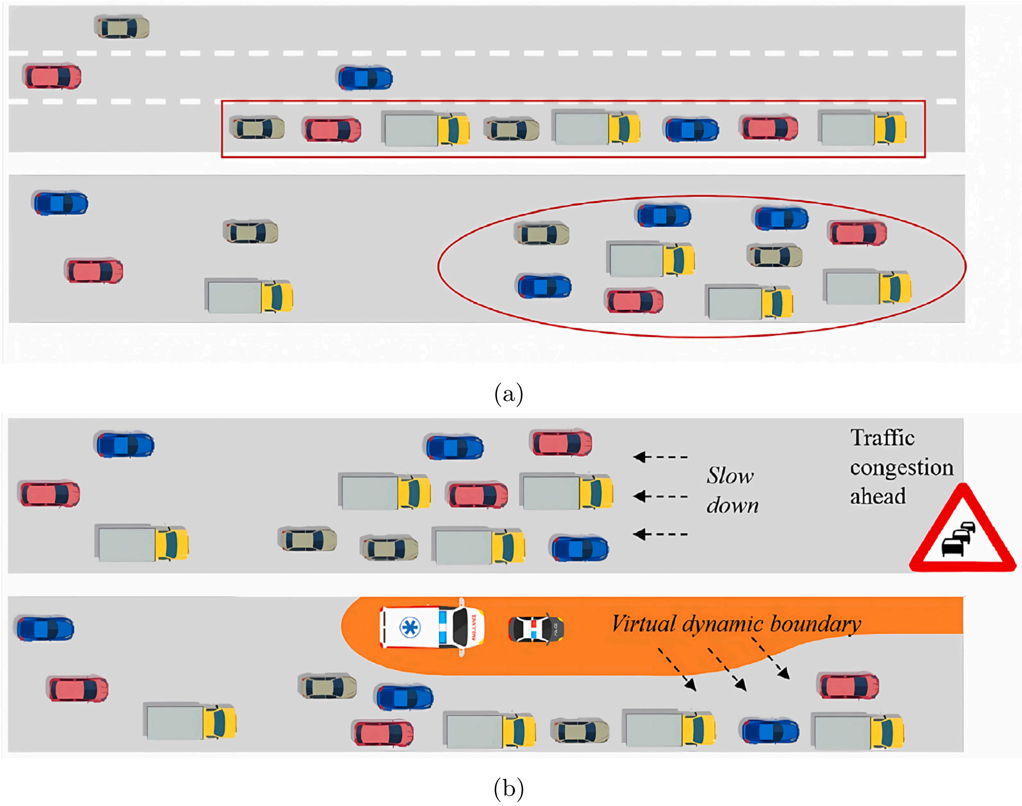


Fig. 3. The concept of vehicle flocking: (a) schematic representation of a vehicle platoon and a vehicle flock and (b) repulsive force among different flocks. *Source:* Adopted from Rostami-Shahrbabaki et al. (2023).

to the specified waypoints. It was tested in a MATLAB environment using two IPG CarMaker vehicles and successfully achieved a collision-free trajectory.

Artificial intelligence algorithms such as reinforcement learning have been used to control lane-free traffic by treating AVs as agents to establish their intelligent movement strategies. Berahman et al. (2022) used DDPG to control the CAVs longitudinally. The environment states are the speed of subject vehicle and preceding vehicle, the output is the acceleration of the subject vehicle, and the reward function is comprised of the distance gap-error reduction and acceleration penalty. Reinforcement learning does not require manual modeling and is highly intelligent, but it usually requires a large amount of calculation and has relatively weak interpretability.

Papageorgiou et al. (2021) introduced the 'Traffic-Fluid' concept, a unique approach to dealing with lane-free traffic in analogy to fluid flow through a pipe. Based on a connected environment, Traffic-Fluid has two coupled elements: lane-free traffic and nudging. The nudging effect is characterized by the communication capabilities of CAVs. As depicted in Fig. 4, the yellow vehicle, which is driving at a higher desired speed than the one in front of it, applies a nudge force to overtake the slower vehicle and attain the higher desired speed. This concept has been applied in both experimental and simulation studies (Levy and Haddad, 2022; Yanumula et al., 2023).

Furthermore, based on the concept of 'Traffic-Fluid', TrafficFluid-Sim, an extension of SUMO for modeling lane-free traffic streams that fills the gap in current traffic simulators that lack a control strategy for vehicle lateral flow dynamics has seen multiple applications (Troullinos et al., 2021a; Papageorgiou et al., 2021; Malekzadeh et al., 2021c, 2022a).

