

ORIGINAL PAPER

Open Access



# Impact of connected and autonomous vehicle dedicated lane on the freeway traffic efficiency

Shanglu He<sup>1\*</sup> , Fan Ding<sup>2</sup>, Chaoru Lu<sup>3</sup> and Yong Qi<sup>1</sup>

## Abstract

**Background:** The imminent emergence of connected and autonomous vehicles (CAVs) highlights the need for preparing the road infrastructure for traffic flows mixed with CAVs and human-driven vehicles. A dedicated lane (DL) for CAVs is one of the practical and potential ways to upgrade the road infrastructure for the mixed traffic.

**Methods:** This paper proposes a theoretical method to discuss the influence of implementing a CAV DL policy on the freeway traffic efficiency. In detail, the impact was measured by capacity and throughput. The calculation methods of these efficiency measurements under different CAV DL policies were proposed.

**Experiments:** Numerical experiments were conducted under various compositions of CAV DL policies and traffic conditions. More specifically, the relationship between the traffic conditions (i.e., traffic demand, market penetration rate (MPR) of CAVs, platoon intensity of CAVs, willingness of CAVs using the CAV DL) and the CAV DL policies (i.e., lane configuration, DL access control policy) were discussed.

**Results and Conclusion:** The results have led to some interesting findings, including the critical values of MPR that are valuable to guide an appropriate implementation of a CAV DL policy under a specific traffic condition.

**Keywords:** Connected and autonomous vehicle, Dedicated lane, Human-driven vehicle, Mixed traffic flow, Traffic efficiency

## 1 Introduction

Connected and Autonomous Vehicles (CAVs) are expected to bring benefits to traffic efficiency, safety, and energy-saving [1, 2]. And there will be a long transition period with the coexistence of CAVs and Human-driven Vehicles (HVs). This mixed traffic condition is one of the major challenges in future traffic because of its complexity. For instance, CAVs might have six automation levels identified by the Society of Automotive Engineers (SAE), which results in different driving behaviors. The unpredictable human driving behavior could cause confusion and potentially unsafe situations to the CAVs. As a result,

the expected outstanding performance of CAVs might be affected, especially with a low market penetration rate (MPR) [3]. It urges some appropriate and effective management or control strategies for the mixed traffic condition.

Inspired by the lane management techniques, the researchers have considered to apply the dedicated-lane (DL) techniques to manage the mixed traffic [4]. The lane management techniques have been widely applied in practice, e.g. High Occupancy Vehicle lanes, High Occupancy Toll lanes, and dedicated bus lanes, which have achieved great success in improving the traffic efficiency of the traditional HV traffic [5]. Ideally, assigning one or more lanes to CAVs might bring several benefits. It could reduce the potential conflicts between CAVs and HVs by the physical separation, as well as avoid the subsequent

\*Correspondence: slhemickey@126.com

<sup>1</sup> Nanjing University of Science and Technology, No.200 Xiaolingwei Street, Nanjing 210094, Jiangsu, China  
Full list of author information is available at the end of the article

legal disputes. Besides, it could guide the CAVs to drive in the same lane, increasing the probability of forming CAV platoons, which has been proven to be more efficient (D. [1, 6]. To some extent, it seems that the lane management could make the introduction of CAVs on the road smoother, safer, faster and more acceptable.

Before the field application of a CAV DL policy, it is essential to evaluate its impact on the efficiency, safety, and equity. However, due to the unknown and complex future mixed traffic with the unformed high-automation-level CAVs, it is still a challenging and on-going task to make an extensive validation of a CAV DL policy. As a start, this study will conduct an impact evaluation of different CAV DL policies on the traffic efficiency. Accordingly, the rest of this paper is organized as follows: second section summarizes the existing studies. Third section introduces the detailed methodologies about the CAV DL policies and the traffic-efficiency measures. Numerical experiments and analysis are presented in fourth section. Fifth section gives the main findings and the future works.

## 2 Literature review

A batch of studies have made efforts to explore the application of DL policy under the novel traffic flow mixed with CAVs and HVs. Razmi Rad et al. reviewed the existing studies that underpin their conceptual framework illustrating the relationship among (1) the design and operation of CAV dedicated lane, (2) driver behavior, and (3) the impact on environment, traffic efficiency, and safety (Solmaz Razmi [4]. Following their work, this study extends the review on the relationship between CAV DL policy and traffic efficiency. For a better comparison, Table 1 lists five perspectives of the state-of-the-art studies, including the mixed traffic composition, main method, performance measures, discussed variables, and main results, which also inspires this study to some extent.

Based on the scale of studied roadway, these existing studies are categorized into the network-based studies and the link-based studies. Those network-based studies would commonly use such methods as the network equilibrium and traffic assignment models. And the network-wide issues have been discussed, e.g., selecting out the road segments in the network fitting to implement the DL, and the optimal tolling rate for using the DL, etc. From a view of a road link/segment/corridor, the link-based studies have used different methods which are classified into the theoretical methods and the simulation methods. The simulation methods are based on the modeling of microscopic driving behaviors, while the theoretical methods derivate the traffic flow models using the mathematical or physical theory. Both these methods

could generate the macroscopic traffic performance measures (e.g., capacity, flow), while it seems that the simulation methods could achieve additional measures (e.g., speed, travel time, etc.). Comparatively, the theoretical methods are more meso or macro, which derivate the macroscopic performance measures more directly. Besides, the theoretical methods are more convenient in modeling the multiple possibilities of future CAVs, instead of a heavy workload of different microscopic driving behavior modeling in the simulation methods. Therefore, this study decides to use the theoretical method for convenience at a primary stage of research. As the mostly used flow-related measures in the theoretical methods, the capacity and throughput are also selected as the performance measures in this study. And then, an updated theoretical method to derivate the performance measures will be proposed in the following.

Table 1 indicates that the market penetration rate (MPR) of CAVs has been definitely discussed in these existing studies. Besides, headway distributions, number of DLs, traffic demand, CAV platooning intensity, segregation policy, access strategies, speed limit are partially discussed. To make a more comprehensive exploration, this study expands the research by discussing various combinations of traffic-condition-related variables and CAV-DL-policy-related variables.

As Table 1 shows, the headway-based method is the mostly explored theoretical method. A challenge is that the headway distribution of mixed traffic is not yet sufficient to be conclusive. A review of studies on the headway distribution are summarized in Table 2 which is updated based on the study of Ghiasi et al. [1]. A popular assumption is that a CAV could keep a shorter distance with the preceding vehicle compared with an HV. From a security standpoint, some researchers would argue CAVs should keep a larger distance with a preceding HV to adapt to the randomness of human driving behavior [19]. Table 2 also indicates that the simulation method is mostly used to study the mixed traffic. Therefore, it would be meaningful for this study to further explore the various possibilities of CAV headways with a theoretical method.

