Lane management for asymmetric mixed traffic flow on bidirectional multi-lane roadways

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To manage the bidirectional asymmetric mixed traffic flow with connected and automated vehicles (CAVs) and human-driven vehicles, the study proposes a lane management (LM) model based on the joint LM policy of CAV dedicated lanes (CDLs), CAV reversible lanes (CRLs), and CAV access strategies (CASs) for non-managed lanes. Based on the formulated models of traffic capacity and throughput, an analytical LM model is developed to determine the optimal numbers of CDLs and CRLs and the optimal CASs that maximize overall mixed traffic throughputs, considering the traffic demand and its directional imbalance percent (DIP), CAV market penetration rate (MPR), and maximum platoon size under aggressive, moderate, and conservative CAV technology scenarios. The results show that the proposed LM policy can significantly improve overall throughputs compared with the benchmark policy, using the optimal CASs and deploying optimal CRLs/CDLs in one/two directions under the aforementioned three scenarios. Moreover, for the LM policy, the overall throughput gradually rises as the four parameters increase, except for the asymptotical increments with the MPR under the conservative scenario and the asymptotical reductions with the DIP under the three scenarios.

Keywords: connected and automated vehicles; lane management; dedicated lane; reversible lane; access strategy; mixed traffic flow

1. Introduction

With the advanced automated control and Vehicle-to-Vehicle/Vehicle-to-Infrastructure communication technologies, connected and automated vehicles (CAVs) have the potential to improve traffic efficiency, safety, and fuel consumption (Ma et al. 2017; Zheng et al. 2019; Bai et al. 2022). Real-time wireless communication and precise controls between CAVs allow them to travel on the roads cooperatively in a form of a platoon to yield greater traffic throughput and less fuel consumption (Wang et al. 2014; Bian et al. 2019; Zhou, Wang, and Ahn 2019). The widespread adoption of CAVs will make unprecedented impacts on the characteristics and modeling of traffic flow and warrant fundamental policy changes to travel behavior modeling, transportation infrastructure development, lane access strategies, etc. (Li et al. 2020; Guo and Ma 2020; Pan et al. 2021; Zheng et al. 2020). Take the lane management (LM) policies as an example, CAV dedicated lanes (CDLs) have been proposed to manage the unidirectional mixed traffic flow with CAVs and human-driven vehicles (HDVs) on roadways (Chen et al. 2017; Razmi Rad et al. 2020; Zhang et al. 2022). By separating the CAVs from the mixed traffic flow, the conflicts between CAVs and HDVs can be significantly reduced and the platooning efficiency of CAVs can be increased, which in turn has the potential to improve the mixed traffic throughput. Nevertheless, the asymmetry in bidirectional traffic flow is commonly seen under traffic conditions like rush hour, emergency evacuation, and traffic accidents in roadway scenarios such as bridges, urban expressways, and some roadway segments, etc., which will also appear for mixed traffic flow in the transition period toward the era of CAV (Fitzpatrick et al. 2016; Fu, Tian, and Sun 2021). It creates new challenges for the management of mixed traffic flow on bidirectional roadways. Obviously, the single CDL policy may not be sufficient to improve the bidirectional overall mixed traffic throughput (Chen, Wang, and Meng 2022). Therefore, the development of efficient LM policies considering the emerging CAV technology is of particular significance for future traffic management.

1.1. Literature review

Motivated by the CAV development, many research efforts have been made to analytically explore the applications of CDLs to improve the mixed traffic capacity and throughput in a unidirectional roadway segment (Chen et al. 2017; Ghiasi et al. 2017; Ghiasi et al. 2020; He et al. 2022). The core idea of these analytical studies is to derive the macroscopic analytical formulation of mixed traffic capacity based on the probability theory so that the impacts of CDLs on mixed traffic capacity and throughput are analyzed. For example, Chen et al. (2017) developed an analytical formulation for the periodic mixed traffic flow with each cycle including one *n*-CAV platoon and *m*-HDVs. They considered mixed traffic demands, CAV market penetration rates (MPRs), and two CAV access strategies (CASs) for non-managed lanes. Thus, two CDL policies were proposed using two (CASs). One was that CAVs and HDVs were only allowed on CDLs and non-managed lanes, respectively, and another allowed CAVs to travel on both CDLs and non-managed lanes with HDVs. The analytical formulation could be used to figure out the best CDL policy based on the maximum mixed traffic capacity given the mixed traffic demand and CAV MPRs. He et al. (2022) further discussed the impacts of the two aforementioned CDL policies on mixed traffic capacity using the two analytical models formulated separately based on the probability theory. It considered the four CAV technology scenarios of aggressive, neutral, conservative, and safe for numerical analysis, which can be represented by the different time headways of CAVs following HDVs. Numerical results indicated that the CAV MPR was critical to the implementation of CDL under different CAV technology scenarios. To maximize the mixed traffic throughput on unidirectional highway segments, Ghiasi et al. (2017) proposed an analytical LM model based on a Markov chain method to determine the optimal numbers of CDLs considering the mixed traffic demands, CAV MPRs, platooning intensities, and three CAV technology scenarios including aggressive, moderate, and conservative scenarios. It was found that only under certain CAV technology scenarios, the mixed traffic throughput gradually increases with the increment of the CAV MPR given the mixed traffic demands and platooning intensities. Ghiasi et al. (2020) further extended the LM model to determine the optimal numbers of CDLs considering the narrow width of CAV lanes. Numerical analysis indicated that the optimal deployment of the CDLs and mixed traffic throughputs were marginally affected by platooning intensities. However, the two studies only considered that CAVs were allowed to travel on both the CDLs and non-managed lanes, and thus the difference in impacts between CASs for non-managed lanes on the mixed traffic throughput was not discussed. In addition, simulation is another effective method to investigate the impacts of CDLs on mixed traffic capacity and throughput (Talebpour, Mahmassani, and Elfar 2017; Ye and Yamamoto 2018; Abdel-Aty et al. 2020). The simulation method can obtain the traffic capacity and throughput information through microscopic CAV and HDV behavior modeling and considerable simulation work. Interested readers can refer to the recent paper for a summary of related studies on the CDL using the simulation method (He et al. 2022).

Compared to the fruitful outcomes of the studies for CDL, only very few studies have explored the application of other LM policies for CAVs. The reversible lane policy has been developed to reduce traffic congestion on roadways by allowing some lanes to reverse their travel directions considering the bidirectional asymmetric spatial-temporal traffic demand. It can be utilized in the era of CAVs based on the superior automation and connectivity ability with road infrastructure (Hausknecht et al. 2011; Fu, Tian, and Sun 2021; Chen, Wang, and Meng 2022). Hausknecht et al. (2011) put forward an aggressive LM policy for CAVs, hereinafter referred to as CAV reversible lanes (CRLs), to be implemented in a traffic network to improve traffic capacity. An integer linear model was developed to determine the optimal lane reversal configuration that maximizes the network traffic capacity. Numerical results showed that traffic network efficiency was improved using the CRLs. Fu et al. (2021) investigated the effectiveness of dynamic reversible lanes to manage the bidirectional traffic flow in a full CAV environment. A bi-objective optimization model was formulated based on the cell transmission model to decide the optimal dynamic lane direction and number of CRLs that minimize the total travel delays and driving safety hazards. The results suggested that the application of dynamic CRL can significantly reduce total travel delays. Chen et al. (2022) proposed a dynamic CRL and traffic control strategy and formulated a mixed-integer linear programming model to determine the optimal lane direction of bidirectional center lanes by minimizing the total travel times on a bidirectional roadway. As indicated by the results, road congestion can be effectively mitigated by the dynamic CRL compared with traditional traffic management without the CRL. Despite the great potential to improve traffic throughput and reduce total travel delays by other LM policies, no one has explored the applications of CRL in a mixed traffic environment with CAVs and HDVs.

As mentioned above, most studies focused on CDL policy development to manage the unidirectional mixed traffic flow based on the analytical models of traffic capacity and throughput. For the model formulations of traffic capacity that involve different time headways of CAVs and their probability calculation, previous studies have analyzed the impacts of platoon size on the probabilities of different CAV time headways. However, the influences of platoon size and multi-vehicle communication on the time headway of

CAVs have not been considered. Moreover, as indicated by previous studies, the models of traffic throughput using the two aforementioned CASs for non-managed lanes were formulated separately. As a result, a unified model to find the optimal CASs for improving the traffic throughput is lacking. Based on the merits of the emerging CAVs providing the flexible and combined lane management mode, we can see that the CDL, CRLs, and CASs have different deployment purposes and advantages in mitigating traffic congestion from the traffic supply side. In addition, to effectively manage the bidirectional asymmetric mixed traffic flow on roadways, the LM models considering the joint application of different types of LM policies such as CDLs and CRLs have not been analytically studied.

To fill the above gaps, we propose an LM model based on the joint LM policy of the CDLs, CRLs, and CASs to manage the bidirectional asymmetric mixed traffic flow with CAVs and HDVs on multi-lane roadway segments. The models of traffic capacity are formulated by incorporating the differentiated string-stable time headways of CAVs in a platoon considering multi-vehicle communication and platooning operation of CAVs. The models of traffic throughput are proposed by unifying two CASs for non-managed lanes, in addition to the CDL and CRL policies. Based on the newly formulated models of traffic capacity and throughput, an analytical LM model is developed to determine the optimal numbers of CDLs and CRLs and the optimal CASs for non-managed lanes in each direction to maximize the overall mixed traffic throughput. Numerical experiments are further conducted to investigate the impacts of total traffic demand and its directional imbalance percent, CAV MPR, and MPS on the optimal numbers of CDLs and CRLs and the optimal CASs, and maximum overall throughputs of mixed traffic flow under three CAV technology scenarios of aggressive, moderate, and conservative scenarios.

The rest of the study is organized as follows. Section 2 presents the assumptions and problem description. Section 3 formulates the analytical LM model for mixed traffic flow. The numerical experiments and detailed analysis are provided in Section 4. Section 5 concludes the study with a summary of the findings and future research directions.

2. Assumptions and problem description

Consider a bidirectional multi-lane roadway segment including a total of 2*N* lanes with *N* lanes in each direction of equal width with no on-ramps and off-ramps. Let ‘1’ and ‘2’ represent two opposite directions of mixed traffic flow with CAVs and HDVs on the roadway segment. Without loss of generality, we assume that direction 1 is the major-flow direction for ease of description. Let $d = d_1 + d_2$ denote the traffic demand of mixed traffic flow on the bidirectional roadway segment, where d_1 and d_2 denote the traffic demand of directions 1 and 2, respectively. We define δ as the directional imbalance percent (DIP) of traffic demand, which is the ratio of traffic demand of direction 1 to traffic demand, i.e., $\delta = d_1/d$. Let *p* be the MPR of CAVs on the roadways.