In addition to the typical theories and methods mentioned above, some studies have designed their own algorithms for lane-free traffic control. A detailed study by Johansen and Løvland (2015) started from the microscopic decision-making behavior of vehicles, and designed a layered behavior model to control the CAVs, which includes locomotion layer, autonomous vehicle layer, and flocking layer. In this layered model, all of the CAVs should follow a set of steering behaviors with clear physical meaning that include road tangent, avoid, keep inside road, avoid oncoming, avoid prioritized, keep right, on camp, waiting on ramp, and cohesion, which are all defined in detail based on the spatial position of the CAVs and the laws of motion. Zhang et al. (2023) proposed a potential line strategy to optimize lateral vehicle distribution based on desired speeds, and used the Probability Integral Transform (PIT) to map non-uniform speed distributions to a uniform lateral spread. Vehicles are assigned lateral positions where faster vehicles move towards the left, mimicking conventional overtaking rules. The control model includes a potential line controller that adjusts each vehicle's lateral position and artificial potential fields to avoid collisions by applying virtual forces between vehicles.

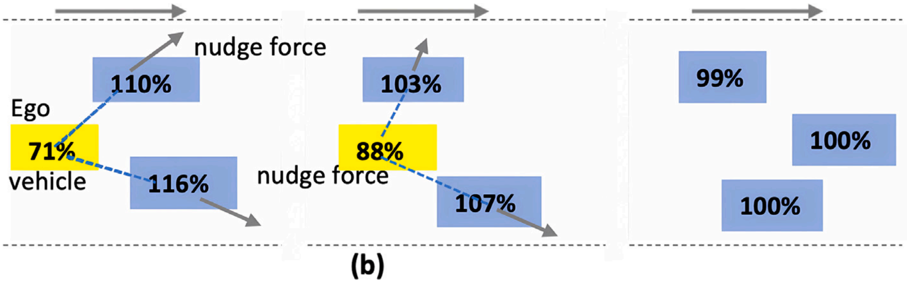


Fig. 4. Nudging effect. *Source*: Adopted from Papageorgiou et al. (2021).

Some other approaches such as a Lyapunov-like function (Karafyllis et al., 2024), a Lyapunov–Krasovskii function (Tang and Li, 2018), a nonlinear heat equation (Theodosis et al., 2024), nonlinear feedback controllers (Naderi et al., 2023), and graph theory (Troullinos et al., 2021b) have also been considered.

Although the communication among CAVs generally achieves high efficiency in cooperative control, it is susceptible to occasional delays or failures among certain vehicles. In light of this, Li and Zhang (2018) explored fault-tolerant cooperative motion planning for CAVs in scenarios where actuator failures occur. Using a Nonlinear Model Predictive Control (NMPC) strategy and a parallel computing framework, they achieved real-time path replanning across various failure scenarios. In the failure detection phase, multiple sensor inputs are used to monitor the vehicle state in real-time. Upon detection of a failure, NMPC is immediately employed to optimize the paths of the remaining healthy vehicles. The objective function is designed to minimize the driving time and energy consumption of replanning, while the constraints are related to vehicular dynamics, degraded vehicle performance following failure detection, and spatial distance to prevent collisions.

Apart from the above studies based on connected environment, a series of innovative decentralized controllers for the safe operation of unconnected vehicles on lane-free roadways were proposed by Karafyllis et al. (2021), Naderi et al. (2022) and Theodosis et al. (2022). Karafyllis et al. (2022) developed a decentralized nonlinear cruise controller and employing the Control Lyapunov Function (CLF) technique for two-dimensional movements of AVs on lane-free straight roadways. Defining the system's kinetic energy as in Newtonian mechanics, the authors suggested two categories of cruise controls: inviscid (flow with zero viscosity) and viscous. The first type of cruise control, inviscid, relies solely on measuring the distance from the adjacent vehicle for effective control, while the second category, viscous, requires both distance and speed measurements for effective control. Karalakou et al. (2022) implemented a deep reinforcement learning approach to capture the dynamics of lane-free traffic. In their method, the environment is the position and velocity of the subject and surrounding vehicles, and the reward function is comprised of longitudinal target, overtake motivation term, collision avoidance term, and potential fields used to quantify the real-time risk.