## 3 Methodology

### 3.1 Dedicated lane policies

Three aspects of a DL policy are discussed in this study, including the eligibility, number of DL, access strategy. Firstly, for convenience of implementation, this study defines that a freeway CAV DL is one of the freeway lanes assigned to be used by CAVs in a full automation mode only. The mentioned CAV eligible to use the DL drives the car by itself, which approximately refers to SAE Level 3–5 under the automated driving mode. Those vehicles that are ineligible to use the DL include the CAVs in

**Table 1** A list of reviewed studies on the CAV dedicated lane

Index of study	Composition of mixed traffic	Method	Performance measures	Discussed variables	Main results
<i>Link-based studies</i>					
1 Hussain et al. [7]	CAV and HV	An analytical model	Capacity; Throughput	MPRs; Mixed headway settings; Number of CAV DLs; Mixed traffic demand	More aggressive CAVs need less DLs
2 Ghiasi et al. [1]	CAV and HV	A Markov chain method	Capacity	MPRs; CAV platooning intensity; Mixed headway settings; Number of CAV DLs	No CAV DL is the optimal solution in the unsaturated traffic or when CAV adopts a larger headway than that of mixed traffic; The number of CAV DL should be increased with the CAV demand
3 Chen et al. [6]	AV (automated vehicle) and HV	A theoretical framework of capacity	Capacity	MPRs; Demands; Segregation policy	The strict segregation of AVs and HVs will lead to the lower capacity; AVs should be distributed to the most efficient lanes
4 Ramezani et al. [8]	AV and HV	A theoretical model for headway, capacity and delay	Capacity; Delay	MPRs; Mixed headway settings; Multiple lane configurations	The achievement of minimum delay depends on the MPR
5 Ivanchev et al. [9]	AV and HV	An analytical evaluation based on simulation	Throughput; BPR-based travel time; Fuel consumption	MPRs; With or without a DL; Headways of AV	Travel times of AVs are significantly reduced with a low MPR; HV's are delayed due to the reduced capacity for them
6 Talebpour et al. [10]	AV and HV	Simulation	Throughput; Travel time reliability	MPRs; Three DL access strategies	The optional use of DL can relieve the congestion; The potential benefit of DL to throughput can be seen when MPR is over 50% for the 2-lane highway and 30% for the 4-lane highway
7 Laan and Sadabadi [11]	AV and HV	CORridor MACro simulation	Flow; Speed	MPRs; Reaction times of AV	The performance of implementing a DL increases with MPRs adding up to 30%, 40%, or 50%, and then, it will deteriorate
8 Ye and Yamamoto [12]	CAV and HV	Simulation based on cellular automation	Flow; Flow-density diagram	MPRs; Demand levels; Number of DLs; Speed limit	When MPR is low, a CAV DL will deteriorate the traffic throughput; The benefit of DLs could be obtained within a medium density range; A higher speed limit for CAVs on a DL is beneficial
9 Abdel-Aty et al. [13]	CV (connected vehicle) and HV	Vissim simulation	SSAM; Average speed; Average delay	MPRs; Multiple lane configurations	Managed CV platooning lane could significantly improve the traffic speed

**Table 1** (continued)

Index of study	Composition of mixed traffic	Method	Performance measures	Discussed variables	Main results
10 Nickkar and Lee [14]	AV and HV	AIMSUM and SIDRA simulation	Travel time; Delay; Speeds; Queue	MPRs; With or without AV/DLs	The improvement brought by the DLs to the performance of a roundabout can be seen at a high MPR, but it is not significant
11 Wang et al. [15]	CAV and HV	Simulation	Capacity	MPRs CAV platoon coefficient	The impact on the on-ramp junctions
<i>Network-based studies</i>					
13 Chen et al. [16]	AV and HV	A multi-class network equilibrium model	Minimize the social costs	MPRs (Market Penetration Rates); The deployment plan of AV/DLs	A progressive deployment of AV lanes; Wide deployment when MPR reaches a high level (e.g., 20%)
14 Qom et al. [17]	CACC (Cooperative Adaptive Cruise Control) vehicle and HV	Static and dynamic traffic assignment model	Throughput	MPRs; A tolling policy; Traffic demand	Results from STA (Static Traffic Assignment) and DTA (Dynamic Traffic Assignment) are consistent; The toll incentives are not beneficial until the MPR reaches a high level
15 Liu and Song [18]	CAV and HV	User equilibrium model	Capacity; Travel time	MPRs; With or without CAV/DLs; CAV/DL toll rates	The implementation of AV lanes or AV toll lanes can significantly improve the traffic performance
16 Wang et al. [15]	CAV and HV	A multiclass traffic assignment model with elastic demand	Link flow	CAV/DL toll rates; Traffic demands	The optimal toll rates for the HVs using CAV/DL

**Table 2** Studies about headway distribution in mixed traffic

Index of study	Automation level of CAV	Data source	Headway between HVs (s)	Headway for an HV following a CAV (s)	Headway for a CAV following an HV (s)	Headway between CAVs (s)
1 Joel VanderWerf et al. [20]	ACC	Simulation	–	–	Uniform 1.0–2.0	Uniform 0.5–1.4
2 Bose and Ioannou, [21]	ACC/CACC	Simulation	Uniform 0.7–2.2	–	Uniform 0.5–1.5	–
3 Arem et al. [22]	CACC	Simulation	Fixed 1.4	Fixed 1.4	Fixed 1.4	Fixed 0.5
4 Christopher Nowakowski et al. [23]	CACC	Field test	–	–	Uniform 1.1–2.2	Uniform 0.6–1.1
5 Schakel et al. [24]	ACC	Field test	–	–	Gaussian $1.2 \pm 0.15$ and $1.2 \pm 0.3$	Gaussian $1.2 \pm 0.15$ and $1.2 \pm 0.3$
6 Larsson [25]	ACC	Survey	–	–	Uniform 1.0–2.6	–
7 Altay et al. [26]	ACC/CACC	Field test	–	–	Uniform 0.6–2.0	Uniform 0.6–2.0
8 Li Zhao and Sun [27]	ACC/CACC	Simulation	–	–	Fixed 1.4	Fixed 0.5
9 Kumar et al. [28]	None	Field data	Uniform 1.3–2.4	–	–	–
10 Arnaout and Bowling [29]	CACC	Simulation	Uniform 1.0–1.8	Uniform 1.0–1.8	Uniform 0.8–1.0	Fixed 0.5
11 Nikolos et al. [30]	ACC/CACC	Numerical Simulations	–	–	Uniform 0.8–2.2	–
12 Hussain et al. [7]	CAV	Numerical analysis	Fixed 1.8	1.2 or 1.8	1.2 or 1.8	0.3 and 0.45
13 Ivanchev et al. [9]	AV	Agent-based macroscopic simulation	Fixed 1.8	Fixed 1.8	Uniform 0.5–1.0	Uniform 0.5–1.0
14 Darbha et al. [31]	ACC	Numerical simulation	–	–	–	0.68–0.88 or 0.27–0.5 or 0.31–0.58
15 [1]	CAV	Numerical analysis	Uniform 0.8–2.2	Uniform 0.8–2.2	Uniform 0.7–1.5	Uniform 0.6–1.1
16 [32]	AV	Simulation	Fixed 1.8	Fixed 1.8	Fixed 1.2	Fixed 0.9
17 Lu et al. [33]	AV	Simulation	Fixed 0.9	Fixed 0.9	Fixed 0.6	Fixed 0.6
18 Nishimura et al. [34]	AV	Simulation	Normal average 1.69	Normal average 1.69	Uniform 0.1–3.0	Uniform 0.1–3.0
19 Zhao et al. [35]	CAV	Simulation	Fixed 1.2	Fixed 1.2	Fixed 0.9	Fixed 0.9
20 Martin-Gasulla et al. [19]	CAV	Simulation	Fixed 0.9	Fixed 0.9	Uniform 1.5–2.5	Fixed 0.6

SAE Level 1–2 and human-driving mode of Level 3–4, as well as those pure manual driving vehicles, which are all called as HVs in the following study for convenience. It should be noted that if a CAV changes its automated driving mode to the manual driving mode, then it is urged to leave the DL.

Second, different possibilities of CAV DL number will be explored in the following study, which are valued from zero to the total number of lanes.

Third, two access control policies are proposed, i.e., mandatory use and optional use. Following the ‘mandatory use’ policy, CAVs are obligated to travel on the DL, which strictly separates CAVs from HVs. Under this policy, the lanes are divided and named as the CAV DL and the general-purpose lane (GPL). The ‘optional use’ policy allows the CAVs to choose either driving on a DL or the other lane. In this case, the other lane is named as the mixed lane (ML), which could be used by both CAVs and

HVs. It should be noted that the on- or off-ramps and weaving sections are not in the scope of this study and these access control policies are not suitable to apply on these sections. An illustration of these two access control policies is shown in Fig. 1.