Two types of LM policies for CAVs, i.e., CDL and CRL, can be implemented on the roadway segment. The former allows the CAVs in the same direction to travel on the CDLs, whereas the latter allows the CAVs in the opposite direction to travel on the CRLs. Both CDLs and CRLs will be deployed from the center lane in either direction. The consecutive CAVs in the same lane can form CAV platoons under the limitation of MPS denoted by *s*. When the size of a CAV platoon reaches *s*, the subsequent CAV will form a new CAV platoon. Therefore, there are two types of time headways based on the travel patterns of CAVs, i.e., travel-alone or platooning, in the pure CAV traffic flow on CDLs and CRLs: (i) time headway of a CAV in the same platoon denoted by τ_f and (ii) time headway of a CAV following the maximum-size CAV platoon denoted by τ_s. Both CDLs and CRLs are called managed lanes, while the other lanes are called non-managed lanes, which can be used by both HDVs and CAVs. It is assumed that CAVs will travel on the CDLs first, followed by CRLs and non-managed lanes in sequence, if the CDLs and CRLs are oversaturated under the access strategy allowing CAVs on non-managed lanes. In this study, we assume the time headway of an HDV following HDV and CAV are the same since it depends on the following behaviors of HDVs. Given the vehicle type, i.e., CAVs and HDVs, on the non-managed lanes for mixed traffic flow, in addition to the aforementioned two types of headways in the pure CAV traffic flow, there exist another two types of headways under mixed traffic flow: (i) time headway of a CAV following an HDV denoted by τ_l and (ii) time headway of an HDV following an HDV or a CAV denoted by τ_h. Four types of time headways under mixed traffic flow are illustrated in Figure 1. Since the time headways can affect the mixed traffic capacity, the influences of different CAV technology scenarios characterized by time headways of CAVs following other vehicles will be explored. Kindly note that the study focuses on LM from a point of view of macroscopic stationary traffic at an equilibrium state on a roadway segment, in which all lane-changing and stop-and-go scenarios are assumed to be aggregated to derive the macroscopic analytical formulation of traffic capacity.

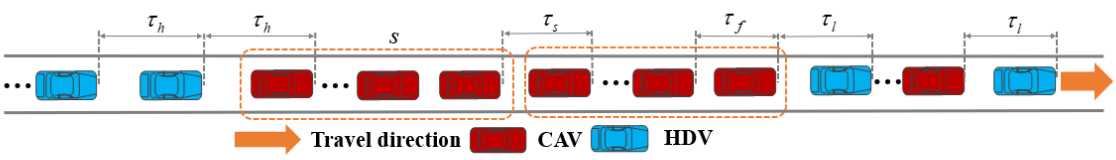

Figure 1. Illustration of four types of headways under mixed traffic flow.

The objective of this study is to maximize the overall mixed traffic throughput of the bidirectional asymmetric mixed traffic flow on roadways by determining the optimal numbers of CDLs and CRLs and the optimal CASs for non-managed lanes in each direction, considering the traffic demand, DIP of traffic demand, CAV MPR, and MPS under different CAV technology scenarios. Figure 2 illustrates the LM problem settings under mixed traffic flow. It can be seen that there are 4 lanes of equal width in each direction of the roadway segment in this example. Directions 1 and 2 represent the direction of mixed traffic flow from left to right and from right to left, respectively. The red and blue vehicles represent the CAVs and HDVs, respectively. A feasible solution for the LM problem is illustrated in Figure 2. One center lane in direction 2 is deployed as the CRL for the CAV traffic flow of direction 1, i.e., CRL_2, which is represented by the green lane. Two CDLs in direction 1 and one CDL in direction 2 are also deployed, i.e., CDL_1 and CDL_2, which are represented by the gray lanes. The other remaining lanes are non-managed lanes for the mixed traffic flow with CAVs and HDVs.

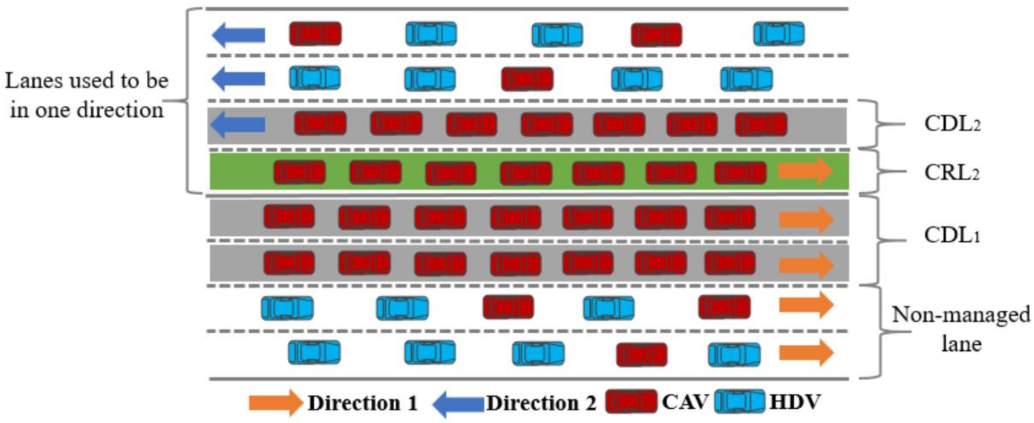

Figure 2. Illustration of the LM problem setting under mixed traffic flow.

3. Methodology

In this section, the models of pure CAV traffic and CAV-HDV mixed traffic capacities can be first formulated based on different types of time headways and their probabilities. Moreover, the models of pure CAV and mixed traffic throughputs in each direction can be formulated considering CDL and CRL policies and two CASs for non-managed lanes under the traffic capacity restriction. Finally, we formulate the analytical LM model for managing bidirectional mixed traffic flow.

3.1. Traffic capacity

As mentioned above, considering the applications of CDLs and CRLs, there are mixed traffic and pure CAV capacities on a roadway segment. In what follows, the models of mixed traffic and pure CAV capacities on non-managed and managed lanes (i.e., CDLs and CRLs), respectively, will be formulated.

Let $\tilde{p}$ be the penetration rate of CAVs on the non-managed lanes and p_h be the probability of an HDV which should equal $1-\tilde{p}$. Let p_l , p_s, and p_f be the probability of a CAV following an HDV, a CAV following a maximum-size CAV platoon, and a CAV following another CAV in the same platoon, respectively, and then the sum of the three probabilities should be $\tilde{p}$. We assume that all the vehicles are mixed randomly on the roadway segment. The probability of a CAV following an HDV is calculated based on the Bernoulli distribution below

$$p_l = \tilde{p}p_h = \tilde{p}(1-\tilde{p}) \tag{1}$$

The probability of a CAV following a maximum-size CAV platoon can be calculated by

$$p_s = \frac{(1-\tilde{p})\tilde{p}^{s+1}}{1-\tilde{p}^s} \tag{2}$$

We can then obtain the probability of a CAV following another CAV in the same platoon as follows

$$p_f = \tilde{p} - \tilde{p}(1-\tilde{p}) - \frac{(1-\tilde{p})\tilde{p}^{s+1}}{1-\tilde{p}^s} = \frac{\tilde{p}^2(1-\tilde{p}^{s-1})}{1-\tilde{p}^s} \tag{3}$$

We assume that all the vehicles are mixed randomly on the road segment. Therefore, the average time headway of the mixed traffic flow with CAVs and HDVs on a non-managed lane is estimated as:

$$\overline{\tau}^{mix} = p_l\tau_l + p_s\tau_s + p_f\tau_f + p_h\tau_h = p_l\tau_l + p_s\tau_s + p_f\tau_f + (1-\tilde{p})\tau_h \tag{4}$$

where τ_h is the time headway of an HDV following an HDV or a CAV, τ_l and τ_s are the time headways of a CAV following an HDV and a full-size platoon, respectively, and τ_f is the time headway of a CAV following other CAVs in the same platoon, which are assumed to be same.

According to the previous study (Chen et al. 2021; Zheng et al. 2023), sufficient conditions of string stability for CAV platoons under multiple predecessor-follower communication topologies were derived. It can be expressed as a function with respect to the time headway, the number of communicated predecessors, and controller parameters. Specifically, the time headway of CAV *i* in a platoon with a platoon size *k*, denoted by $\tau_{i,f}$, should satisfy:

$$\tau_{i,f} \geq \frac{4k_v}{k_s(1+n_i)}, \forall i \in \{0,1,...,k-1\} \tag{5}$$

where k_v and k_s are the pre-specified controller parameters, and n_i is the number of predecessors that the CAV *i* can communicate with. For the convenience of calculation, let $4k_v/k_s$ be the time headway of a CAV without the communicated predecessor, which should thus equal τ_l.

Let τ_f be the time headway of the first following CAV in a platoon under predecessor-follower communication, indicating that the number of the communicated predecessors is 1 and τ_f equals $\tau_l/2$, and τ_{safe} be the pre-specified time headway for safety concerns.

By linking the order of CAVs in a platoon and the number of communicated predecessors, the time headway of the following CAV *i* in a platoon can be written as follows:

$$\tau_{i,f} \geq \left(\frac{2}{1+i} \tau_f , \tau_{safe} \right), \forall i \in \{1, ..., k-1\} \tag{6}$$

If the number of communicated predecessors is fixed to be *K*, the time headway of the following CAV *i* in a platoon is calculated below

$$\tau_{i,f} \geq \begin{cases} \left(2\tau_f / (K+1), \tau_{safe} \right), \forall i > K \\ \left(2\tau_f / (1+i), \tau_{safe} \right), \forall i \leq K \end{cases} \tag{7}$$

Different from the previous studies that used identical time headway for the CAVs in a platoon, to further consider the effects of multi-vehicle commutation and platoon size on time headways of CAVs while ensuring the stability of CAV platoons, we first introduce the differentiated string-stable time headways of CAVs in a platoon to calculate the traffic capacity. The average time headway of the mixed traffic flow on a non-managed lane can be calculated by

$$\begin{aligned} \bar{\tau}^{mix} &= (1-\tilde{p})\tau_h + p_l\tau_l + p_s\tau_s + p_f\tilde{\tau}_f \\ &= (1-\tilde{p})\tau_h + p_l\tau_l + p_s\tau_s + p_f\left(\frac{1}{s-1}\frac{2}{1+1}\tau_f + ... + \frac{1}{s-1}\frac{2}{s}\tau_f \right) \\ &= (1-\tilde{p})\tau_h + p_l\tau_l + p_s\tau_s + p_f\frac{1}{s-1}\sum_{i=1}^{s-1}\frac{2}{1+i}\tau_f \\ &= \underbrace{(1-\tilde{p})\tau_h + p_l\tau_l + p_s\tau_s + p_f\tau_f}_{(1)} + \underbrace{p_f\left(\frac{1}{s-1}\sum_{i=1}^{s-1}\frac{2}{1+i} - 1 \right)\tau_f}_{(2)} \end{aligned} \tag{8}$$

where $\tilde{\tau}_f$ is the average time headway of CAVs in a platoon. It can be seen that the first term in Eq. (8) is the average time headway of the mixed traffic flow under the restriction of platoon size and the identical time headway of CAVs in a platoon. It is intuitive to see that $\left[\sum_{i=1}^{s-1} 2/(1+i) \right] \Big/ (s-1)$ is smaller than 1 for the second term in Eq. (8). Therefore, the second term represents the reduced average time headway due to the applications of the differentiated time headways of CAVs in a platoon.

The mixed traffic capacity on a lane, i.e., $\bar{C}^{mix}$, with respect to $\tilde{p}$, is thus calculated by

$$\bar{C}^{mix} = \frac{1}{\bar{\tau}^{mix}} = \frac{1}{(1-\tilde{p})\tau_h + p_l\tau_l + p_s\tau_s + p_f\tau_f + p_f\left(\frac{1}{s-1}\sum_{i=1}^{s-1}\frac{2}{1+i} - 1\right)\tau_f} \tag{9}$$

Under the condition of full CAVs on a lane, the average time headway of the CAV traffic flow is $\bar{\tau}^{CAV} = \left(\tau_l + \sum_{k=1}^{s-1}\frac{2}{1+k}\tau_f\right)\Big/ s$. Therefore, the pure CAV traffic capacity on a managed lane under the limit of platoon size is given by

$$\bar{C}^{CAV} = \frac{1}{\bar{\tau}^{CAV}} = \frac{1}{\left(\tau_l + \sum_{k=1}^{s-1}\frac{2}{1+k}\tau_f\right)\Big/ s} \tag{10}$$

If the number of communicated predecessors is fixed to be *K*, the pure CAV traffic capacity on a managed lane under the restrictions of platoon size and communicated predecessors is calculated by

$$\bar{C}^{CAV} = \frac{1}{\bar{\tau}^{CAV}} = \frac{1}{\left(\tau_l + \sum_{k=1}^{K}\frac{2}{1+k}\tau_f + \frac{s-K-1}{K+1}\tau_f\right)\Big/ s} \tag{11}$$

3.2. Traffic throughput

Given the pure CAV and mixed traffic capacities, traffic demand in each direction, CAV MPR, and the total number of road lanes, we will calculate the pure CAV traffic throughputs on CDLs and CRLs, and mixed traffic throughputs on non-managed lanes in each direction. The total mixed traffic throughput in each direction can be obtained by summing up the respective traffic throughputs on the managed lanes, i.e., CDLs and CRLs, and non-managed lanes under the traffic capacity restriction.