On a bidirectional lane-free road, vehicles can travel freely, so the road width can be assigned dynamically according to the traffic flow in each direction, which is called internal boundary control (IBC), as shown in Fig. 5. Although IBC is not an algorithm for controlling AVs, it can improve the operating efficiency of AVs in bidirectional lane-free condition. IBC is usually used in conjunction with cell transmission model (CTM). CTM divides the road network into multiple cells, with each cell representing a road segment in the network. Vehicles transfer among these cells so that the movement of traffic flow through a road network can be simulated. Malekzadeh et al. (2021a) used IBC to model the lane-free traffic, they divided the roadway into multiple segments and assign road width and capacity to each direction in real time based on traffic density. The boundary to separate the directions of traffic is adjustable and controlled by a model-free adaptive control scheme. Malekzadeh et al. (2021b) used an extended CTM to describe the transmission effect of CAV traffic flow, and employed feedback-based linear–quadratic regulators with or without integral action to efficiently calculate the numerical solution of the IBC problem. Jin et al. (2022) used a CTM based non-holding-back quadratic programming optimal control model to achieve the IBC for lane-free traffic. They also integrated ramp metering by introducing a ramp queue model to avoid the traffic congestion when the total bi-directional traffic flow exceeds the total roadway capacity. Malekzadeh et al. (2021c) solved the IBC problem in lane-free traffic by modeling it as a convex Quadratic Programming (QP) problem, which includes all constraints and minimizes a physical performance criterion (Malekzadeh et al., 2022b). Malekzadeh et al. (2023) proposed two different overlapping decentralized control schemes as an extension of IBC, achieving similar efficiency as QP while being simpler. The first approach is a contractible controller that is used in a decomposed manner, while the second approach is modeled as a linear matrix inequalities problem. The core idea overlapping that can improve the system reliability and reduce the monitoring and maintenance effort is shown in Fig. 6, where the information of control inputs of the overlapping sections are from both adjacent subsystems. Malekzadeh et al. (2024b) implemented LQR with a feed-forward term to effectuate IBC to account for external disturbances such as entering flow and on-ramp flows.

Overall, this section reviews recent modeling approaches for lane-free traffic control, including optimization models, artificial intelligence algorithms, potential field methods, and internal boundary control. These methods enhance traffic performance by reducing travel time, improving safety, and effectively managing vehicle movements in complex lane-free scenarios.

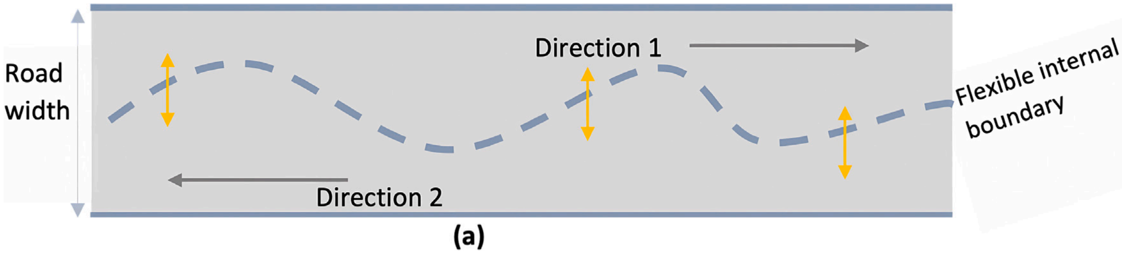


Fig. 5. The principle of IBC algorithm. *Source*: Adopted from Malekzadeh et al. (2021a).

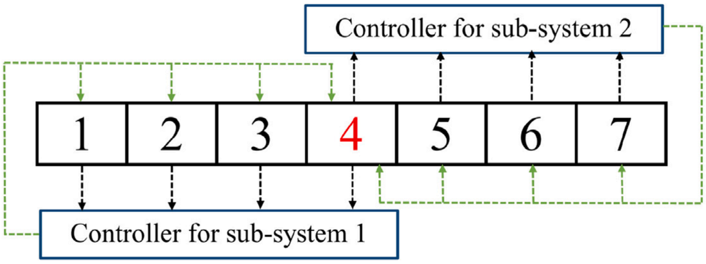


Fig. 6. A block diagram of overlapping control scheme for two subsystems. *Source*: Adopted from Malekzadeh et al. (2023).

4.3. Potential impacts

The lane-free movement of AVs on roadways will have significant implications for automated road transport. Understanding the potential impact of lane-free traffic on roadway is crucial.