### 3.2 Efficiency measures

#### 3.2.1 Capacity

Three types of lanes are involved in the different DL policies, i.e., DL, GPL, and ML. Obviously, the traffic on a DL and GPL can be regarded as two extreme cases on an ML. Therefore, the capacity calculation method of an ML is introduced as a representative. As an ML example in Fig. 2, there are four types of car-following behaviors corresponding to four types of time headways which are defined as: (1)  $h_{CC}$  for a CAV follows another CAV, (2)  $h_{CH}$  for a CAV follows an HV, (3)  $h_{HC}$  for a HV follows a

CAV, (4)  $h_{HH}$  for an HV follows another HV. It should be noted that each type of time headway represents an average value.

The average headway of a mixed traffic flow on an ML can be calculated by:

$$\overline{h_{mix}} = \frac{n_{CC} \cdot h_{CC} + n_{CH} \cdot h_{CH} + n_{HC} \cdot h_{HC} + n_{HH} \cdot h_{HH}}{N_{mix}} \tag{1}$$

where  $n_{CC}$ ,  $n_{CH}$ ,  $n_{HC}$ , and  $n_{HH}$  are the number of CAVs following CAV, the number of CAVs following HV, the number of HVs following CAV, and the number of HVs following HV.  $N_{mix}$  is the sum of  $n_{CC}$ ,  $n_{CH}$ ,  $n_{HC}$ , and  $n_{HH}$ , which approximately equals to the traffic volume on the lane. Similarly,  $N_C = n_{CC} + n_{CH}$  is the total CAV volume on the lane, and the MPR of CAVs on a lane could be calculated by:

$$p_C = \frac{N_C}{N_{mix}} \tag{2}$$

Besides, the platooning intensity (PI) of CAVs is proposed to reflect the proportion of CAVs forming the platoons to all CAVs:

$$p_{CC} = \frac{n_{CC}}{N_C} \tag{3}$$

Similarly, we have  $p_H$  representing the percentage of HVs on a lane and  $p_{HH}$  representing the ratio of HVs following HV to the total number of HVs. Based on the average time headway of a lane (in seconds), the capacity of a ML (in veh/h) could be inferred by:

$$\begin{aligned} C_{mix} &= \frac{3600}{\overline{h_{mix}}} \\ &= \frac{3600}{(n_{CC} \cdot h_{CC} + n_{CH} \cdot h_{CH} + n_{HC} \cdot h_{HC} + n_{HH} \cdot h_{HH})/N_{mix}} \\ &= \frac{3600}{p_C \cdot p_{CC} \cdot h_{CC} + p_C \cdot (1 - p_{CC}) \cdot h_{CH} + p_H \cdot (1 - p_{HH}) \cdot h_{HC} + p_H \cdot p_{HH} \cdot h_{HH}} \end{aligned} \tag{4}$$

The independent variables in Eq. (4) include different types of headway, MPR of CAVs and HVs, PI of CAVs and HVs, which will jointly determine the capacity of a ML.

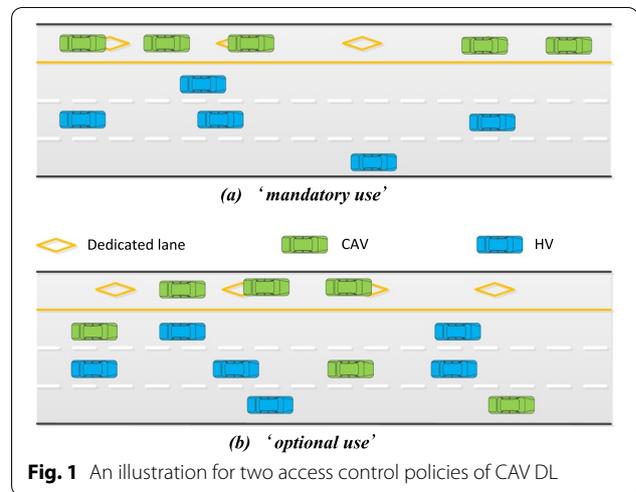


Fig. 1 An illustration for two access control policies of CAV DL

Accordingly, the formulas for the capacity of a CAV DL and a GPL could be inferred as:

$$C_{DL} = \frac{3600}{h_{CC}} \tag{5}$$

$$C_{GPL} = \frac{3600}{h_{HH}} \tag{6}$$

### 3.2.2 Throughput

The expectation of implementing a DL policy is to achieve a larger throughput of a freeway segment. Assuming that

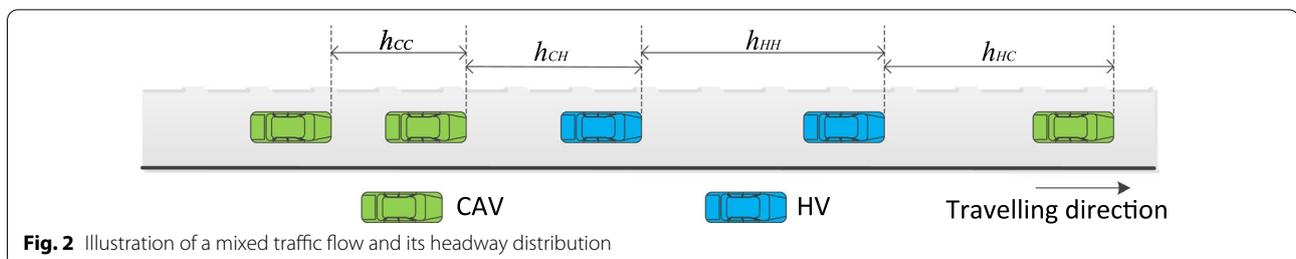


Fig. 2 Illustration of a mixed traffic flow and its headway distribution

a studied freeway segment has  $L$  lanes in one direction,  $L_{DL}$  lanes are assigned as the CAV DLs where  $L_{DL} \in [0, L)$ , and the left  $L - L_{DL}$  lanes are GPLs or MLs depending

on the applied access control policy. The traffic flow rate of this segment will be influenced by both traffic related factors (e.g., traffic demand ( $D$ ), time headway, MPR of CAVs, PI of CAVs) and DL related factors (e.g., number of CAV DL, DL access control policy, selection rate of DL). According to the applied DL policy, there could be three scenarios, i.e., no application of DL policy, implementing the DL policy with ‘mandatory use,’ and implementing the DL policy with ‘optional use.’ The corresponding three conditional optimization functions are as follows:

Scenario 1: No application of CAV DL policy. The segment flow is a summation of ML flows, while the lane flow is restricted to the ML capacity and the segment flow should be no more than segment capacity and demand. Therefore, the flow maximization function could be expressed as

$$\begin{aligned}
 \text{Maximize } F &= \sum_{i=1}^L f_i \\
 \text{subjected to } &0 \leq f_i \leq C_{mix} \\
 &0 \leq F \leq \min(D, L \cdot C_{mix})
 \end{aligned} \tag{7}$$

where  $F$  is the segment flow;  $f_i$  is the flow of  $i$ th lane;  $C_{mix}$  is the capacity of an ML;  $L$  is the number of lanes in the segment;  $D$  is the traffic demand of the segment.