For the convenience of description, the CDL in direction 1 and CRL in direction 1 for CAV traffic flow of direction 2 are denoted by CDL_1 and CRL_1, respectively, and the CDL in direction 2 and CRL in direction 2 for CAV traffic flow of direction 1 are denoted by CDL_2 and CRL_2, respectively. Let x_1^d and x_2^r be the numbers of CDL_1 and CRL_2, respectively. Given the traffic demand of direction 1, the pure CAV traffic throughputs on the CDL_1 and CRL_2, denoted by Q_1^d and Q_1^r, respectively, can be calculated by

$$Q_1^d = \min(pd_1, x_1^d \bar{C}^{CAV}) \tag{12}$$

$$Q_1^r = \min(pd_1 - Q_1^d, x_2^r \bar{C}^{CAV}) \tag{13}$$

Let λ_1 be a binary decision variable for direction 1: $\lambda_1 = 1$ represents that CAVs are allowed to drive on the non-managed lanes in direction 1 in addition to on CDLs and CRLs, and $\lambda_1 = 0$ otherwise. By excluding the CAVs traveling on the CDLs and CRLs, the penetration rate of the remaining CAVs on the non-managed lanes for the mixed traffic flow in direction 1 can be obtained below

$$\tilde{p}_1 = \lambda_1 \frac{\max(0, pd_1 - x_1^d \bar{C}^{CAV} - x_2^r \bar{C}^{CAV})}{d_1 - Q_1^d - Q_1^r}, \forall \lambda_1 \in \{0,1\} \tag{14}$$

Let x_1^r be the number of the CRL_1. Then the total number of the non-managed lanes for the mixed traffic flow in direction 1, denoted by x_1^n, depends on the decisions of x_1^d and x_1^r, which is calculated by

$$x_1^n = N_1 - x_1^d - x_1^r \tag{15}$$

Given the mixed traffic capacity on a non-managed lane with respect to $\tilde{p}_1$, the mixed traffic throughput on the non-managed lanes in direction 1, denoted by Q_1^n, is calculated as follows:

$$Q_1^n = \min\left(d_1 - Q_1^d - Q_1^r, x_1^n \bar{C}^{mix}\right) \tag{16}$$

Let x_2^d be the number of the CDL₂. Let λ_2 be a binary variable for direction 2: $\lambda_2 = 1$ represents that CAVs are allowed to travel on the non-managed lanes in direction 2 in addition to on CDLs and CRLs, and $\lambda_2 = 0$ otherwise. The pure CAV traffic throughputs on CDL_2 and CRL_1, denoted by Q_2^d and Q_2^r, respectively, and the penetration rate of remaining CAVs on the non-managed lanes for mixed traffic flow in direction 2, denoted by $\tilde{p}_2$, are calculated by

$$Q_2^d = \min(pd_2, x_2^d \bar{C}^{CAV}) \tag{17}$$

$$Q_2^r = \min(pd_2 - Q_2^d, x_1^r \bar{C}^{CAV}) \tag{18}$$

$$\tilde{p}_2 = \lambda_2 \frac{\max(0, pd_2 - x_2^d \bar{C}^{CAV} - x_1^r \bar{C}^{CAV})}{d_2 - Q_2^d - Q_2^r}, \forall \lambda_2 \in \{0,1\} \tag{19}$$

The total number of non-managed lanes x_2^n in direction 2 is given by

$$x_2^n = N_2 - x_2^d - x_2^r \tag{20}$$

Given the mixed traffic capacity on a non-managed lane with respect to $\tilde{p}_2$, the mixed traffic throughput on the non-managed lanes in direction 2 is calculated as follows:

$$Q_2^n = \min\left(d_2 - Q_2^d - Q_2^r, x_2^n \bar{C}^{mix}\right) \tag{21}$$

3.3. Lane management

The performance of mixed traffic throughput in the minor-flow direction may significantly degrade and be even worse than that of the major-flow direction if too many lanes of the minor-flow direction are assigned to the traveling of CAVs of the major-flow direction. To this end, we need to introduce constraints in the proposed LM model to maintain the performance of mixed traffic throughput for minor-flow direction.

Moreover, the upper bound constraints of the CDLs and CRLs for one direction are considered according to actual traffic operational capabilities of achieving a smooth traffic flow on roadways. The total number of lanes on the studied and adjacent roadway segments should be considered in the LM model to reduce the changes in lanes on the studied roadway segment and this one with the adjacent roadway segments for one direction. Let Q_1 and Q_2 be the total throughput of mixed traffic flow for directions 1 and 2, respectively. The LM problem for asymmetric mixed traffic flow on bidirectional multi-lane roadways can be formulated by the following optimization model:

$$\max_{\{x_1^d, x_2^d, x_1^r, x_2^r, \lambda_1, \lambda_2\}} Q = Q_1 + Q_2 = (Q_1^d + Q_1^r + Q_1^n) + (Q_2^d + Q_2^r + Q_2^n) \tag{22}$$

subject to

$$x_1^d + x_1^r \le N_1 \tag{23}$$

$$x_2^d + x_2^r \le N_2 \tag{24}$$

$$x_1^r x_2^r = 0 \tag{25}$$

$$x_1^d \le \lfloor \alpha_1 \min(N_1, N_{1,u}, N_{1,d}) \rfloor \tag{26}$$

$$x_1^r \le \lfloor \alpha_1 \min(N_1, N_{1,u}, N_{1,d}) \rfloor \tag{27}$$

$$x_2^d \le \lfloor \alpha_2 \min(N_2, N_{2,u}, N_{2,d}) \rfloor \tag{28}$$

$$x_2^r \le \lfloor \alpha_2 \min(N_2, N_{2,u}, N_{2,d}) \rfloor \tag{29}$$

$$Q_1 / Q \ge \beta \tag{30}$$

$$Q_2 / Q \ge \beta \tag{31}$$

$$x_1^d, x_2^d, x_1^r, x_2^r \in \mathbb{N} \tag{32}$$

$$\lambda_1, \lambda_2 \in \{0,1\} \tag{33}$$

where α_1 and α_2 lie between 0 and 1 and represent the level of traffic operational capabilities for achieving the smooth traffic flow against the negative effects of traffic dynamics oscillations caused by the change of lanes on traffic throughputs in directions 1 and 2, respectively, N_u and N_d are the total number of lanes on the adjacent upstream and downstream roadway segments of the studied roadway segment, and β lies between 0 and 1 and represents the minimum ratio between the traffic throughput in one direction and overall mixed traffic throughput.

The objective function in Eq. (22) is the overall mixed traffic throughput of the bidirectional mixed traffic flow, which is the sum of total mixed traffic throughputs for directions 1 and 2. Constraints (23) and (24) ensure that the total numbers of CDLs and CRLs in directions 1 and 2 should not be more than N_1 and N_2, respectively. Constraint (25) guarantees that the CRLs should be deployed in one direction at most. Constraints (26)-(29) restrict the number of CDLs and CRLs not exceeding the number of lanes realized by the traffic operational capabilities of achieving smooth traffic flow. Constraint (30) and (31) ensure that at least a certain proportion of mixed traffic flow in each direction should be released, which can effectively maintain the performance of mixed traffic throughput. Constraints (32) and (33) defines the domain of decision variables.

We can see that the proposed LM model is an integer non-linear optimization model, which is not easily solved by commercial solvers. Nevertheless, it can be observed that there are only six decision variables in the proposed model and the number of lanes on the roadways is limited in realistic traffic conditions. For example, the number of solutions is at most 1250 when the number of lanes in both two directions is 4 and the CASs of directions 1 and 2 are the same. In light of this, the proposed LM model can be easily solved by an intelligent enumeration method, in which some rules can be specified in the method to abandon the unfeasible solutions and accelerate the solving speed. For example, some unfeasible combinations of decision variables, i.e., the number of CRLs in each direction is simultaneously larger than 0, can be abandoned based on the constraint (20) during the solving process. Kindly note that for different solutions with the same overall mixed traffic throughput, we will choose a solution with a minimal number of CRLs in each direction, a solution with a minimal number of CDLs in each direction for the same combination of CRLs, or a solution with a larger number of CDLs in the major-flow direction for the same combination of CDLs.

4. Numerical analysis

In this section, we conduct numerical experiments to investigate the impacts of traffic demand and its DIP, CAV MPR, and MPS on the optimal solutions and optimal overall mixed traffic throughputs of the proposed LM model. The total number of lanes in each direction is set to be 4, i.e., $N_1 = N_2 = 4$. The default parameter values in the numerical analysis are $d = 20,000$ veh/h, $\delta = 2/3$, $p = 0.5$, $s = 10$, $\alpha_1 = \alpha_2 = 0.5$, $\beta = 0.2$, $K = 3$ and the CAS of directions 1 and 2 are the same, in which $d_1 = 40,000/3$ veh/h and $d_2 = 20,000/3$ veh/h for the traffic demand of directions 1 and 2 (Fitzpatrick et al. 2016; Xiao et al. 2018; Ghiasi et al. 2020). Three LM policies are adopted for the numerical analysis, including LM1, LM2, and 'no LM'. Two CASs are considered and CASs 1 and 2 are to allow and not allow CAVs to travel on the non-managed lanes, respectively. The LM1 policy is to apply the CAS1 or CAS2 obtained by the proposed LM model, in addition to the CDL and CRL policies. The LM2 policy is to use the CDLs and CRLs and execute CAS1. The 'no LM' policy means that the CDLs and CRLs do not be deployed and the CAS1 is used for non-managed lanes.

The time headway between two CAVs among the four types of time headways is assumed to be the smallest. There are more increments in the time headway when a CAV follows an HDV. Two possibilities for the increment in time headway will be explored in this study. One is that the increment is not too much and the time headway is still not larger than that of an HDV, i.e., $\tau_l \le \tau_h$. Another is that the time headway is not smaller than that of an HDV, i.e., $\tau_l \ge \tau_h$. The time headway of a CAV following a full-size CAV platoon is assumed to be the same as that of a CAV following an HDV because a new leader appears. As a result, there are three kinds of CAV technology scenarios represented by different time headway settings, which are called aggressive, moderate, and conservative scenarios. According to the existing literature (Ghiasi et al. 2020; Zhou and Zhu 2021; He et al. 2022), the time headways of the three CAV technology scenarios are set as follows:

- Aggressive scenario: $\tau_h = 2.0s$, $\tau_l = \tau_s = 2.5s$, and $\tau_f = 1.25s$;
- Moderate scenario: $\tau_h = 2.0s$, $\tau_l = \tau_s = 2.0s$, and $\tau_f = 2.0s$;
- Conservative scenario: $\tau_h = 2.0s$, $\tau_l = \tau_s = 1.5s$, and $\tau_f = 0.75s$.

