Unleashing the Power of Connected and Automated Vehicles: A Dedicated Link Strategy for Efficient Management of Mixed Traffic

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***Abstract*— The proper management of mixed traffic is crucial for unleashing the benefits of connected and automated vehicles (CAVs). Generally, the benefits of CAVs can be categorized into one-dimensional benefits in car-following performance and two-dimensional benefits in efficiently addressing right-of-way conflicts. Currently, the most effective approach to achieve this is by establishing a dedicated right-of-way for CAVs. However, existing strategies are limited to dedicated lane strategy, which can only unleash the one-dimensional benefits of CAVs while the two-dimensional benefits remain untapped. Therefore, this paper proposes a novel management approach for mixed traffic called the dedicated link strategy. The dedicated link refers to the road link that only allows CAVs to use. This strategy can unleash both the one-dimensional and two-dimensional benefits of CAVs via: (i) dedicated link deployment at the road network level and (ii) a novel intersection management approach. Specifically, at the macroscopic road network level, we introduce a bi-level dedicated link deployment model and design an artificial bee colony based algorithm to solve the optimal dedicated link deployment. At the microscopic intersection level, we develop a novel intersection management approach that integrates traditional traffic signal strategy with the emerging signal-free cooperative driving method, thereby boosting the efficiency of intersections. The macroscopic and microscopic methods will complement each other to achieve efficient management of network-wide mixed traffic systems. Finally, we verify the performance of the dedicated link strategy through comprehensive experiments. In essence, the proposed dedicated link strategy unifies the existing dedicated lane strategy and dedicated intersection strategy, providing a general solution for mixed traffic management.**

***Index Terms*— Connected and automated vehicles (CAVs), mixed traffic, dedicated link strategy, intersection management.**

I. Introduction

THE evolution from the traditional human-driven environment to a fully autonomous driving environment inevitably involves a prolonged period of mixed traffic, where both connected and automated vehicles (CAVs) and human-driven vehicles (HDVs) run on the road. Despite the various performance benefits of CAVs, their advantages will be significantly diminished in mixed traffic due to the uncertainty and randomness of HDVs' driving behaviors. Therefore, the proper management of mixed traffic becomes crucial to unleashing the benefits of CAVs [1], [2], [3], [4], [5]. The survey [1] concludes that the benefits of CAVs for the transportation system primarily manifest in two aspects: (*i*) the one-dimensional benefits, mainly due to the excellent car-following performance of autonomous vehicles, and (*ii*) the two-dimensional benefits, mainly due to the more efficient utilization of limited road resources by CAVs in areas with right-of-way conflicts.

In recent years, researchers have proposed various management methods for mixed traffic, among which, the most effective approach is establishing dedicated right-of-way for CAVs [6], [7], [8], [9], [10]. CAV dedicated right-of-way strategy refers to setting up certain right-of-way within the road network for CAVs use only, while restricting HDVs use, such as dedicated lanes [11], [12], dedicated zones [13], etc. In summary, there are two main advantages to setting up a dedicated right-of-way for CAVs. First, it can separate CAV traffic flow from HDV traffic flow, thereby effectively avoiding the negative impacts on CAVs caused by the uncertainty and randomness of HDVs' driving behavior [12], [14]. Second, it can create driving scenarios exclusively for CAVs, thus facilitating the deployment of efficient driving strategies for CAVs such as multi-vehicle cooperative adaptive cruise control [15], [16], [17], [18], [19] and cooperative driving at intersections [20], [21], [22], [23], [24], [25], [26], [27]. The CAV dedicated lane strategy [11], [28], [29] has received extensive research attention as a dedicated right-of-way approach. According to the aforementioned benefits classification, the dedicated lane strategy aims to take advantage of the one-dimensional benefits of CAVs, such as shorter and more stable car-following performance. This strategy can effectively improve the efficiency and capacity of traffic scenarios without right-of-way conflicts, particularly on highways.