Scenario 2: Implementing the ‘mandatory use’ CAV DL policy. Under this scenario, the segment flow consists of the DL flows and the GPL flows. Similarly, the lane flow should be restricted to the lane capacity. Different from the previous scenario, a sum of flows in the same type of lanes will be restricted to the corresponding capacity and demand. The flow maximization function will be:

$$\begin{aligned}
 \text{Maximize } F &= F_{DL} + F_{GPL} = \sum_{i=1}^{L_{DL}} f_{DLi} + \sum_{j=1}^{L-L_{DL}} f_{GPLj} \\
 \text{subjected to } &0 \leq f_{DLi} \leq C_{DL} \\
 &0 \leq f_{GPLj} \leq C_{GPL} \\
 &0 \leq F_{DL} \leq \min(D \cdot P_{CAV}, L_{DL} \cdot C_{DL}) \\
 &0 \leq F_{GPL} \leq \min[D \cdot (1 - P_{CAV}), (L - L_{DL}) \cdot C_{GPL}] \\
 &0 < L_{DL} < L
 \end{aligned} \tag{8}$$

$$\text{Maximize } F = F_{DL} + F_{mix} = \sum_{i=1}^{L_{DL}} f_{DLi} + \sum_{j=1}^{L-L_{DL}} f_{mixj}$$

$$\begin{aligned}
 \text{subjected to } &0 \leq f_{DLi} \leq C_{DL} \\
 &0 \leq f_{mixj} \leq C_{mix} \\
 &0 \leq F_{DL} \leq \min(D \cdot P_{CAV} \cdot O_{DL}, L_{DL} \cdot C_{DL}) \\
 &0 \leq F_{mix} \leq \min[D \cdot (1 - P_{CAV} \cdot O_{DL}), (L - L_{DL}) \cdot C_{mix}] \\
 &0 < L_{DL} < L
 \end{aligned} \tag{9}$$

**Table 3** Tested scenarios

Number of lanes	Number of DL	DL accessibility	Index of scenario	Lane configurations
2	0	–	2–1	2 MLs
	1	Mandatory	2–2	1 DL and 1 GPL
3	0	Optional	2–3	1 DL and 1 ML
		–	3–1	3 MLs
	1	Mandatory	3–2	1 DL and 2 GPLs
	Optional	3–3	1 DL and 2 MLs	
4	2	Mandatory	3–4	2 DLs and 1 GPL
	Optional	3–5	2 DLs and 1 ML	
	0	/	4–1	4 MLs
	1	Mandatory	4–2	1 DL and 3 GPLs
	Optional	4–3	1 DL and 3 MLs	
	2	Mandatory	4–4	2 DLs and 2 GPLs
Optional	4–5	2 DLs and 2 MLs		
3	Mandatory	4–6	3 DLs and 1 GPL	
	Optional	4–7	3 DLs and 1 ML	

where  $F_{DL}$  is the flow on the DLs;  $F_{GPL}$  is the flow on the GPLs;  $f_{DLi}$  is the flow of  $i$ th DL;  $f_{GPLj}$  is the flow of  $j$ th GPL;  $C_{DL}$  is the DL capacity;  $C_{GPL}$  is the GPL capacity;  $L_{DL}$  is the number of DLs;  $P_{CAV}$  is MPR of CAVs in the segment.

Scenario 3: Implementing the ‘optional use’ CAV DL policy. Under this scenario, the segment flow is made up of the DL flows and the ML flows. Similarly, the lane flow is restricted to the lane capacity and the flows of a certain type of lane are restricted to the corresponding traffic demand and capacity. Besides, a new variable, the selection rate  $O_{DL}$ , is introduced to indicate the willingness of CAVs to use the DL. It could be calculated by the ratio of CAVs choosing to use the DL to all CAVs. The corresponding maximization function can be modeled as

where  $F_{mix}$  is the flow on the MLs;  $f_{mixj}$  is the flow on  $j$ th ML.

## 4 Numerical analysis

### 4.1 Experiment settings

The numerical experiments are set up as follows:

(a) Lane configurations

Three types of freeway segments, i.e., 2 lanes, 3 lanes, and 4 lanes in one direction, are tested. Table 3 shows the detailed lane configurations in each testing scenario.

(b) Headway distribution

Table 2 indicates that the existing studies have adopted different headway distributions including fixed-value distribution, uniform distribution, and Gaussian distribution. Obviously, the former two distributions are mostly discussed. Although the fixed-value distribution ignores the heterogeneities of different vehicles, it takes advantage of a simple and fast calculation. The uniform distribution exhibits the heterogeneities to some extent but increases the computational efforts. Since the proposed methods use the average headways, the fixed-value distribution seems more suitable and convenient. Referring to Table 2, four types of headways have been valued in the following ranges respectively:  $h_{CC} \in [0.3, 3.0]$  s,  $h_{CH} \in [0.5, 3.0]$  s,  $h_{HC} \in [0.8, 2.2]$  s, and  $h_{HH} \in [0.7, 2.4]$  s. This study also selects the fixed values of average headways from these value ranges. Most studies in Table 2 assume that HVs maintain the same average headway either following another HV or a CAV. And this study adopts the same assumption, i.e.,  $h_{HC} = h_{HH}$ . Besides, it is assumed that the average time headway between two CAVs is the shortest among the four types of car-following behaviors. There will be an increase in the average time headway when CAV follows an HV. And two possibilities of the increase will be explored. One possibility is that the increase is not that large and  $h_{CH}$  is still smaller than  $h_{HH}$ . Another possibility is  $h_{CH}$  grows over  $h_{HH}$ . Accordingly, there will be four kinds of CAV driving modes which are named as aggressive mode, neutral mode, conservative mode, and safe mode. In the former three modes, the relationship among different types of average headways is that  $h_{CC} < h_{CH} < h_{HC} = h_{HH}$ . In the safe mode, the relationship is  $h_{CC} < h_{HC} = h_{HH} < h_{CH}$ . The average time headways in each mode are valued as follows:

- ① Aggressive mode, where  $h_{CC} = 0.8s$ ,  $h_{CH} = 1.2s$ ,  $h_{HC} = h_{HH} = 2.0s$ ;
- ② Neutral mode, where  $h_{CC} = 1.0s$ ,  $h_{CH} = 1.5s$ ,  $h_{HC} = h_{HH} = 2.0s$ ;
- ③ Conservative mode, where  $h_{CC} = 1.5s$ ,  $h_{CH} = 1.8s$ ,  $h_{HC} = h_{HH} = 2.0s$ ;
- ④ Safe mode, where  $h_{CC} = 1.5s$ ,  $h_{CH} = 2.4s$ ,  $h_{HC} = h_{HH} = 2.0s$ .

(iii) MPR of CAVs in a lane and in a segment

It could be imagined that CAVs will be introduced into the market gradually. In this light, this study set the MPR of CAVs as 1%, 5%, 10%, and then, increasing with 10% step to 100%. There are two kinds of MPRs in this study. One is defined as the MPR of CAVs in a lane ( $p_C$ ), and the other is named as the MPR of CAVs in a segment ( $P_{CAV}$ ). A freeway segment is made up of several lanes. If the traffic is uniformly distributed across the lanes in a segment, then  $P_{CAV}$  equals to  $p_C$ . Otherwise,  $P_{CAV}$  is valued as before, while  $p_C$  has to be recalculated according to the DL access control policy and the traffic distribution across different lanes as the following Eq. (11).

(iv) PI of CAVs in a lane

To investigate the influence of platoon intensity ( $p_{CC}$ ), this ratio was valued from 0 to 100% with 10% step. However, it should be noted that the lower limit of  $p_{CC}$  will be changed when the number of CAVs exceeds the number of HVs. Under this condition, even though every HV is followed by a CAV, there are still  $(N_C - N_H)$  CAVs following other CAV. Accordingly, the threshold of  $p_{CC}$  will be:

$$\frac{N_C - N_H}{N_C} \leq p_{CC} \leq 100\% \tag{10}$$

(e) DL access control policy

Under the ‘optional use’ policy, the willingness of CAV choosing to use DL (selection rate  $O_{DL}$ ) is not sure in the future application. Therefore, this study proposes three willingness states (i.e., weak, moderate, and strong) and assigns 0.2, 0.5, and 0.8 to  $O_{DL}$  correspondingly. And then, the distribution of CAVs across different types of lanes could be inferred. For instance, if the MPR of CAVs in a segment is  $P_{CAV}$ , then the proportion of CAVs traveling on MLs and DLs will be  $P_{CAV} \cdot (1 - O_{DL})$  and  $P_{CAV} \cdot O_{DL}$  respectively.