4.1. Impact of total traffic demand

In this subsection, we explore the traffic demand in a range of 10,000 veh/h to 30,000 veh/h with an interval of 1000 veh/h on the optimal numbers of CDLs and CRLs and the optimal CASs as well as maximum overall mixed traffic throughputs under three CAV technology scenarios. The results of optimal numbers of CDLs and CRLs and the optimal CASs under different CAV technology scenarios are displayed in Figure 3. It can be seen from Figure 3(a) that the numbers of CDL_1, i.e., x_1^{d*}, increase to 1 at traffic demands d of 15,000 veh/h and 16,000 veh/h. It indicates that one CDL_1 should be deployed to improve overall throughputs at smaller traffic demands under the aggressive scenario. When the traffic demands are larger than 16,000 veh/h, the numbers of CDL_1 are 0 in Figure 3(a) and the numbers of CRL_2, i.e., x_2^{r*}, are 1 in Figure 3(c), suggesting that one CRL_2 should be deployed to replace the CDL_1 against the increased traffic demands. When the traffic demands exceed 21,000 veh/h, the numbers of CDL_2, i.e., x_2^{d*}, are 1 in Figure 3(b). It indicates that the deployment of one CDL_2 can discharge more traffic flows in direction 2 to maximize the overall throughputs in all directions. The numbers of CRL_1, i.e., x_1^{r*}, are 0 for all traffic demands in Figure 3(d), indicating that the deployment of CRL_1 is not required. The same results can be found under moderate and conservative scenarios in Figures 3(h) and 3(l), which suggests that the CRLs should only be deployed in the minor-flow direction 2. Moreover, the LM policies can apply the CAS1 for all traffic demands under all scenarios, except for the adoptions of CAS2 at traffic demands from 19000 veh/h to 22000veh/h under the conservative scenario in Figure 3(i)-3(l). It indicates that CAS2 only allows CAVs to travel on CDLs and CRLs are more beneficial to improving overall throughputs at moderate traffic demands under the conservative scenario for LM1 policy.

Figure 4 illustrates the optimal overall throughputs under three LM policies and CAV technology scenarios. To facilitate the numerical comparisons between the traffic demands and optimal overall throughputs, a black dotted line with a slope of 1 is added. The critical traffic demands corresponding to the traffic flow from an unsaturated to a saturated state represented by the red, green, and blue dotted lines for three LM policies are also illustrated in Figure 4. It shows that when the traffic demands are smaller than 14,000 veh/h, the overall throughputs, i.e., Q^*, increase linearly with the traffic demands for all LM policies under the aggressive scenario in Figure 4(a). When the traffic demands exceed 14,000 veh/h, the overall throughputs are smaller than the traffic demands for the 'no LM' policy, suggesting that the traffic flow changes from an unsaturated to a saturated state. The LM policies keep the overall throughputs increasing linearly with the traffic demands up to 22,000 veh/h, indicating the merits of LM policies in improving overall throughputs so that the larger traffic demands are satisfied. As traffic demands rise, the overall throughputs are smaller than traffic demands for LM policies, and thus traffic flow becomes saturated. Nonetheless, *the LM policies can improve the overall throughputs by 1.9% to 31.2% compared with the 'no LM' policy under the aggressive scenario at traffic demands larger than 14,000 veh/h*. In addition, the total throughput results of directions 1 and 2 for three LM policies under the aggressive scenario are illustrated in Figures 4(b) and 4(c). Black dotted lines represent the minimal mixed traffic throughput in each direction in the figures. It can be seen that the total throughputs of directions 1 and 2 gradually increase with the increments in traffic demand. Particularly, the total throughputs of direction 2 for LM policies are reduced compared with the 'no LM' policy at larger traffic demands, because the lanes in minor-flow direction 2 are used for the CAVs of direction 1 to maximize the overall throughputs in all directions.

Under the moderate scenario, the main difference is that the CDL_1, CDL_2, and CRL_2 are initiated to be deployed at the smaller traffic demands than that of the aggressive scenario based on the results in Figures 3(e), 3(f), and 3(g). More CDL_1 deployments are required at the larger traffic demands in Figure 3(e). Similar results for the conservative scenario are found in Figures 3(i), 3(j), and 3(k). With such deployments, the CRLs and CDLs can be deployed earlier to mitigate the adverse impacts of conservative CAV technology on the mixed traffic throughput. On the contrary, the overall throughputs decrease accordingly under the moderate scenario for all LM policies compared with the aggressive scenario in Figure 4(d). The critical traffic demands from an unsaturated to a saturated traffic state drop to 20,000 veh/h and 14,000 veh/h for LM and 'no LM' policies, respectively. As shown in Figure 4(g), the overall throughputs for all LM policies further decrease under the conservative scenario in contrast to the moderate scenario, and the critical traffic demands reduce to 19,000 veh/h, 18,000 veh/h, and 10,000 veh/h for the LM1, LM2, and 'no LM' policies, respectively. The results suggest that different CAV technology scenarios have a significant impact on the overall throughput. Moreover, compared with the 'no LM' policy, the overall throughputs for the proposed LM policies can be improved by 4.27% to 33.1% at traffic demands of more than 14,000 veh/h under the moderate scenario and 0.2% to 54.4% at traffic demands more than 13,000 veh/h under the conservative scenario. It demonstrates the superiority of the LM policies in improving overall mixed traffic throughputs. The overall throughputs for the LM1 policy are larger than that of the LM2 policy at traffic demands from 19000 veh/h to 22000veh/h in Figure 4(g), implying that the LM1 has better traffic throughput performance under the aggressive scenario. It is due to the applications of optimal CASs only allowing CAVs on CDLs and CRLs at moderate traffic demands. Furthermore, as shown in Figures 4(e), 4(f), 4(h), and 4(i), the total throughputs of directions 1 and 2 keep gradually increasing with the increments of traffic demand under moderate and conservative scenarios. In particular, under the conservative scenario, the LM policies can improve traffic throughputs of both directions 1 and 2 compared with the 'no LM' policy at most ranges of traffic demands in Figures 4(h) and 4(i), and the LM1 policy maintains better performance in traffic throughput of direction 1 than LM2 policy in Figure 4(h).

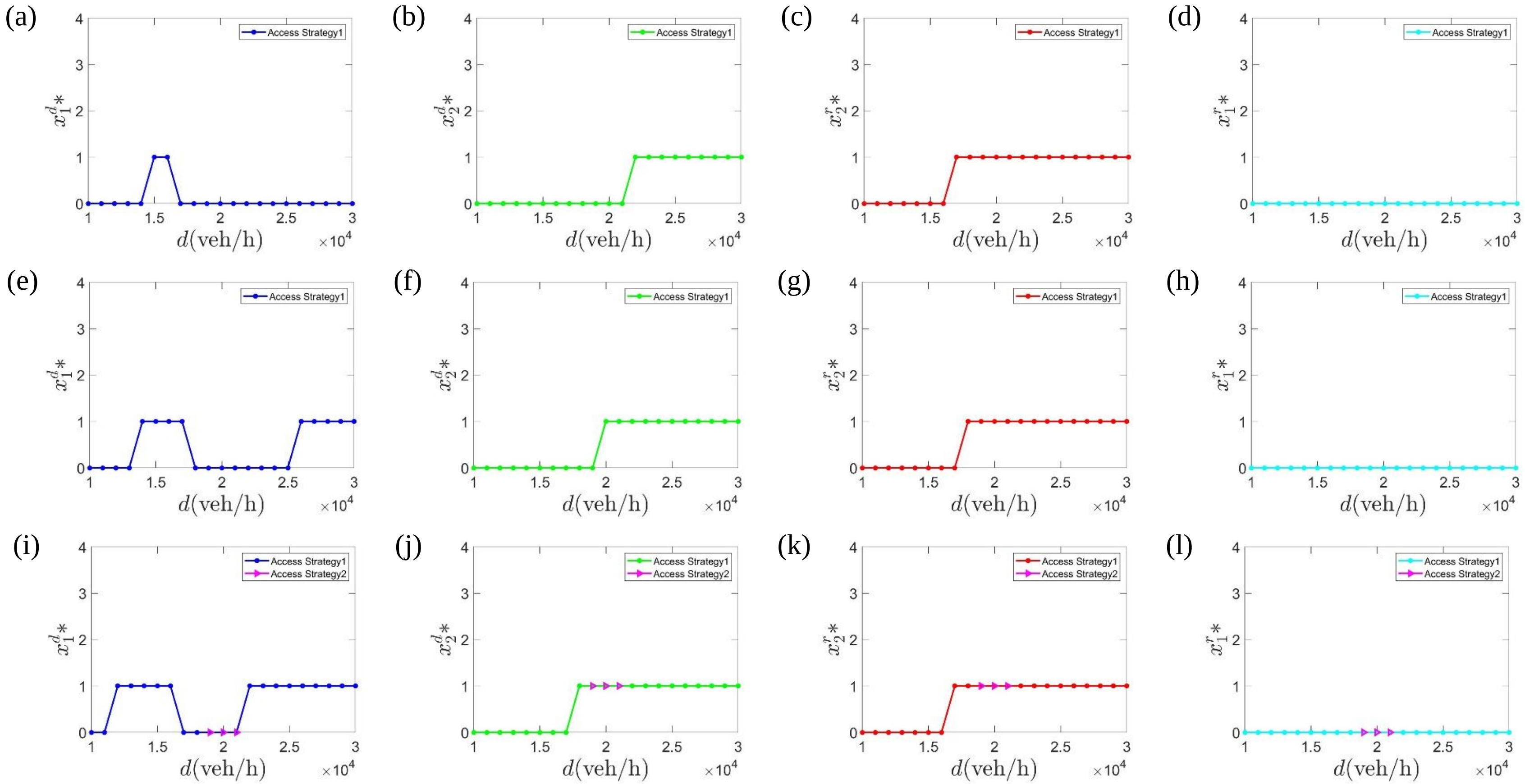

Figure 3. Results of traffic demand on optimal numbers of CDLs and CRLs and the optimal CASs. (a), (b), (c), and (d) aggressive scenario; (e), (f), (g), and (h) moderate scenario; (i), (j), (k), and (l) conservative scenario.