Papageorgiou et al. (2021) pointed out that the nudging effect of lane-free concept would boost flow and capacity by allowing for more flexible use of the roadway, and it would be especially advantageous for bidirectional traffic since it allows for sharing of the area based on the demand from each direction. Karafyllis et al. (2021) investigated the operational aspects of 10 identical AVs based on collision avoidance techniques, and their findings stated that AVs on lane-free roadways allow the use of the entire road width, which increases the lateral occupancy of the road space by 45% compared with its lane-based counterpart. The authors indicated that the effects of nudging that increase acceleration and speed are relevant to the study of the traffic flow dynamics of AVs on lane-free roads.

Johansen and Løvland (2015) conducted simulation experiment using Unreal Engine 4 and found that for a one-way road with the width equivalent to four lanes, there were no incidents when the traffic flow was below 9000 veh/h, and only one incident when the traffic flow reached 14,000 veh/h. The SUMO simulation results of Berahman et al. (2022) indicated that the capacity of AVs for three lanes is 7812 veh/h, whereas the capacity of the lane-free model proposed on the road with an equivalent width is 14,520 veh/h. Interestingly, when the traffic flow is lower than 7200 veh/h, the average delay can be negative because of the nudge-effect on the leading vehicle. Applying coordination graphs and a max-plus controlling (CGMC) algorithm, Troullinos et al. (2021b) demonstrated that lane-free traffic systems increase flow rate and speed as well as a reduction in deviation from the desired speed, both in high- and low-traffic situations, as compared to lane-based traffic; a 10.2 m roadway's maximum throughput, for instance, could be increased from 7300 to 9000 veh/h. Their recent laboratory experiment-based study (Levy and Haddad, 2022) applying the same control strategy demonstrated an increase in traffic flow by up to about 18%.

In addition to comparing lane-free traffic to lane-based traffic with AVs, some studies also compared it to lane-based traffic with HVs. For example, Yanumula et al. (2021) revealed an improvement in traffic performance: a flow of 9,592 veh/h (equivalent to 3,197 veh/h/lane) was attained in the same space as a roadway with three lanes of traditional traffic, which is more than the 2,500 veh/h/lane that is a typical upper-bound for human-driven traffic. Yanumula et al. (2023) assumed that the typical capacity flow of HVs is 2,500 veh/h/lane, and on the lane-free road of three-lane width, more than double that flow (18,332 veh/h) was achieved.

Levy and Haddad (2021) developed a nonlinear MPC to improve the traffic flow performance of a roadway with a curve. Their results showed that the lane-free concept can reduce the travel time by 11.3% compared to the lane-based traffic. A centralized controlling scheme presented by Amouzadi et al. (2022) pointed out that the crossing time at intersections can be reduced by about 40% compared with state-of-the-art lane-based methods. In addition, Tang and Li (2018) highlighted that as the trailing vehicles progressively follow the leading vehicle in lane-free traffic, a vehicle platoon forms, demonstrating that time delay can be reduced.

The analysis of flock stability by Rostami-Shahrbabaki et al. (2023) shows that compared to lane-based traffic, vehicles in a lane-free environment can adjust their lateral position flexibly, reducing the impact of the leading vehicle's disturbance on the following vehicle. Xiao et al. (2022) studied the car-following model on a hypothetical circular roadway with a homogeneous fleet of 100 vehicles. This simulation of both forward and backward vehicle information finds that lane-free movement improves traffic flow stability. Furthermore, Li et al. (2017) presented a model based on the lateral gap and electronic throttle opening angle under a connected environment. The results show that a lane-free and throttle-based car-following model outperforms existing models in terms of stability and smoothness, making it more suitable for describing the traffic flow of AVs in a connected traffic environment.

In addition, IBC can further amplify the advantages of lane-free traffic. Malekzadeh et al. (2021b) developed a CTM-based IBC to improve traffic performance as measured by the total time spent (TTS) by all vehicles in the highway stretch. Their results showed that LQI (Linear–Quadratic regulators with Integral action) could improve TTS by 20.5–27.8%. In comparison, LQ (Linear–Quadratic regulators without Integral action) resulted in a rise of 19.3–25.6%. Contrarily, both controllers have the same impact (increasing from 21.4 to 28.9%) on uncongested situations. In their recent study, Malekzadeh et al. (2022b) highlighted the TTS can be improved by 8.2% compared to no control cases by applying an overlapping decentralized IBC scheme. Jin et al. (2022) show that the TTS value with the IBC is 183.3 veh h, which is 41.0% less than that in no-control case, and the total delay with the IBC is 9.7 veh h, which is 92.9% less than the no-control case.