(f) Traffic demand

Four scenarios of traffic demand will be discussed, i.e., 1500 veh/h, 2500 veh/h, 3500 veh/h, and 4500 veh/h. Compared with the capacity of a traditional freeway lane for HVs, some demand scenario under a certain DL policy might cause the lane oversaturation. Although the discussion of lane overflow is essential, it is not in the scope of this study and planned in a future study. On this basis, the penetration rate of CAVs on different type of lanes under the optional use policy could be inferred. For example, if the traffic demand of a two-lane mainline segment is  $D$ , and one lane is reserved as a CAV DL, then the traffic on the DL is  $D \cdot P_{CAV} \cdot O_{DL}$ , and  $p_C$  on ML is:

$$p_C = \frac{D \cdot P_{CAV} \cdot (1 - O_{DL})}{D - D \cdot P_{CAV} \cdot O_{DL}} = \frac{P_{CAV} \cdot (1 - O_{DL})}{1 - P_{CAV} \cdot O_{DL}} \tag{11}$$

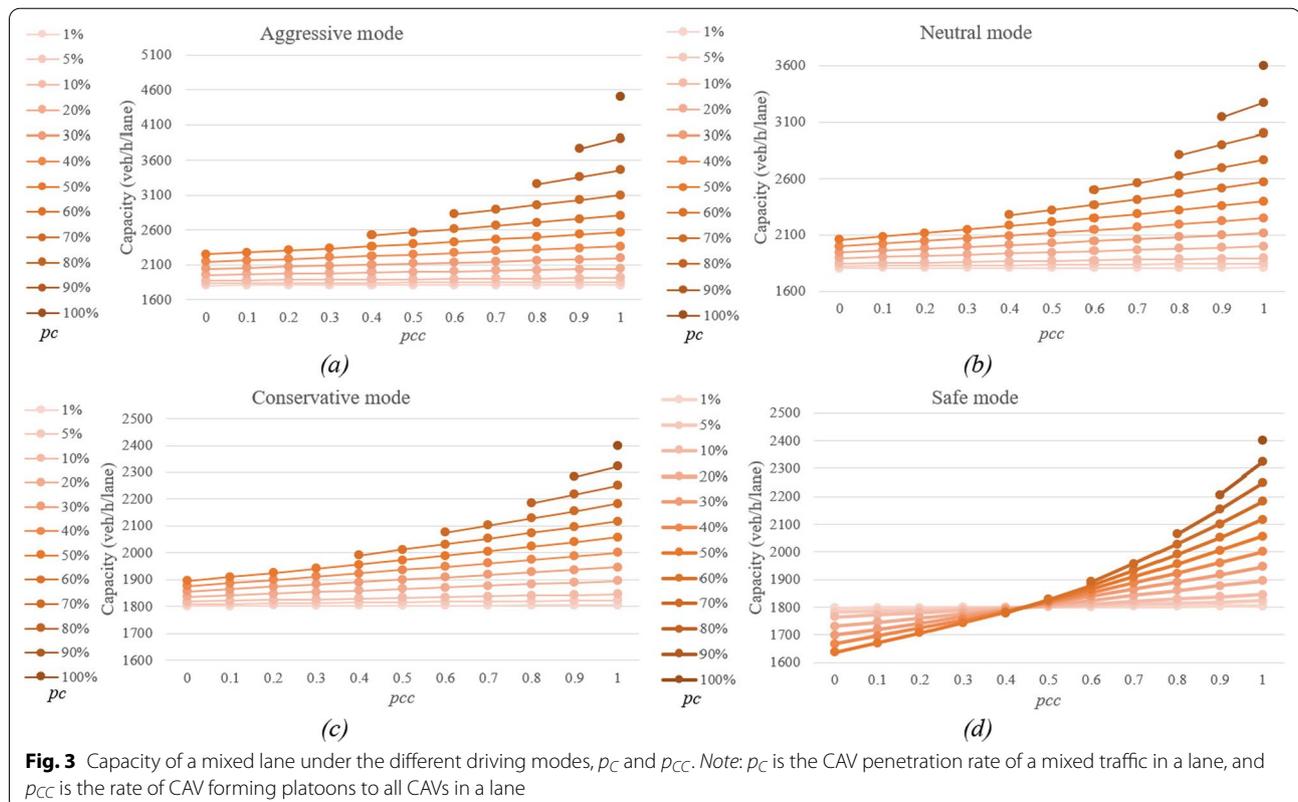
Besides, it is assumed that if the adjacent lanes belong to the same type, then the traffic will be evenly distributed across these lanes.

4.2 Results and evaluations

4.2.1 Capacity

Based on Eq. (5), the capacity of a DL under the aggressive mode, the neutral model, the conservative mode, and the safe mode are 4500 veh/h/lane, 3600 veh/h/lane, 2400 veh/h/lane, and 2400 veh/h/lane respectively. The capacity of a GPL is 1800 veh/h/lane calculated using Eq. (6). Figure 3 illustrates the capacity of an ML under the different CAV driving modes and different compositions of  $p_C$  and  $p_{CC}$ , and a darker color represents a larger  $p_C$ .  $p_C$  reflects the proportion of CAVs to the traffic in a lane, while  $p_{CC}$  indicates the platoon intensity of CAVs. Obviously, the aggressive mode of CAVs significantly increases the ML capacity. From the Fig. 3a–c, it can be seen that both  $p_C$  and  $p_{CC}$  have a positive impact on the capacity, but this impact is insignificant when MPR of CAVs is small especially below 10%. Figure 3d indicates that if CAVs use a safe driving mode, then the increase of CAVs would decrease the ML capacity. This negative impact could be mitigated with the increase of PI ( $p_{CC}$ ). Besides, when  $p_{CC}$  grows over 50%, the increase of CAVs will always be beneficial to the capacity in all driving modes.

Under an ideal condition, the capacity of a freeway segment would be a sum of all lanes' capacity. According to the applied DL policy, a freeway segment would



**Table 4** Capacity and the corresponding ideal condition

Index of scenario	Capacity under different headway distributions (veh/h)				Ideal condition (the value of $P_{CAV}$ ) for aggressive, neutral, conservative, and safe driving modes respectively
	Aggressive	Neutral	Conservative	Safe	
2-1	[3614, 9000]	[3610, 7200]	[3604, 4800]	[3272, 4800]	100%
2-2	6300	5400	4200	4200	71%, 67%, 57% and 57%
2-3	[6307, 9000]	[5405, 7200]	[4202, 4800]	[4036, 4800]	100%
3-1	[5321, 13,500]	[5415, 10,800]	[5406, 7200]	[4908, 7200]	100%
3-2	8100	7200	6000	6000	56%, 50%, 40% and 40%
3-3	[8114, 13,500]	[7210, 10800]	[6004, 7200]	[5672, 7200]	100%
3-4	10,800	9000	6600	6600	83%, 80%, 73% and 73%
3-5	[10807, 13,500]	[9005, 10,800]	[6602, 7200]	[6436, 7200]	100%
4-1	[7228, 18,000]	[7220, 14,400]	[7208, 9600]	[6544, 9600]	100%
4-2	9900	9000	7800	7800	45%, 40%, 31% and 31%
4-3	[9921, 18,000]	[9015, 14,400]	[7806, 9600]	[7308, 9600]	100%
4-4	12,600	10,800	8400	8400	71%, 67%, 57% and 57%
4-5	[12614, 18,000]	[10810, 14,400]	[8404, 9600]	[8072, 9600]	100%
4-6	15,300	12,600	9000	9000	88%, 85%, 80% and 80%
4-7	[15307, 18,000]	[12605, 14,400]	[9002, 9600]	[8836, 9600]	100%

consist of different types of lanes. The above analysis indicates that only the capacity of ML will be impacted by the traffic conditions (MPR and PI of CAVs). Therefore, when a segment contains ML, its range of capacity variation and ideal traffic condition to achieve the largest capacity are concluded in Table 4.