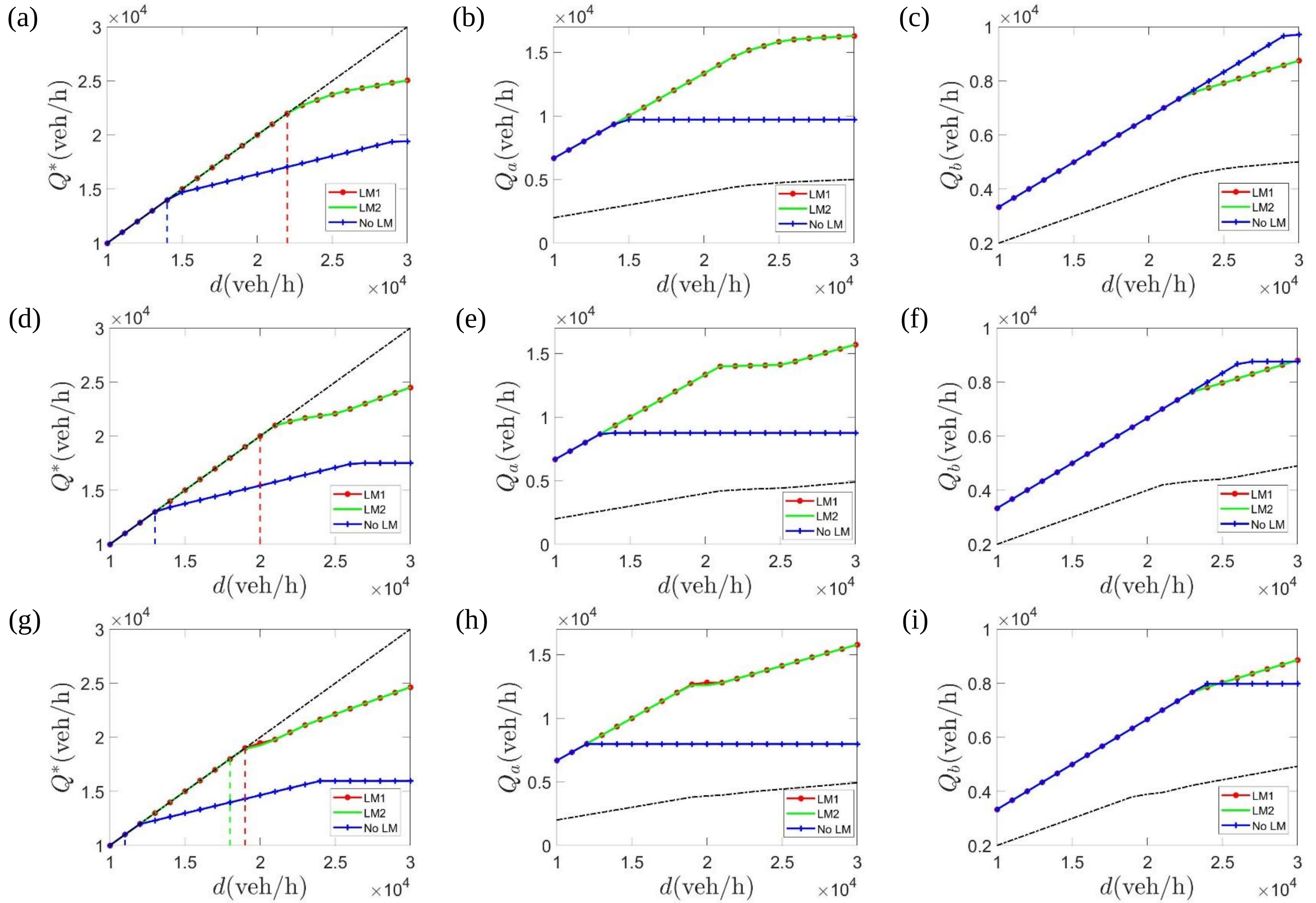

Figure 4. Results of traffic demand on optimal overall throughput. (a), (b), and (c) aggressive scenario; (d), (e), and (f) moderate scenario; and (g), (h), and (i) conservative scenario.

4.2. Impact of directional imbalance percent

This subsection is to investigate the impacts of directional imbalance percent (DIP) of traffic demand in a range of 0.5 to 0.87 with an interval of 0.01 on the optimal numbers of CDLs and CRLs and the optimal CASs as well as maximum overall mixed traffic throughputs under three CAV technology scenarios, which are illustrated in Figures 5 and 6. It can be seen from Figure 5(a) that the numbers of CDL_1, i.e., x_1^{d*}, increase to 1 at smaller and larger DIPs, i.e., δ, showing that one CDL_1 in each direction should be deployed for improving overall throughputs under the aggressive scenario. When the DIPs are ranged from 0.59 to 0.8, the numbers of CDL_1 are 0 in Figure 5(a), and CRL_2, i.e., x_2^{r*}, are 1 in Figure 5(c), suggesting that at least one CRL_2 should be deployed to replace the CDL_1 against the increased asymmetries between the traffic demands of directions 1 and 2 at the moderate DIPs. The numbers of CDL_2 increase to 1 at the DIPs from 0.5 to 0.62 and from 0.6 to 0.64 in Figure 5(b), indicating that the CDL_2 should also be deployed at the smaller DIPs. The numbers of CRL_1, i.e., x_1^{r*}, are 0 for all DIPs in Figure 5(d), suggesting that the deployment of CRL_1 is not required. The same results can be found under moderate and conservative scenarios in Figures 5(h) and 5(l). In addition, as shown in Figures 5(i)-5(l), the CAS2 is the optimal access strategy for non-managed lanes under the LM1 policy when the DIPs are from 0.54 to 0.56, from 0.64 to 0.69, and from 0.83 to 0.86 under the conservative scenario. Therefore, the overall throughputs can be improved using the LM1 policy compared with the other LM policies at some DIP ranges, indicating the effectiveness of applying the optimal CASs obtained by the LM model.

Figure 6 shows the optimal overall throughputs under three LM policies and CAV technology scenarios. The overall throughputs, i.e., Q^*, reach the traffic demand of

20,000 veh/h at the DIPs less than 0.56 for LM policies under the aggressive scenario in Figure 6(a). This is mainly attributed to the deployment of CDL_1. With the increments of DIPs from 0.56 to 0.62, the deployment of one CDL_1 cannot accommodate the increased traffic demand of direction 1, and thus overall throughputs decrease. As the DIPs increase from 0.63 to 0.74, the CRL_2 deployment can effectively improve the overall throughputs, and thus traffic flow becomes unsaturated. When the DIPs are larger than 0.74, the overall throughputs decrease gradually with the DIPs, although the CRL_2 are deployed. This is because the HDV traffic flow in major-flow direction 1 has become saturated at the larger DIPs. As the DIP increases by 0.01, only half CAVs (i.e., 100 veh/h) of the increased traffic demand of direction 1 (i.e., 200 veh/h) can be discharged by the CRLs, and thus the total throughput of direction 1 is only increased by 100 veh/h. The total throughput of direction 2 is directly decreased by 200 veh/h. Therefore, the overall throughputs reduce at the DIPs larger than 0.74. On the contrary, for the 'no LM' policy, the overall throughputs are 19,421 veh/h at the DIPs of 0.5 and 0.52 in Figure 6(a). With the increment of DIPs, the total throughputs remain the same in direction 1 but decrease in direction 2. As a result, the overall throughputs decrease linearly as the DIPs increase without the LM policy. Moreover, we can see that the overall throughputs under LM policies are improved by *2.9% to 42.2% compared with the 'no LM' policy under the aggressive scenario*. The results suggest the effectiveness of the proposed LM policies in managing the bidirectional asymmetric mixed traffic flow. Moreover, the results of the total throughput of directions 1 and 2 for all LM policies under the aggressive scenario are shown in Figures 6(b) and 6(c). It is found that there is a critical DIP value of 0.8 in Figure 6(b). As the traffic demand of direction 1 increases caused by the increment of DIPs, the total throughputs of direction 1 first gradually increase and then asymptotically reduce at the DIP larger than the critical value for LM policies. There are the same total throughputs of direction 1 for the 'no LM' policy under the aggressive scenario in Figure 6(b). The total throughputs of direction 2 gradually decrease with the reduction of its traffic demands for all LM policies in Figure 6(c).

Under the moderate scenario, one CDL_2 should be deployed at a larger range of DIP than that under the aggressive scenario as shown in Figure 5(f). More deployments of CRL_2 are required at the DIPs from 0.74 to 0.8 in Figure 5(g). Under the conservative scenario, one CDL_2 and more CDL_2 should be further deployed in some ranges of DIP based on the increased numbers of CDL_2 and CRL_2 in Figure 5(j) and 5(k) than that under the moderate scenario. We can see from Figures 6(d) and 6(g) that the variations of overall throughputs under moderate and conservative scenarios are similar to that under the aggressive scenario for all LM policies. There are smaller overall throughputs for all LM policies under the two scenarios compared with the aggressive scenario. The DIP ranges of the overall throughputs reaching traffic demands are reduced for LM policies under moderate and conservative scenarios. For the 'no LM' policy, the overall throughputs keep at 17,520 veh/h at the DIPs from 0.5 to 0.56 under the moderate scenario in Figure 6(d) and 14,399 veh/h at the DIPs from 0.5 to 0.6 under the conservative scenario in Figure 6(g), indicating that overall throughputs are not sensitive to the increased asymmetries between traffic demands of directions 1 and 2 in these DIP ranges due to the decreased mixed traffic capacity. When the DIPs exceed the critical values, the overall throughputs linearly decrease under the two scenarios. Furthermore, it can be seen that in contrast to the 'no LM' policy, the LM policies can significantly improve overall throughputs by *14.1% and 53.6% under the moderate scenario and by 25.5% and 64.4% under the conservative scenario*. The results further demonstrate that the proposed LM policies are effective to manage the bidirectional asymmetric mixed traffic flow. Moreover, as illustrated in Figures 6(e), 6(f), 6(h), and 6(i), the variations in both total throughputs of directions 1 and 2 under moderate and conservative scenarios are similar to that of the aggressive scenario for all the LM policies.

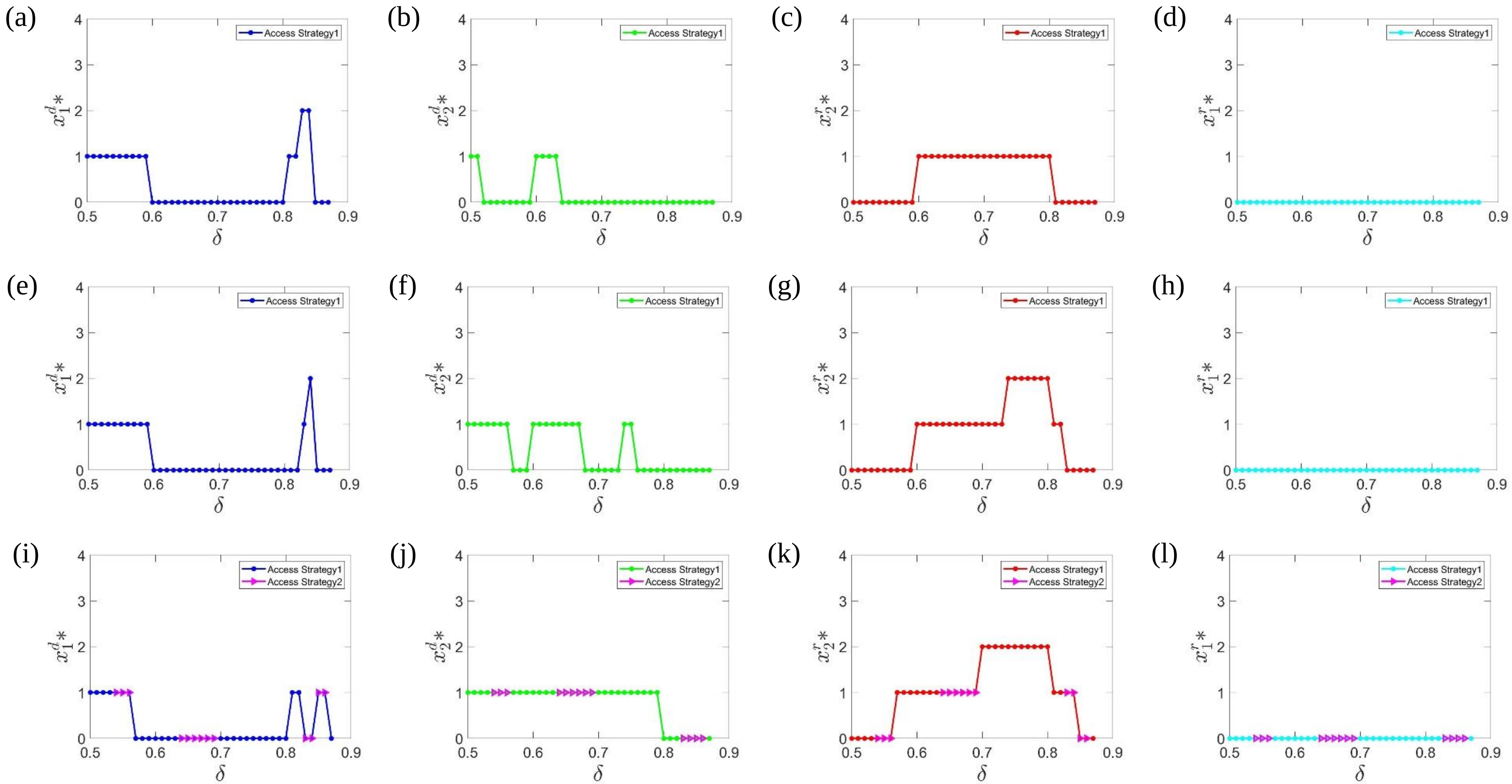

Figure 5. Results of directional imbalance percent on optimal numbers of CDLs and CRLs and the optimal CASs.
(a), (b), (c), and (d) aggressive scenario; (e), (f), (g), and (h) moderate scenario; (i), (j), (k), and (l) conservative scenario.