However, lane-free traffic can cause some negative impact on roadway traffic such as increasing side-to-side collisions and increasing the energy consumption. Karalakou et al. (2022) reveals a clear conflict between collision avoidance and maintaining a desired speed, as slower-moving vehicles prioritize safety while faster vehicles must learn intricate maneuvers to overtake safely. The lane-free movement of AVs could also result in side-to-side collisions more frequently compared to the lane-based traffic, but the collisions will be significantly less severe than rear-end collisions (Papageorgiou et al., 2021). Li et al. (2017) explored the car-following models and corresponding energy consumption. Their findings pointed out that 30% raises the energy consumption in the lane-free model during acceleration and by 21.3% during deceleration since lane-free vehicles react more quickly than lane-based ones. Nonetheless, there is also a study pointing out that lane-free traffic can reduce the crossing time at intersections by 40% compared with lane-based traffic without a rise in energy consumption due to acceleration (Amouzadi et al., 2022).

In brief, this section highlights the potential impacts of lane-free traffic. It shows that lane-free systems can increase road capacity, improve traffic flow, and reduce travel time. However, lane-free traffic can also lead to higher energy consumption and an increased risk of side-to-side collisions.

5. Discussion

In the study of lane-less traffic, the main thrust of research has been to empirically analyze the decision-making patterns and operating habits of human drivers, and accordingly to build models to simulate the drivers' driving behavior, and to explore the potential effects of lane-less traffic compared to lane-based traffic on the traffic performance, fundamental diagram, and roadway safety.

In comparison, the main task of proposed future lane-free traffic control is to design the algorithms of perception, decision-making, and actuation for AVs to guarantee the desired speed, passenger comfort, and collision avoidance. When applying these algorithms to a simulated environment, the potential impacts of AVs in lane-free traffic can be explored.

Based on the literature reviewed in Table 4, three main types of high-level control strategies for AVs in lane-free traffic can be outlined. The first category is model-based controllers, including CLF, optimal control, non-linear decentralized control, coordination graphs and max-plus controlling, non-linear model predictive controller, centralized optimal control, and linear quadratic regulators. Subsequently, coordination-based controlling approaches, including centralized control systems, consensus-based control, and overlapping decentralized control, are applied in the literature. Lastly, the learning-based approaches with a reward function design have been studied.

In order to have a clear quantitative understanding of both lane-less and lane-free traffic, we summarized the values of three indicators (traffic flow, time headway, and TTC) given by existing studies, as shown in Table 5. These studies obtained indicator values through observing actual data or through conducting simulation experiments. We converted traffic flow to flux with the unit of veh/h/m because of the absence of lanes in lane-less and lane-free traffic. In the conversion, we used the lane width provided in the references and used 0.4 as the passenger car unit value of motorcycles according to Highway Capacity Manual 2000. As shown in Table 5, there is currently no research on the specific values of TTC and time headway in lane-free traffic. Instead, most studies focused on lateral and longitudinal spatial distances among vehicles (Amouzadi et al., 2022; Levy and Haddad, 2021; Yanumula et al., 2023; Berahman et al., 2022; Rostami-Shahrbabaki et al., 2023). In future studies, time-related indicators such as TTC and time headway should be given more attention in lane-free traffic.

There remains dispute about the effectiveness of lane-less traffic. A few studies show that lane-less traffic can influence roadway traffic positively, such as reducing the control delay and queue length (Patel et al., 2016) and improving the stability of traffic flow (Li et al., 2015a; Xiao et al., 2022). However, most studies have reached the opposite conclusion, suggesting that lane-less traffic reduces capacity and traffic flow (Das and Chattaraj, 2020; Nguyen et al., 2012), increases travel time (Shokry et al., 2020), decreases headway time (Khansari et al., 2020; Das and Maurya, 2018), reduces TTC (Das and Maurya, 2020), and increases energy consumption (Li et al., 2015b). The main reason is that in a non-lane-based environment, drivers must rely on their own judgment and awareness to navigate through traffic, which increases the driving difficulty significantly.

In comparison, lane-free traffic is based on AVs with algorithms that have high capability of information processing and actuation, and CAVs allow the optimization of moving strategies at the level of entire road and to be controlled collaboratively. This leads that the impact of lane-free traffic on roadway is generally positive. Specifically, it can reduce the time delay (Tang and Li, 2018), boost flow and capacity (Papageorgiou et al., 2021; Yanumula et al., 2021; Troullinos et al., 2021b), improve the stability and smoothness of traffic flow (Li et al., 2017), and guarantee vehicles' desired speed (Troullinos et al., 2021b).