First, Table 4 shows that under the ideal condition, the maximum capacity under no-DL or ‘optional use’ DL policy is larger than that under the ‘mandatory use’ DL policy. The ideal condition under no-DL or ‘optional use’ DL policy is when CAVs fully conquer the vehicle market. On the other hand, the ideal MPR under the ‘mandatory use’ DL policy to reach the maximum capacity is obviously lower than 100%. Since the ‘mandatory use’ policy strictly distinguishes the right of way by vehicle type, the ideal condition happens when there is a match between the traffic distribution and the lane composition. Otherwise, the mismatch would lead to a waste of lane resource or a lane congestion. Moreover, under the same traffic condition and DL access control policy, the increase of DL number will benefit the capacity, but this benefit is trivial when  $P_{CAV}$  is small. Besides, the ‘mandatory use’ performs better than the ‘optional use’ when CAVs use the safe driving mode and  $P_{CAV}$  is small.

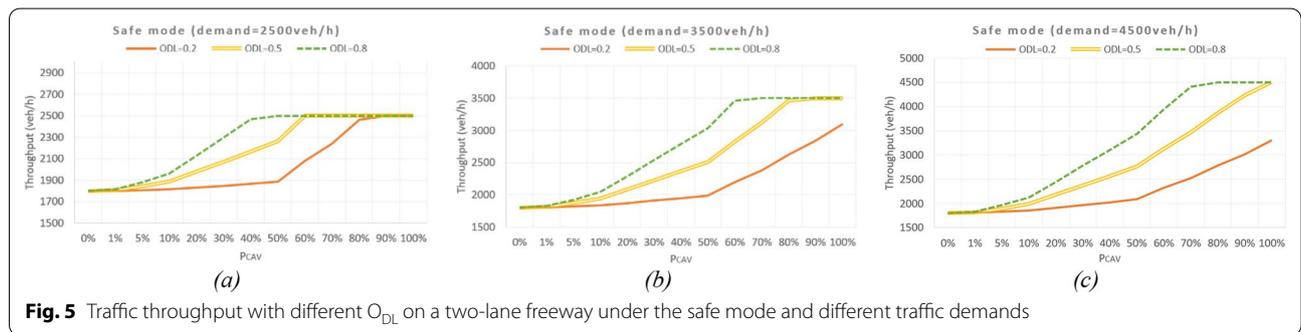
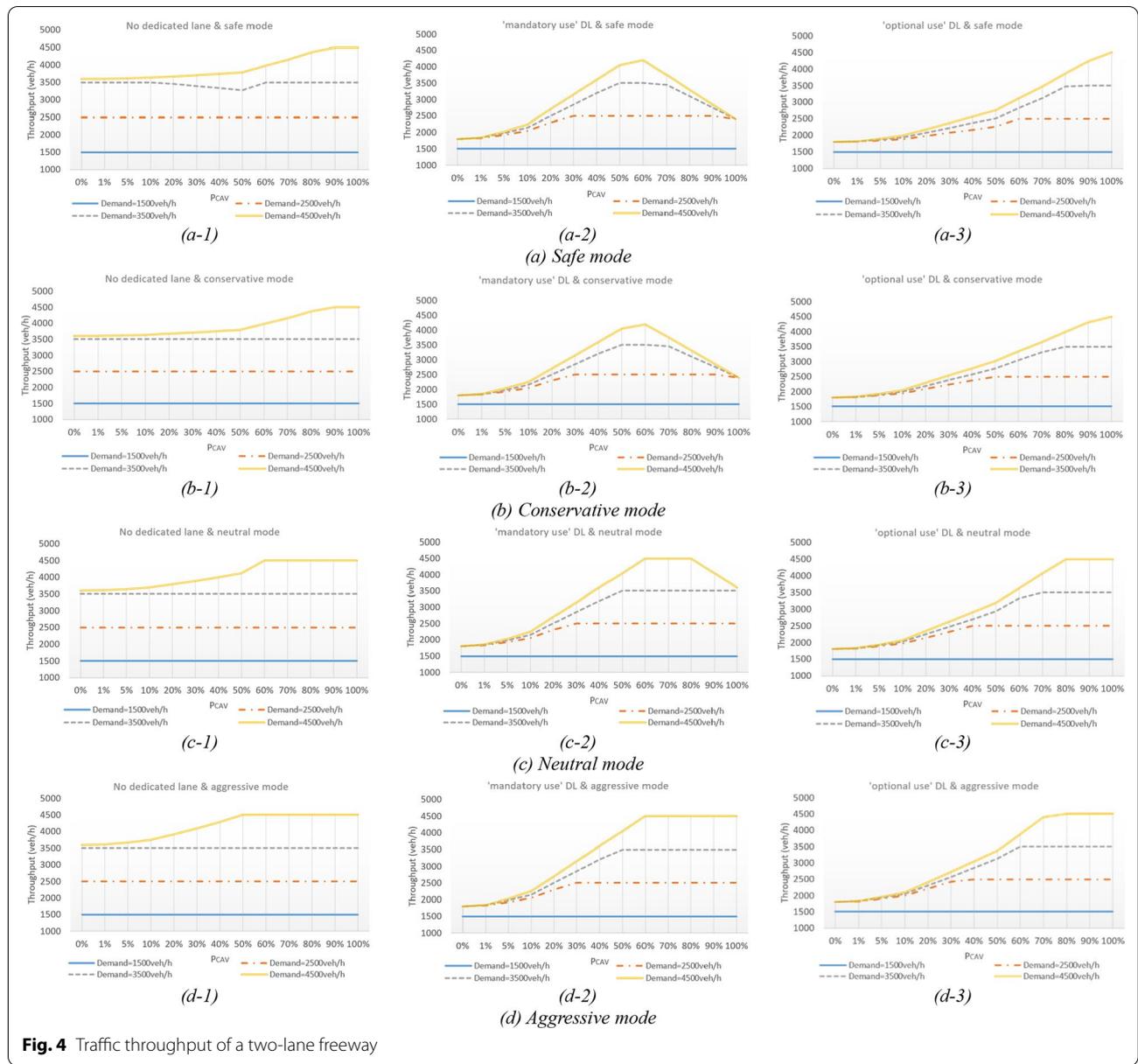
#### 4.2.2 Throughput

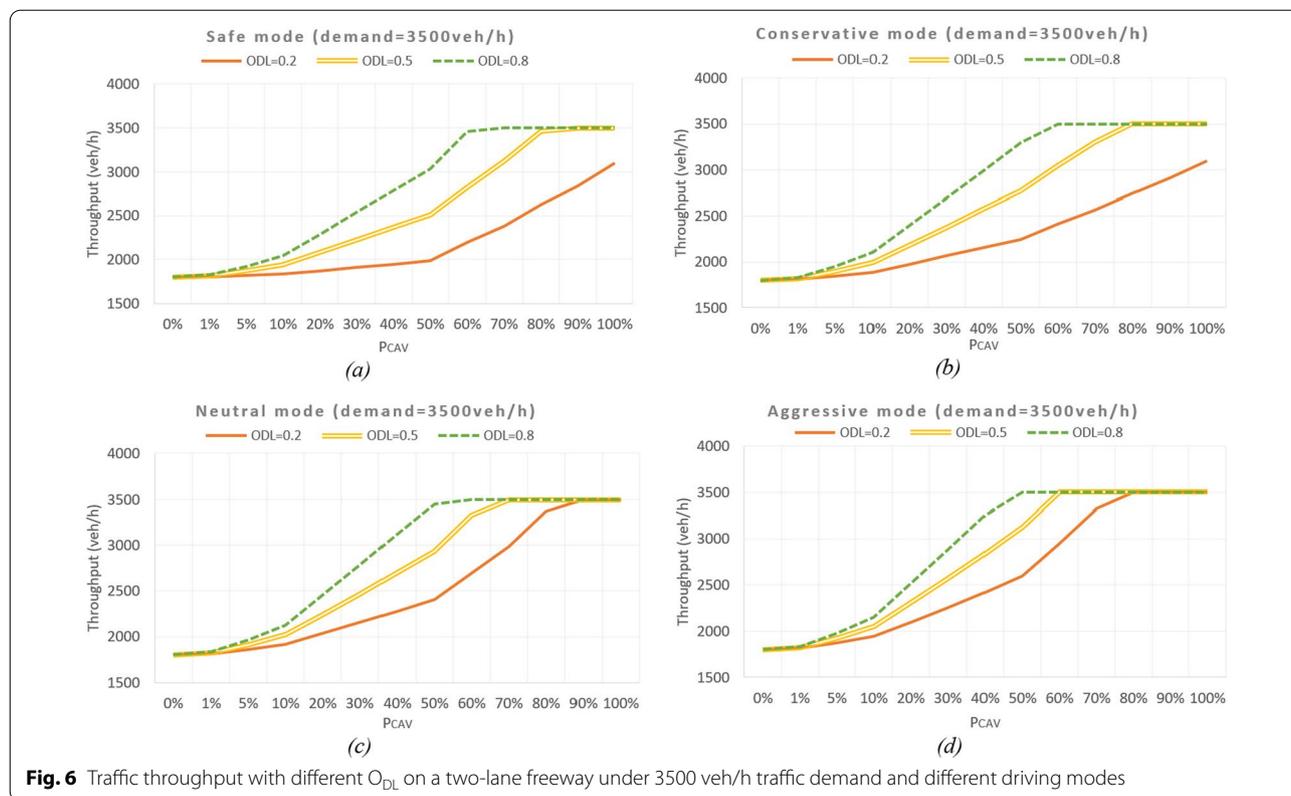
As a start, a freeway segment with two lanes in a direction is taken as an example, and the  $O_{DL}$  in the ‘optional use’ policy is set as 0.5. The traffic throughputs under