However, the previous studies [1], [30], [31] have demonstrated that in urban road networks, which encompass various types of right-of-way conflicts like intersections, the two-dimensional right-of-way conflicts play a dominant role in influencing the efficiency and capacity of the traffic system

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compared with one-dimensional car-following performance. Consequently, the dedicated lane strategy has limited effectiveness in enhancing the efficiency of urban network-wide mixed traffic systems.

Therefore, this paper proposes a novel management approach for mixed traffic, called the dedicated link strategy. The dedicated link strategy refers to setting part of the links within the road network exclusively for CAVs, while restricting the use of HDVs. This will bring advantages in two aspects. On the one hand, the one-dimensional car-following benefits of CAVs can be achieved on these dedicated links. On the other hand, the formation of CAV dedicated links at microscopic intersections enables the implementation of more efficient signal-free cooperative driving methods, thereby unleashing the two-dimensional benefits of CAVs. The two advantages of the dedicated link strategy will complement each other and work together to fully unleash the one-dimensional and two-dimensional performance benefits of CAVs.

Specifically, the dedicated link strategy comprises two core components: one at the macroscopic road network level and the other at the microscopic intersection level. First, the key problem at the macroscopic road network level is the dedicated link deployment problem. It refers to determining which links within the road network should be set up as dedicated links. To achieve this, we develop a bi-level dedicated link deployment model and introduce an artificial bee colony based algorithm for solving the optimal dedicated link deployment. Second, at the microscopic intersection level, we propose a novel intersection management approach that integrates the traditional traffic signal control strategy with the signal-free cooperative driving method, which can improve the utilization of limited right-of-way resources at intersections and thus unleash the two-dimensional benefits of CAVs. Moreover, it should be clarified that the dedicated link strategy is to set some links within the road network as CAV dedicated, while the dedicated lane strategy is to sets some lanes on the link as CAV dedicated.

The experimental results demonstrate that the proposed dedicated link strategy can significantly enhance the efficiency of the mixed traffic system. From the perspective of individual vehicles, this strategy reduces the travel time of CAVs while having little impact on the travel time of HDVs. From the perspective of the transportation system, this strategy increases the traffic flow of the road network system, particularly at medium and high traffic densities. Furthermore, the proposed artificial bee colony based algorithm can find near-optimal dedicated link deployment schemes within a reasonable time. The microscopic traffic simulation experiments further verify the performance of the dedicated link strategy. The results demonstrate that the novel management approach developed for microscopic intersections can effectively reduce the queuing time caused by right-of-way conflicts, which has great potential for boosting the efficiency of the urban transportation system and reducing energy consumption.

The key contributions of this paper are threefold:

1) First, we propose a novel dedicated link strategy for the management of mixed traffic, which can simultaneously unleash the one-dimensional and two-dimensional benefits of CAVs. It can significantly improve the travel efficiency of CAVs while minimizing the impact on HDVs.
2) Second, we develop a bi-level model for the dedicated link deployment problem, along with a corresponding artificial bee colony based algorithm. By decoupling the deployment problem with the traffic assignment problem, we can find near-optimal solutions for this *NP*-hard problem in a reasonable time.
3) Third, we introduce a novel intersection management paradigm and method, which integrates the traditional traffic signal strategies and the emerging signal-free cooperative driving methods. This integrated approach provides a more efficient and flexible intersection management scheme for mixed traffic systems.

To better present our work, the rest of this paper is organized as follows. *Section II* presents the literature review. *Section III* introduce the framework of the dedicated link strategy. *Section IV* presents the bi-level model and the artificial bee colony based algorithm for dedicated link deployment problem. *Section V* introduces the novel management approach for microscopic intersections. *Section VI* presents the numerical experiments. Finally, we conclude the paper in *Section VII*.

II. LITERATURE REVIEW

This section provides a literature review of the literature that is closely related to this paper. *Section II-A* reviews the most popular CAV dedicated right-of-way approach: the dedicated lane strategy. *Section II-B* reviews the literature related to cooperative driving at signal-free intersections.