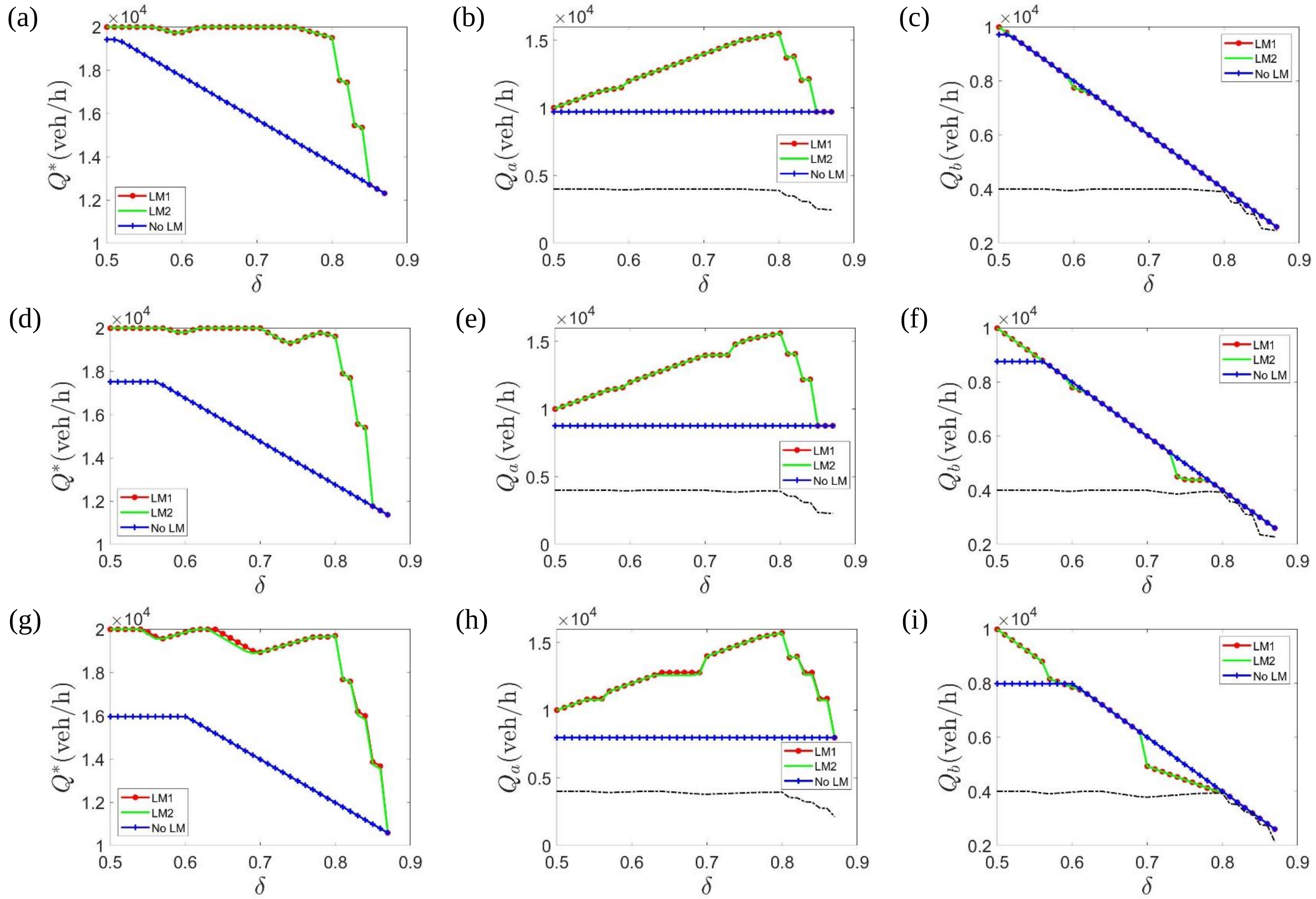

Figure 6. Results of directional imbalance percent on optimal overall throughput. (a), (b), and (c) aggressive scenario; (d), (e), and (f) moderate scenario; and (g), (h), and (i) conservative scenario.

4.3. Impact of CAV market penetration rate

This subsection is to assess the CAV market penetration rate (MPR) in a range of 0 to 1 with an interval of 0.02 on the optimal numbers of CDLs and CRLs and the optimal CASs as well as maximum overall mixed traffic throughputs under three CAV technology scenarios, which are displayed in Figures 7 and 8. With the increment of the MPR, i.e., *p*, from 0.1 to 0.58, the numbers of CRL_2, i.e., x_2^{r*}, are 1 under the aggressive scenario in Figure 7(c), suggesting that one CRL should be deployed to improve overall throughputs. As the MPRs increase from 0.6 to 0.72, the numbers of CRL_2 are 0 in Figure 7(c), and CDL_1, i.e., x_1^{d*}, become 1 in Figure 7(a). It shows that the CDL_1 should be deployed for the CAV traffic flow of direction 1 to replace the deployment of CRL_2. The numbers of CDL_2, i.e., x_2^{d*}, and CRL, i.e., x_1^{r*}, are 0 for all MPRs in Figures 7(b) and 7(d), indicating that the deployments of CDL_2 and CRL_1 are not required. In other words, the configuration of non-managed lanes in direction 2 is sufficient to match the mixed traffic capacity to the traffic demand in this direction. When the MPRs range from 0.02 to 0.26 and from 0.4 to 0.52 in Figures 7(i)-7(l), the CAS2 is the optimal LM strategy for non-managed lanes under the conservative scenario. It shows that *the optimal CAS2 can yield higher overall throughput at these MPRs under the LM1 policy by only allowing CAVs on CDLs and CRLs, rather than the CAVs to travel on any lanes*.

Figure 8 illustrates the optimal overall throughputs under three LM policies and CAV technology scenarios. It can be seen from Figure 8(a) that all LM policies have the same overall throughputs, i.e., Q^*, when the MPRs are smaller than 0.1 under the aggressive scenario. As the MPRs increase from 0.1 to 0.46, the LM policies can improve overall throughputs compared with the 'no LM' policy, and *the largest overall throughput improvement is 25%*. When the MPRs exceed 0.46, the overall throughput equals the traffic demand, indicating that traffic flow becomes unsaturated under LM policies. For the 'no LM' policy, the unsaturated traffic flow can be realized when the MPRs are larger than 0.76. The above results demonstrate the merits of the proposed LM policies in enhancing overall mixed traffic throughputs. Moreover, the total throughput results of directions 1 and 2 for three LM policies under the aggressive scenario are illustrated in Figures 8(b) and 8(c). The changes in the total throughputs of direction 1 are similar to that of overall throughputs for all LM policies. The total throughputs of direction 2 maintain the same without the LM policy and reduce for LM policies compared with that of the 'no LM' policy at the MPRs of 0.1 to 0.44. This is because CRL_2 is deployed for the CAV traffic flow of direction 1 at smaller MPRs, which leads to reductions in mixed traffic flow discharged by the decreased lanes of direction 2.

Under the moderate scenario, in addition to one CRL_2 deployed at the MPRs of 0.1 to 0.72 in Figure 7(g), more CDL_1 at the MPRs of 0.74 to 0.8 in Figure 7(e) and one CDL_2 at the MPRs of 0.36 to 0.5 in Figure 7(f) should be deployed to improve overall throughputs than that under the aggressive scenario. Under the conservative scenario, we can observe that the CDL_1, CDL_2, and CRL_2 at the larger MPR ranges should be deployed in Figures 7(i), 7(j), and 7(k) than that of the moderate scenario. It is not required to deploy the CRL_1 for all MPRs under the two scenarios in Figures 7(h) and (l). On the contrary, the LM policies have the same overall throughputs as the 'no LM' policy under moderate and conservative scenarios when the MPRs are smaller than 0.1 in Figures 8(d) and 8(g). The traffic flow changes from a saturated to an unsaturated state under the moderate scenario when the MPRs reach 0.46 and 0.82 in Figure 8(d) for LM and 'no LM' policies, respectively. Under the conservative scenario, the critical MPRs are 0.6 and 0.92 in Figure 8(g) for LM and 'no LM' policies, respectively. *The maximum improvements of 32% and 31.2% in overall throughputs can be achieved with the LM* *policies over the ‘no LM’ policy under moderate and conservative scenarios, respectively*. Moreover, at the smaller MPRs from 0.02 to 0.26 and from 0.4 to 0.52 in Figure 8(g), the overall throughputs for the LM1 policy using the optimal CAS are larger than that of the LM2 policy at these MPRs under the conservative scenario. The results also demonstrate the effectiveness of using the best CAS in improving overall throughputs at different MPRs under the conservative scenario. The changes in total throughputs of directions 1 and 2 under moderate and conservative scenarios are similar to that of aggressive scenarios for all LM policies in Figures 8(e), 8(f), 8(h), and 8(i). The differences are that the LM1 policy can improve both total throughputs of directions 1 and 2 compared with other LM policies in some ranges of MPRs under the conservative scenario.