four traffic demands are inferred based on Eqs. (7)–(9) as shown in Fig. 4.

Some findings could be inferred from the subfigures of Fig. 4. First, when the demand is lower than the capacity, implementing a DL almost has no effect on the throughput. Second, converting a lane into a DL will have a negative impact on the traffic throughput, when the MPR of CAVs ( $P_{CAV}$ ) is low. And this negative impact lasts until  $P_{CAV}$  reaches 50%. Third, the DL with ‘mandatory use’ appears to have the most significant and positive impact when  $P_{CAV}$  is within the range of 50% to 60%. The increase of traffic demand would enhance this benefit, which will gradually vanish when the driving mode of CAVs gets more aggressive. Fourth, it indicates that the ‘mandatory use’ policy overperforms the ‘optional use’ policy when CAVs in the safe and conservative driving modes and  $P_{CAV}$  is lower than 80%, while the ‘optional use’ policy will be more advantageous when  $P_{CAV}$  is over 80%. Under the neutral driving mode, this critical point of  $P_{CAV}$  is 90%. Under the aggressive driving mode, the ‘mandatory use’ policy always has a better performance.

A further discussion is to explore the different willingness states of using the CAV DL which are represented by three different values of  $O_{DL}$  0.2, 0.5, and 0.8. The results of throughput under different demands with CAVs in the same driving mode (safe driving mode) are shown in Fig. 5. And Fig. 6 exhibits the throughput under different driving modes with the same demand (3500 veh/h). It can be concluded from these two figures that encouraging more CAVs to use the DL is beneficial to the traffic throughput. And this encouragement should be





**Fig. 6** Traffic throughput with different  $O_{DL}$  on a two-lane freeway under 3500 veh/h traffic demand and different driving modes

enhanced especially under the following conditions: a higher traffic demand, or a safer driving mode.

Furthermore, the impact of DL number on the throughput is explored on the three-lane freeway segment. According to the previous findings on  $O_{DL}$ , its value is set to 0.8 in this experiment. The results indicate that if DL is going to be implemented, then distributing one lane as a DL is sufficient.

Finally, compared with the findings of the existing studies in Table 1, this study has obtained some consistent results, for instance, when MPR of CAV is low, implementing a CAV DL might reduce the throughput. Besides, this study yields some different results which embody in four points. First, for the number of CAV DL, this study would suggest that if DL is going to be implemented, one DL is sufficient at the introduction stage of CAVs with a low MPR. Second, with a gradual increase of CAV MPR, the ‘mandatory use’ access control policy is suggested especially when CAVs adopt a more conservative or safer car-following behavior. Although this policy might negatively impact the freeway capacity and throughput compared with the scenario without the DL, it is better than ‘optional use’ policy from the view of throughput. Third, when the CAV MPR increases over some specific condition as concluded in Table 4,

it is suggested to use the ‘optional use’ DL or not to implement DL. Fourth, when the ‘optional use’ policy is adopted, efforts should be made to encourage the CAVs to use the DL and thus benefit the throughput.

### 5 Conclusions and future works

This study presents a review of the “state-of-the-art” studies on CAV DL policy under the mixed traffic condition as well as the headway distributions of the mixed traffic. And then, the detailed CAV DL policies and the headway-based theoretical methods evaluating the traffic efficiency are proposed. The discussions based on several numerical experiments give some insights into the relationship between traffic efficiency measures and various conditions (traffic conditions and DL policies). As a final observation, it seems when the MPR of CAVs on a freeway segment is low (e.g., below 50%), the implementation of CAV DL does not have a significant positive impact on traffic efficiency. At this condition, if a DL policy is required, the ‘mandatory use’ is recommended compared with the ‘optional use’, especially when CAVs use the safe driving mode. When MPR of CAVs grows to a high value (e.g., larger than 80%), the ‘optional use’ policy performs better instead. All in all, distributing one lane as a DL is enough as a beginning stage of DL implementation.

In fact, this study has partially finished the discussion, and more extensive explorations are essential. Here is a summation of works that could be conducted in the future. First, different eligibility arrangement of different automation-level vehicles could be explored. Second, to discuss the heterogeneity in headways by using different headway distributions might be interesting. Third, the weaving segment should also be explored to form a complete road network so that the impact of lane overflow could be analyzed. Fourth, except the traffic efficiency, the other safety and equity measures are also needed to validate a DL policy fully.

#### Acknowledgements

Not applicable.

#### Authors' contributions

Study conception and design: SH; Data collection: SH; Analysis and interpretation of results: SH, FD, CL; Draft manuscript preparation and revision: SH, FD, CL, YQ. All authors reviewed the results and approved the revised version of the manuscript. All authors read and approved the final manuscript.

#### Funding

This study was partially supported by National Key Research and Development Program of China (Grant No.2019YFE0123800), National Natural Science Foundation of China (Grant No. 52102380), China Postdoctoral Science Foundation (Grant Nos. 2021T140325 and 2018M642257), National Social Science Fund of China (Grant No. 18CFX062), Fundamental Research Funds for the Central Universities (Grant No. 330920021140), National Natural Science Foundation of China (Grant No. 71971116), 2019 major science and technology project of CCCC (China Communications Construction Company Ltd.) (Grant No. 2019-ZJKJ-ZDZX02).

#### Availability of data and materials

All data, models, and code generated or used during the study appear in the submitted article.

#### Declarations

#### Competing interests

The authors declare that they have no competing interests.

#### Author details

<sup>1</sup>Nanjing University of Science and Technology, No.200 Xiaolingwei Street, Nanjing 210094, Jiangsu, China. <sup>2</sup>Southeast University, No.2 Southeast University Road, Nanjing 211189, Jiangsu, China. <sup>3</sup>Oslo Metropolitan University, Pilestredet 46, 0167 Oslo, Norway.