Table 4
Summary of reviewed literature: automated vehicles.

Indicator	Control/model type	Method/approach	Effect*	Remarks on the findings	Study
Safety	PID	Path planning and tracking	—	A collision-free optimal trajectory was attained using PID control.	Deshpande et al. (2020)
	NDC	Design of a sampled-data controller	—	AVs can achieve collision-free movement where each vehicle has its sampling period.	Theodosis et al. (2022)
	NDC	Microscopic simulations of complex intersections	—	AVs can navigate complex roundabouts while avoiding collisions and staying within practical limits.	Naderi et al. (2022)
	CLF	Design of decentralized control strategy	–	Compared to inviscid controllers, viscous cruise controllers enhance safety.	Karafyllis et al. (2022)
	Reward function	Reinforcement learning	—	The 'All-Components Reward Function' is the best among various reward functions, avoiding collisions and reducing speed deviations.	Karalakou et al. (2022)
	NMPC	Path and trajectory planning with simulation	—	The proposed control algorithm can ensure the traffic performance and driving safety.	Chavoshi and Kouvelas (2021)
	Consensus-based	Cooperative path and trajectory planning	—	The formation of vehicle flocks is achieved efficiently within a few seconds, with a successful alignment of speeds and stable vehicle arrangements across different scenarios.	Rostami-Shahrbabaki et al. (2023)
Stability	–	Numerical experiment	—	With a throttle-based car-following model outperforms existing models in terms of stability and smoothness.	Li et al. (2017)
	—	Full velocity difference model	↑	Lane-free traffic enlarges the stability region of car following maneuver.	Xiao et al. (2022)
Flow	OCP & MPC	Path planning	↑	On a three-lane road, traffic flow increased by over 50%, achieving 3,197 veh/h/lane, exceeding the typical 2,500 veh/h/lane upper limit for HVs.	Yanumula et al. (2021)
	OCP & MPC	Path planning	↑	A flow of 18,332 veh/h is achieved at a density of 200 veh/km, more than double compared to the regular lane-based traffic.	Yanumula et al. (2023)
	CLF	Design of decentralized control strategy	—	Compared to inviscid controllers, viscous cruise controllers provide better traffic flow.	Karafyllis et al. (2022)
	Extension of SUMO simulation	Empirical study of traffic characteristics	↑	Lane-free traffic results in a higher flow, capacity, and critical density, and nudging further improves the traffic flow (e.g., capacity rise by 40%).	Malekzadeh et al. (2022a)
	COCP	Online motion planning	—	AVs can benefit from a two-stage strategy that considers the formations before entering and crossing intersections, which helps facilitate cooperation among vehicles.	Li et al. (2018a)
	Extension of SUMO simulation	DDPG and artificial forces	↑	Achieve a notably greater traffic flow by about 86%.	Berahman et al. (2022)
	Nonlinear heat equation	Numerical experiment	↑	In free-flow condition, the mean flow of the model proposed is 346% higher than that of the LWR model.	Theodosis et al. (2024)
	Nonlinear feedback controllers	Simulation and empirical study	—	The proposed model demonstrates flexibility in implementing various policies, such as prioritizing entering vehicles.	Naderi et al. (2023)
	Potential line control	Probability Integral Transform	—	The 13.95-meter-wide weaving section saw a maximum flow of 17,700 veh/h, far exceeding typical freeway capacity.	Zhang et al. (2023)
	PID	Cooperative path and trajectory planning	↑	A flow of 5,500 veh/h can be obtained in symmetric and lane-free conditions on a 20 m wide road, which is 72% increase compared to lane-based traffic.	Johansen and Løvland (2015)

(continued on next page)

Table 4 (*continued*).