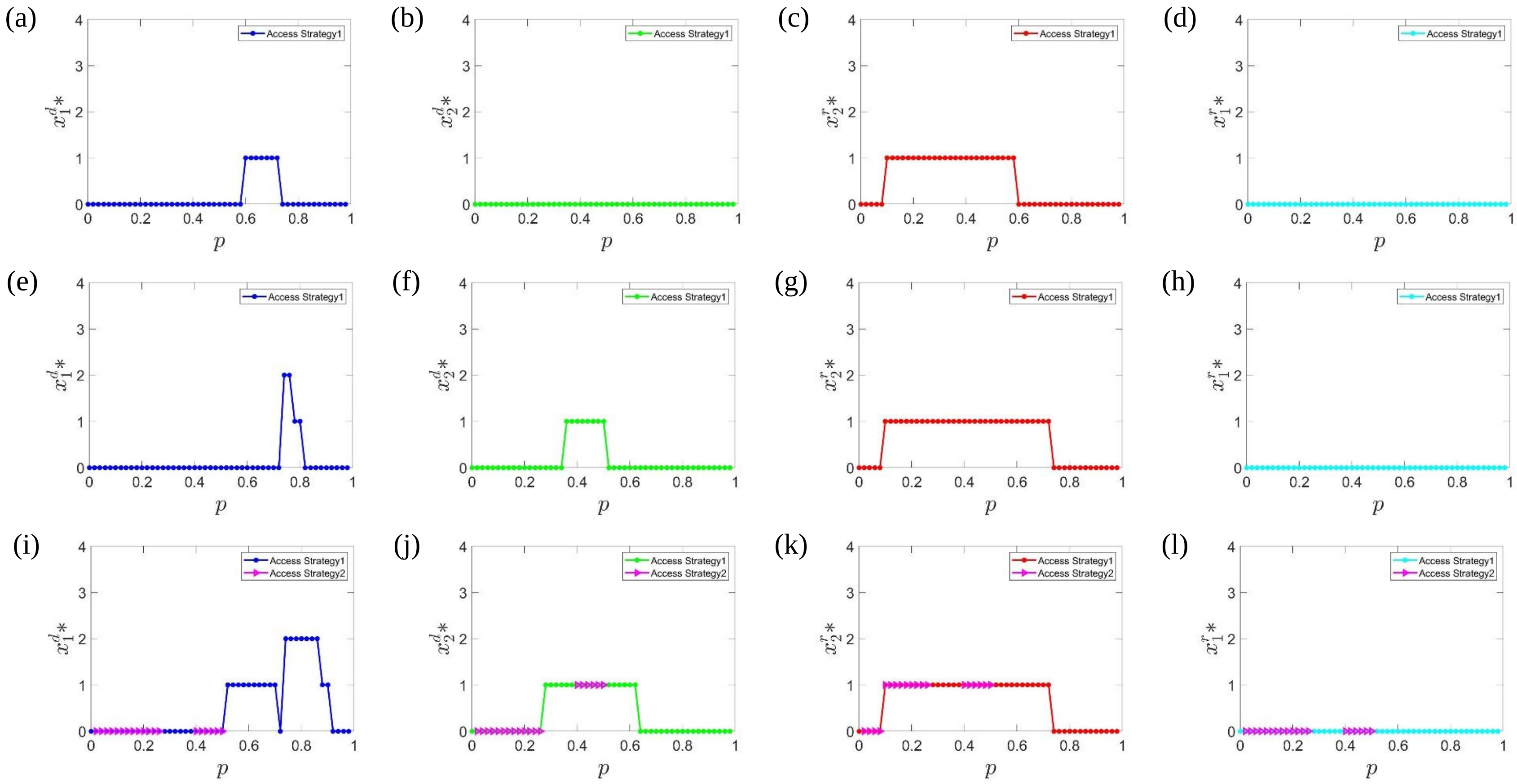

Figure 7. Results of CAV market penetration rate on optimal numbers of CDLs and CRLs and the optimal CASs. (a), (b), (c), and (d) aggressive scenario; (e), (f), (g), and (h) moderate scenario; (i), (j), (k), and (l) conservative scenario.

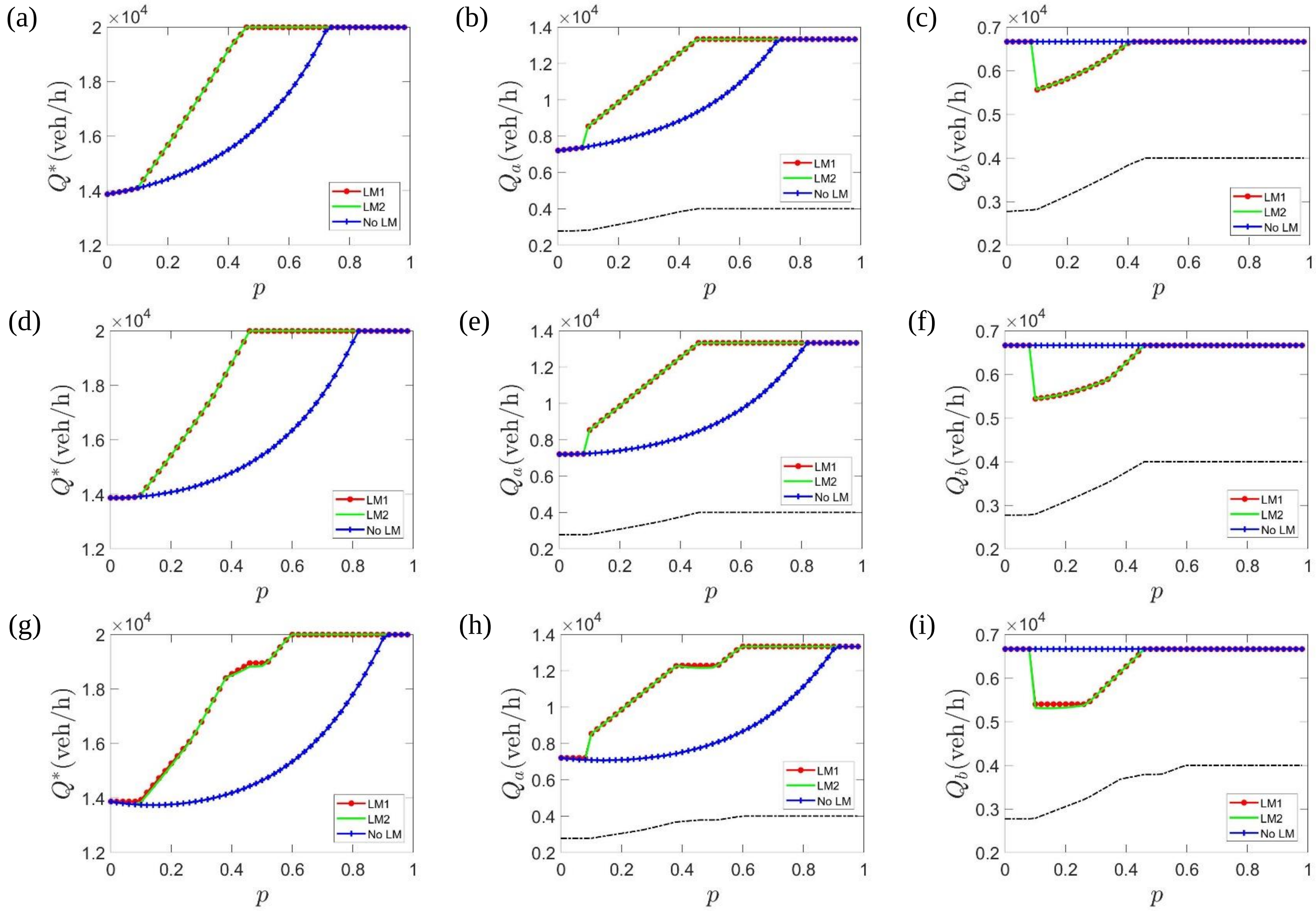

Figure 8. Results of CAV market penetration rate on optimal overall throughput. (a), (b), and (c) aggressive scenario; (d), (e), and (f) moderate scenario; and (g), (h), and (i) conservative scenario.

4.4. Impact of maximum platoon size

In this subsection, we analyze the impacts of maximum platoon size (MPS) in a range of 4 to 16 with an interval of 1 on the optimal numbers of CDLs and CRLs and the optimal CASs as well as maximum overall mixed traffic throughputs under three CAV technology scenarios, which are illustrated in Figures 9 and 10. It can be seen from Figure 9(c) that the numbers of CRL_2, i.e., x_2^{r*}, are 1 for all MPSs, implying that one CRL_2 should be deployed to improve overall throughputs under the aggressive scenario. The numbers of CDL_1, i.e., x_1^{d*}, CDL_2, i.e., x_2^{d*}, and CRL_1, i.e, x_1^{r*}, are 0 in Figures 9(a), 9(b), and 9(d), suggesting that the deployments of CDLs in all directions and CRLs in direction 1 are not required. Note that *overall throughputs can be improved by the LM1 policy using the CAS2 compared with the LM2 policy always using the CAS1 at the MPSs of 4, 5, 9 to 12 under the conservative scenario*. It is attributed to the application of the optimal CASs for non-managed lanes obtained by the LM model for different MPSs.

Figure 10 illustrates the optimal overall throughputs under three LM policies and CAV technology scenarios. As shown in Figure 10(a), the overall throughputs, i.e., Q^*, gradually become larger with the increment of MPS of 4 to 6 and reach the traffic demand when the MPSs exceed 6 for LM policies 1 and 2 under the aggressive scenario. For the 'no LM' policy, the overall throughputs rise as the MPSs increase, and the marginal improvements in overall throughputs are less than 0.1% when the MPS is more than 8. It indicates that a larger MPS can yield a higher overall throughput for all LM policies but no significant improvements can be reaped when the MPS exceeds the specific value without the LM policy. Moreover, we can see that the *overall throughput improvements for LM policies are in a range of 19.9% to 22.5% compared with the 'no LM' policy*. It can demonstrate that the proposed LM policies can effectively improve overall throughputs. In addition, the total throughput results of directions 1 and 2 for three LM policies under the aggressive scenario are illustrated in Figures 10(b) and 10(c). The total throughputs of direction 1 can gradually increase with the increment of MPS for all LM policies in Figure 10(b). There are the same total throughputs of direction 2 for all LM policies in Figure 10(c).

Under the moderate scenario, the difference is that both the numbers of CDL_1 at the MPSs of 4 and 5 in Figure 9(e) and CDL_2 for all MPSs increase to 1 in Figure 9(f) than that of the aggressive scenario. It indicates that one CDL in each direction should be deployed, in addition to the deployment of CRL_2. Under the conservative scenario, the deployments of one CDL_1 are further required at smaller MPSs of 4 to 8 in Figure 9(i). Other deployments of CRLs and CDLs are not changed based on the results in Figures 9(j), 9(k), and 9(l). On the contrary, the overall throughputs gradually increase with the increment of the MPS for all LM policies under moderate and conservative scenarios in Figures 10(d) and 10(g). There are smaller overall throughputs for all LM policies under moderate and conservative scenarios than that for the aggressive scenario. The overall throughput reaches the traffic demand at the MPSs of 9 and 12 for LM policies under moderate and conservative scenarios, respectively. The marginal improvements are less than 0.1% when the MPSs exceed 10 under the two scenarios without the LM policy. Compared with the 'no LM' policy, the LM policies can improve overall throughputs by *24.3% to 29.7% under the moderate scenario and 23.2% to 36.3% under the conservative scenario*. Moreover, the total throughputs of direction 1 maintain increasing for all LM policies under moderate and conservative scenarios as shown in Figures 10(e), 10(f), 10(h), and 10(i), except for the smaller MPS of 4 for the LM2 policy under the conservative scenario in Figure 10(h). The total throughputs of direction 2 keep the same for all LM policies under the conservative scenario, except for the smaller MPS of 4 for

LM1 and LM2 policies under the conservative scenario in Figure 10(i). Besides, the LM1 policy can further improve the total throughputs over the LM2 policy in MPR ranges of 9 to 12 under the conservative scenario.