Received: 13 October 2021 Accepted: 24 March 2022

Published online: 04 April 2022

#### References

- Ghiassi, A., Hussain, O., Qian, Z., & Li, X. (2017). A mixed traffic capacity analysis and lane management model for connected automated vehicles: A Markov chain method. *Transportation Research Part B*, 106, 266–292.
- Li, D., & Wagner, P. (2019). Impacts of gradual automated vehicle penetration on motorway operation: A comprehensive evaluation. *European Transport Research Review*, 11(36), 1–10.
- Talebpoor, A., & Mahmassani, S. H. (2016). Influence of connected and autonomous vehicles on traffic flow stability and throughput. *Transportation Research Part C: Emerging Technologies*, 71, 143–163.
- Rad, S. R., Farah, H., Taale, H., van Arem, B., & Hoogendoorn, S. P. (2020). Design and operation of dedicated lanes for connected and automated vehicles on motorways: A conceptual framework and research agenda. *Transportation Research Part C*, 117, 1–18.
- FHWA. (2008). *Managed lanes, a primer*. Washington, DC: FHWA.
- Chen, D., Ahn, S., Chitturi, M., & Noyce, D. A. (2017). Towards vehicle automations: Roadway capacity formulation for traffic mixed with regular and automated vehicles. *Transportation Research Part B*, 100, 196–221.
- Hussain, O., Ghiassi, A., & Li, X. (2016). *Freeway lane management approach in mixed traffic environment with connected autonomous vehicles* (pp. 1–12). [arXiv:1609.02946](https://arxiv.org/abs/1609.02946) [cs.SY].
- Ramezani, M., Machado, J. A., Skabardonis, A., & Geroliminis, N. (2017). *Capacity and delay analysis of arterials with mixed autonomous and human-driven vehicles*. Paper presented at the 2017 5th IEEE international conference on models and technologies for intelligent transportation systems (MT-ITS), Naples, Italy.
- Ivanchev, J., Knoll, A., Zehe, D., Nair, S., & Eckhoff, D. (2017). *Potentials and implications of dedicated highway lanes for autonomous vehicles* (pp. 1–12). [arXiv:1709.07658v1](https://arxiv.org/abs/1709.07658v1).
- Talebpoor, A., Mahmassani, H. S., & Elfar, A. (2017). Investigating the effects of reserved lanes for autonomous vehicles on congestion and travel time reliability. *Transportation Research Record Journal of the Transportation Research Board*, 2622, 1–23.
- Laan, Z. V., & Sadabadi, K. F. (2017). Operational performance of a congested corridor with lanes dedicated to autonomous vehicle traffic. *International Journal of Transportation Science and Technology*, 6, 42–52.
- Ye, L., & Yamamoto, T. (2018). Impact of dedicated lanes for connected and autonomous vehicle on traffic flow throughput. *Physica A: Statistical Mechanics and its Applications*, 512, 588–597.
- Abdel-Aty, M., Saad, M., Wu, Y., & Rahman, M. S. (2019). *Evaluation of managed lane facilities in a connected vehicle environment*.
- Nickkar, A., & Lee, Y.-J. (2019). *Evaluation of dedicated lanes for automated vehicles at roundabouts with various flow patterns*. Paper presented at the transportation research board annual meeting, Washington DC.
- Wang, J., Lu, L., Peeta, S., & He, Z. (2021). Optimal toll design problems under mixed traffic flow of human-driven vehicles and connected and autonomous vehicles. *Transportation Research Part C*, 125, 1–30.
- Chen, Z., He, F., Zhang, L., & Yin, Y. (2016). Optimal deployment of autonomous vehicle lanes with endogenous market penetration. *Transportation Research Part C*, 72, 143–156.
- Qom, S. F., Xiao, Y., & Hadi, M. (2016). Evaluation of cooperative adaptive cruise control (CACC) vehicles on managed lanes utilizing macroscopic and mesoscopic simulation. *Transportation Research Record Journal of the Transportation Research Board*, 1–16.
- Liu, Z., & Song, Z. (2019). Strategic planning of dedicated autonomous vehicle lanes and autonomous vehicle/toll lanes in transportation networks. *Transportation Research Part C*, 106, 381–403.
- Martin-Gasulla, M., Sukennik, P., & Lohmiller, J. (2019). Investigation of the impact on throughput of connected autonomous vehicles with headway based on the leading vehicle type. *Transportation Research Record: Journal of the Transportation Research Board*, 2673(5), 617–626.
- Joel VanderWerf, S. S., Kourjanskaia, N., Miller, M., & Krishnan, H. (2001). Modeling effects of driver control assistance systems on traffic. *Transportation Research Record: Journal of the Transportation Research Board*, 1748(1), 167–174.
- Bose, A., & Ioannou, P. A. (2003). Analysis of traffic flow with mixed manual and semiautomated vehicles. *IEEE Transactions on Intelligent Transportation Systems*, 4(4), 173–188.
- van Arem, B., van Driel, C. J. G., & Visser, R. (2006). The impact of cooperative adaptive cruise control on traffic-flow characteristics. *IEEE Transactions on Intelligent Transportation Systems*, 7(4), 429–436.
- Christopher Nowakowski, J. O. C., Shladover, S. E., Cody, D. (2010). *Cooperative adaptive cruise control: Driver acceptance of following gap settings less than one second*. Paper presented at the proceedings of the human factors and ergonomics society annual meeting, San Francisco, CA, USA.
- Schakel, W. J., van Arem, B., & Netten, B. D. (2010). *Effects of cooperative adaptive cruise control on traffic flow stability*. Paper presented at the 13th international IEEE conference on intelligent transportation systems, Funchal, Portugal.
- Larsson, F. L. A. (2012). Driver usage and understanding of adaptive cruise control. *Applied Ergonomics*, 43(3), 501–506.

26. Altay, İ, Güvenç, B. A., & Güvenç, L. (2013). Lidar data analysis for time to headway determination in the drivesafe project field tests. *International Journal of Vehicular Technology*, 2013, 1–9.
27. Zhao, L., & Sun, J. (2013). Simulation framework for vehicle platooning and car-following behaviors under connected-vehicle environment. *Procedia - Social and Behavioral Sciences*, 96, 914–924.
28. Kumar, R., Parida, P., & Saleh, W. (2014). Effect of type of lead vehicle on following headway behaviour in mixed traffic. *World Journal of Science, Technology and Sustainable Development*, 11(1), 28–43.
29. Arnaout, G. M., & Bowling, S. R. (2014). A progressive deployment strategy for cooperative adaptive cruise control to improve traffic dynamics. *International Journal of Automation and Computing*, 11(1), 10–18.
30. Nikolos, I. K., Delis, A. I., & Papageorgiou, M. (2015). *Macroscopic modelling and simulation of ACC and CACC Traffic*. Paper presented at the 2015 IEEE 18th international conference on intelligent transportation systems, Las Palmas, Spain.
31. Darbha, S., Konduri, S., & Pagilla, P. R. (2017). *Effects of V2V communication on time headway for autonomous vehicles*. Paper presented at the 2017 American control conference, Seattle, USA.
32. Mohajerpoor, R., & Ramezani, M. (2019). Mixed flow of autonomous and human-driven vehicles: Analytical headway modeling and optimal lane management. *Transportation Research Part C*, 109, 194–210.
33. Lu, Q., Tettamanti, T., Hörcher, D., & Varga, I. (2019). The impact of autonomous vehicles on urban traffic network capacity: An experimental analysis by microscopic traffic simulation. *Transportation Letters*, 12, 1–10.
34. Nishimura, Y., Fujita, A., Hiromori, A., Yamaguchi, H., Higashino, T., Suwa, A., Urayama, H., Takeshima, S., & Takai, M. (2019). *A study on behavior of autonomous vehicles cooperating with manually-driven vehicles*. Paper presented at the 2019 IEEE international conference on pervasive computing and communications (PerCom), Kyoto, Japan.
35. Zhao, L., Malikopoulos, A. A., & Rios-Torres, J. (2019). *On the traffic impacts of optimally controlled connected and automated vehicles*. Paper presented at the 2019 IEEE conference on control technology and applications (CCTA), Hong Kong, China.

## Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Submit your manuscript to a SpringerOpen<sup>®</sup> journal and benefit from:

- Convenient online submission
- Rigorous peer review
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

---

Submit your next manuscript at ► [springeropen.com](https://www.springeropen.com)

---