Indicator	Control/model type	Method/approach	Effect*	Remarks on the findings	Study
Speed	Reward function	Reinforcement learning	—	The 'All-Components Reward Function' is the best among various reward functions, avoiding collisions and reducing speed deviations.	Karalakou et al. (2022)
Throughput,	COCP	Simulation & small scale experiment	—	The increasing number of cooperative AVs initially enhanced throughput, but as their share continued to increase, induced a drop in throughput.	Li et al. (2021)
capacity	–	An extension of SUMO models	↑	Lane-free traffic and vehicle nudging improve capacity proportionally to road width.	Papageorgiou et al. (2021)
	CGMC	Multi-agent collaborative	↑	An increase in speed and throughput(about 9,000 veh/h can be attained for roadways corresponding to 3 lanes).	Troullinos et al. (2021b)
	OCP & MPC	Path planning	↑	A maximum capacity of 8,800 veh/h can be achieved, higher than 5,072 veh/h for traditional signalized intersections.	Naderi et al. (2024)
	NMPC	Cooperative path and trajectory planning	↑	Enhance capacity as fast AVs can overtake the slower ones smoothly.	Levy and Haddad (2022)
TTS	CTM-based OCP	IBC scheme	↓	Linear quadratic regulators improved TTS by 19.3-28.9% compared to no control scenarios.	Malekzadeh et al. (2021b)
	Overlapping decentralized control	IBC scheme	↓	TTS can be improved by 8.2% compared to no control cases.	Malekzadeh et al. (2022b, 2023)
	Model-free adaptive controller	IBC scheme	↓	TTS can be improved by 8.2% compared to no control cases.	Malekzadeh et al. (2021a)
	LQR	IBC scheme	↓	TTS shows significant improvement compared to no-control scenarios.	Malekzadeh et al. (2024a)
	—	IBC scheme	↓	TTS can be improved by 41.0% compared to no control cases.	Jin et al. (2022)
Travel time	COCP	Controlling scheme for lane-free and signal-free intersections	↓	Travel times at lane-free crossings with centralized controller crossings decreased by about 40%.	Amouzadi et al. (2022)
	NMPC	Path and trajectory planning with simulation	↓	The lane-free concept can reduce travel time by at least 11.3% compared to lane-based traffic.	Levy and Haddad (2021)
Congestion	NDC	Design of decentralized control strategy	↓	Lane-free traffic resulted in a 45% rise in lateral occupancy, leading to effective use of space and reducing congestion and travel time.	Karafyllis et al. (2021)
Delay	Consensus-based	Numerical experiment	—	Consensus-based control approach effectively manages lane-free traffic, even with communication time delays.	Tang and Li (2018)
	Overlapping decentralized control	IBC scheme	↓	TD can be improved by 81.4% compared to no control cases.	Malekzadeh et al. (2023)
	LQR	IBC scheme	↓	TD is significantly reduced compared to no control cases.	Malekzadeh et al. (2024b)
	—	IBC scheme	↓	TD can be improved by 92.9% compared to no control cases.	Jin et al. (2022)
Energy consumption	NMPC	Cooperative path and trajectory planning	↓	A smooth traffic flow reduced energy consumption.	Levy and Haddad (2022)
	–	Numerical experiment	↑	The energy consumption of lane-free traffic increases by 30% during acceleration and by 21.3% during deceleration.	Li et al. (2017)

AV: Autonomous Vehicle; HV: Human-driven Vehicle; IBC: Internal Boundary Control; CTM: Cell Transmission Model; DDPG: Deep Deterministic Policy Gradient; OCP: Optimal Control Problem; COCP: Centralized Optimal Control Problem; NDC: Non-linear Decentralized Control; CGMC: Coordination Graphs and a Max-plus Controlling; MPC: Model Predictive Control; NMPC: Non-linear Model Predictive Control; CLF: Control Lyapunov Function; PID: Proportional-Integral-Derivative; LQR: Linear Quadratic Regulators; LWR: Lighthill–Whitham–Richards; TTS: Total Time Spent; TD: Total Delay; *:Effect of lane-free traffic compared with lane-based traffic, or IBC compared with no control; ↑: Increasing; ↓: Decreasing —: Not specified.

Table 5
Overview of indicator values in non-lane-based and lane-based traffic with AV and HV.

	Maximum traffic flux (throughput) (veh/h/m)	Time headway (s)	TTC (s)
Lane-free traffic	880 (Naderi et al., 2024) 882 (Troullinos et al., 2021b) 940 (Yanumula et al., 2021) 1,000 (Johansen and Løvland, 2015) 1,269 (Zhang et al., 2023) 1,424 (Berahman et al., 2022) 1,797 (Yanumula et al., 2023)	–	–
Lane-less traffic	667 (Nguyen et al., 2012)	0.81 (Khansari et al., 2020) 0.87 * (Das et al., 2019a) 1.02 (Das and Maurya, 2018) 0.72 *–1.2 * (Das et al., 2019b)	3.0 (Shahana and Perumal, 2022) 4.27 (Das and Maurya, 2020)
Lane-based traffic with AVs	716 (Troullinos et al., 2021b) 766 (Berahman et al., 2022)	0.6 (Milanés et al., 2013) 0.6–1.1 (Nowakowski et al., 2010)	8.3 (Mahdinia et al., 2020) 1.32–8.66 (Fremont et al., 2020)
Lane-based traffic with HVs	694 (Yanumula et al., 2021, 2023) 815 (Nguyen et al., 2012)	0.9 (Martin-Gasulla et al., 2019) 0.97 (Khansari et al., 2020)	2.0 (Sharma, 2019) 5.0 (Moon and Yi, 2008)