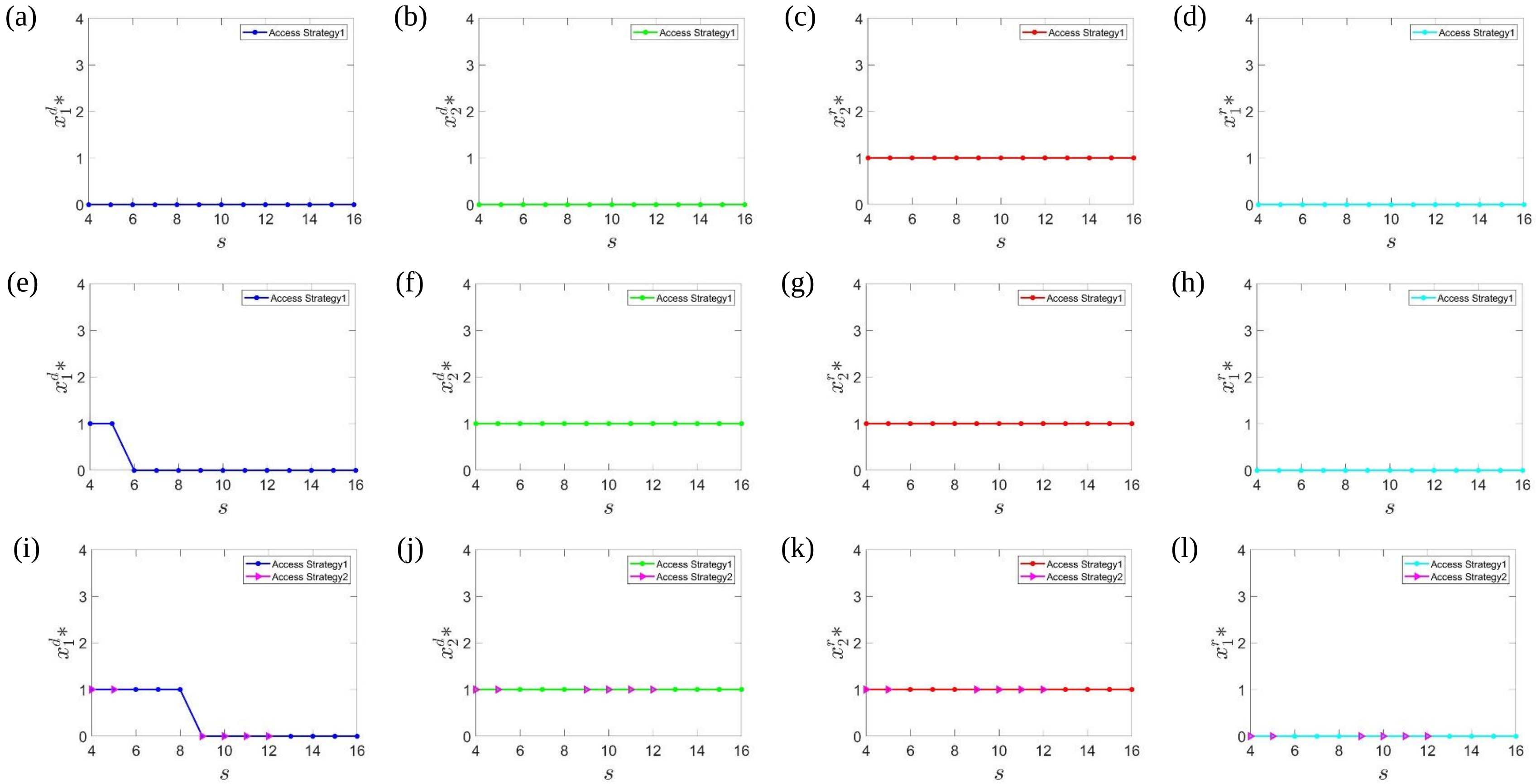

Figure 9. Results of maximum platoon size on optimal numbers of CDLs and CRLs and the optimal CASs. (a), (b), (c), and (d) aggressive scenario; (e), (f), (g), and (h) moderate scenario; (i), (j), (k), and (l) conservative scenario.

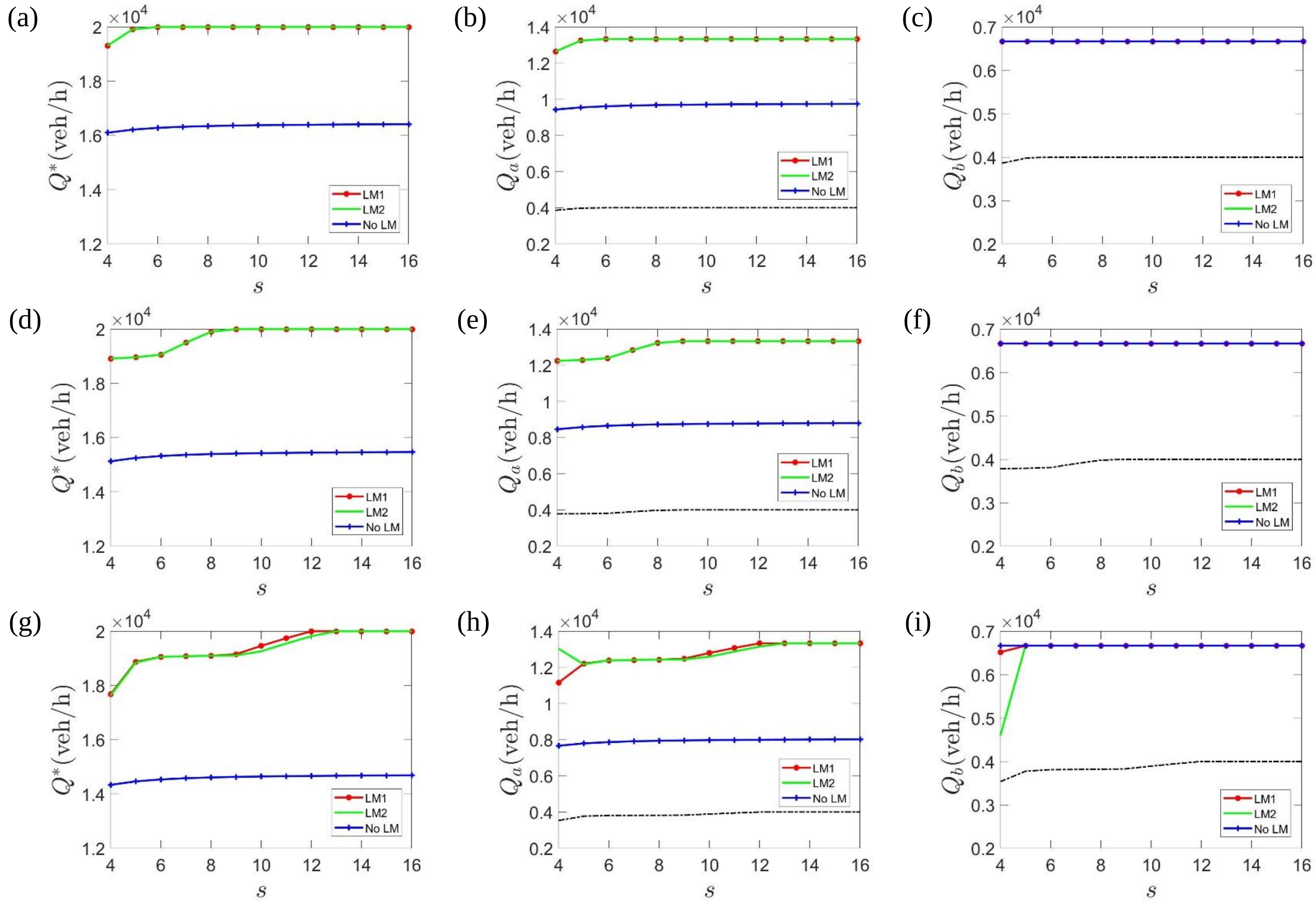

Figure 10. Results of maximum platoon size on optimal overall throughput. (a), (b), and (c) aggressive scenario; (d), (e), and (f) moderate scenario; and (g), (h), and (i) conservative scenario.

5. Discussions

The proposed LM model is essentially a high-level strategic decision tool to determine the optimal numbers of CDLs and CRLs and the optimal CASs for lane management from a point of view of macroscopic stationary equilibrium traffic, rather than a method for dynamic management of traffic flow. The proposed LM model can be applied to find strategic LM solutions for improving roadway traffic management under the joint LM policy. For the practical implementation, the actual traffic throughput results obtained may deviate from the theoretical ones since the excessive oscillations caused by the deployments of CDLs and CRLs can negatively affect the traffic throughputs.

To mitigate the potential adverse impacts of the proposed LM approach on traffic operation, we provide the following three measures. First, in the aspect of model formulation, we have introduced constraints in the proposed LM model to restrict the changes in road lanes, which are shown in Eqs. (26)-(29). The parameter α represents the level of traffic operation abilities to achieve a smooth traffic flow for suppressing the negative effects of traffic dynamics oscillations on traffic throughputs. With these constraints, the proposed LM model for static LM can effectively incorporate the impacts of traffic dynamics. Second, in the aspect of practical implementation, the CAVs can cooperate with other CAVs and actively create the gap for HDVs to mitigate the negative impacts caused by the changes in road lanes, as commanded by the traffic management center through vehicle-to-infrastructure/vehicle-to-vehicle communications. Third, in the aspect of model input, the upstream traffic demand can be first predicted. We can then use the proposed LM model to determine the optimal number of CDLs and CRLs and the optimal CASs for non-managed lanes based on the predicted traffic demand to avoid the frequent changes in road lanes.

6. Conclusions and future directions

In this study, we propose an LM model to manage the bidirectional asymmetric mixed traffic flow with CAVs and HDVs on roadway segments based on the joint LM policy of the CDLs, CRLs, and CASs. The models of traffic capacity are formulated based on different time headways of CAVs and their probability calculation considering the differentiated time headways of CAVs in a platoon. The models of traffic throughput are formulated by unifying two CASs for non-managed lanes, in addition to the CDL and CRL policies. Based on the formulated models of traffic capacity and throughput, an analytical LM model is developed to determine the optimal numbers of CDLs and CRLs and the optimal CASs for non-managed lanes that maximize the overall mixed traffic throughput. Numerical analysis is performed to investigate the impacts of the traffic demand and its DIP, CAV MPR, and MPS on the optimal numbers of CDLs and CRLs and the optimal CASs in each direction and overall throughputs under the aggressive, moderate, and conservative CAV technology scenarios. The results indicate that the proposed LM policies can significantly improve the overall throughput compared with the 'no LM' policy, using the optimal CAS and deploying either CRLs in the minor-flow direction, CDLs in one/two directions, or both under the three scenarios. Moreover, as expected, the overall throughput gradually rises as the four parameters increase for the proposed LM policies, except for the asymptotical increments with the MPR under the conservative scenario and the asymptotical reductions with the DIP under the three scenarios. Particularly, the LM policy with the optimal CAS has higher overall throughputs than the one with the pre-specified CAS under the conservative scenario. The findings of the study can provide useful LM countermeasures to manage the bidirectional asymmetric mixed traffic flow on roadways.

Further research can be conducted in several aspects. First, it is interesting to discuss the heterogeneity in headways for both CAVs and HDVs by using different time headway distributions on traffic throughputs. Moreover, except for traffic efficiency, other performance measures of safety, fuel consumption, and emissions can also be considered to validate the future applications of the CDL and CRL. Furthermore, decreased traffic throughputs may occur in case of the excessive oscillations caused by the LM approach in the practical application, which will be studied in future.

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Figure titles

Figure 1. Illustration of four types of headways under mixed traffic flow.

Figure 2. Illustration of LM problem setting under mixed traffic flow.

Figure 3. Results of traffic demand on optimal numbers of CDLs and CRLs and the optimal CASs. (a), (b), (c), and (d) aggressive scenario; (e), (f), (g), and (h) moderate scenario; (i), (j), (k), and (l) conservative scenario.

Figure 4. Results of traffic demand on optimal overall throughput. (a), (b), and (c) aggressive scenario; (d), (e), and (f) moderate scenario; and (g), (h), and (i) conservative scenario.

Figure 5. Results of directional imbalance percent on optimal numbers of CDLs and CRLs and the optimal CASs. (a), (b), (c), and (d) aggressive scenario; (e), (f), (g), and (h) moderate scenario; (i), (j), (k), and (l) conservative scenario.

Figure 6. Results of directional imbalance percent on optimal overall throughput. (a), (b), and (c) aggressive scenario; (d), (e), and (f) moderate scenario; and (g), (h), and (i) conservative scenario.

Figure 7. Results of CAV market penetration rate on optimal numbers of CDLs and CRLs and the optimal CASs. (a), (b), (c), and (d) aggressive scenario; (e), (f), (g), and (h) moderate scenario; (i), (j), (k), and (l) conservative scenario.

Figure 8. Results of CAV market penetration rate on optimal overall throughput. (a), (b), and (c) aggressive scenario; (d), (e), and (f) moderate scenario; and (g), (h), and (i) conservative scenario.

Figure 9. Results of maximum platoon size on optimal numbers of CDLs and CRLs and the optimal CASs. (a), (b), (c), and (d) aggressive scenario; (e), (f), (g), and (h) moderate scenario; (i), (j), (k), and (l) conservative scenario.

Figure 10. Results of maximum platoon size on optimal overall throughput. (a), (b), and (c) aggressive scenario; (d), (e), and (f) moderate scenario; and (g), (h), and (i) conservative scenario.