AV: Autonomous Vehicle; HV: Human-driven Vehicle; TTC: Time To Collision; The data marked with * indicate that the reference did not give specific values, and we estimated the values based on the figures in the reference.

From the perspective of individual travelers, the exploration and study of heterogeneous traffic comprised of MTWs, MThWs, PCs, and heavy vehicles argues that the non-lane-based traffic system benefits from small-sized vehicles because these vehicles can maneuver smoothly in small pores of the traffic, which has a positive impact in terms of increasing traffic flow (Ambarwati et al., 2014; Gaddam and Rao, 2020). However, in some cases, their abrupt lateral movement may compromise safety by increasing traffic conflict (Shahana and Perumal, 2022).

6. Conclusion

Advances in AV technology contribute to the re-emergence of lane-free traffic concepts, which would bring substantial change to traffic. Nonetheless, the design and control of lane-free traffic for AVs are at an early stage. Specifically, most recent research works with a focus on the simulation of AVs are lane-based scenarios (Beza et al., 2022), and AV field tests have also assumed defined lanes (Boersma et al., 2021). In this context, we reviewed the existing studies on lane-less and lane-free traffic to investigate how AVs could operate in lane-free scenarios, what impacts lane-free traffic can cause on roadway traffic, and what insights can be gained from studies on lane-less traffic with human drivers.

Overall, lane-free traffic has the potential to influence roadway traffic positively, including an increase in traffic performance, a rise in the capacity of the road infrastructure due to efficient use of space, seepage behavior of small-sized vehicles, and greater flexibility of two-dimensional vehicle movement. Nonetheless, a deterrent impact could also be noticed, such as increasing the possibility of side-to-side collisions and energy consumption.

Although a few studies of lane-free traffic have borrowed some methods and framework from studies on lane-less modeling, these two topics overall remain relatively isolated. We believe there should be more cross-fertilization and there are insights to be gained from modeling of lane-less traffic for designing moving strategies for AVs in lane-free traffic, specifically as follows.

- The impact factors on traffic performance included in lane-less traffic studies can be considered in lane-free traffic studies. Specifically, researchers can explore the impact of geometric features of road, proportion of each type of vehicle in heterogeneous traffic, and degree of congestion on the traffic performance, driving safety, and traffic stability of lane-free traffic, and obtain quantitative conclusions in order to facilitate the deployment of the lane-free control algorithms.
- Some empirical results about the parameter values in lane-less traffic studies can be used to design the control algorithms for AVs in lane-free traffic. For example, the required distance of vehicle corner, lateral gap, and time headway of different types of vehicles gained from empirical studies can be taken as reference values to define the constraints or objective function in lane-free traffic strategies.
- In lane-less traffic, drivers tend to perform certain microscopic behaviors to enhance their advantage on the road, which can improve traffic performance. These behaviors can be explored and defined in lane-free traffic control algorithms. For example, small-sized vehicles such as MTWs can navigate through the traffic flow in order to maintain the desired speed. Depending on the surrounding environment, vehicles will choose a left overtaking or right overtaking, and flying overtaking or accelerative overtaking. On the other hand, human drivers' behaviors are not always positive, they may increase crash risk. For example, MTWs are vulnerable on the roadway, their percolation behaviors during the red signal period at the entrance of intersections can increase crash risk and thus should be monitored in lane-free traffic control.

While the current paper has explored the potential implications of the lane-free traffic notions and provided insights for automated road transport, future research should consider mixed traffic consisting of both HVs and AVs in lane-free conditions, and extend the applications of the pedestrian traffic flow concept to lane-free AV traffic in shared spaces.

CRediT authorship contribution statement

Abebe Dress Beza: Writing – original draft, Methodology. **Zhuopeng Xie:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Mohsen Ramezani:** Writing – review & editing, Supervision, Conceptualization. **David Levinson:** Writing – review & editing, Supervision, Project administration.

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