A. CAV Dedicated Lane Strategy

Dedicated lane strategy is the most popular CAV dedicated right-of-way approach, which aims to set up some lanes on multi-lane roads for CAVs only, and can unleash the one-dimensional car-following benefits of CAVs. The key challenge associated with the dedicated lane strategy lies in determining when and how many dedicated lanes should be set up to optimize overall traffic efficiency. Several studies have been conducted by researchers to address this crucial issue. Mahmassani [28] studied the impact of setting up dedicated lanes for autonomous vehicles on traffic flow stability. Ye and Yamamoto [11] investigated the impact of setting up dedicated lanes for CAVs on traffic flow throughput. Yao et al. [12] analyzed the road capacity with and without CAV dedicated lanes, and modeled the fundamental diagram of mixed traffic with CAV dedicated lanes. Chen et al. [29] proposed a mathematical model to optimize the deployment of dedicated lanes for autonomous vehicles in mixed traffic, aiming to minimize social costs and promote autonomous vehicle adoption. To further promote the construction of one-dimensional vehicle platoons, Chen et al. [13] introduced a mathematical framework to optimize the design of autonomous vehicle dedicated zones in a road network.

The dedicated lane strategy can unlock the one-dimensional benefits of CAVs, i.e., the safer and more efficient car-following performance of CAVs. However, the existence

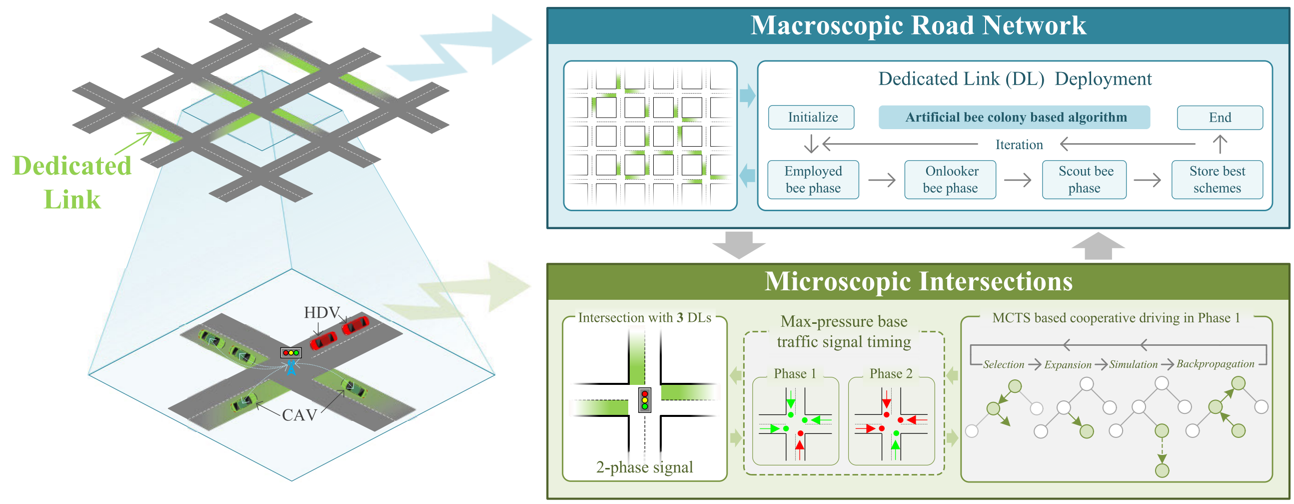

Fig. 1. Au illustration of the dedicated link (DL) strategy for the management of mixed traffic. (*Upper*) For macroscopic road networks, the core issue is to solve the optimal dedicated link deployment to improve the overall efficiency of the network-wide mixed traffic system. (*Lower*) For microscopic intersections, we propose an intersection management approach that integrates traditional traffic signal control strategies with the signal-free cooperative driving methods to unleash the two-dimensional benefits of CAVs.

of HDVs on the links prevents the dedicated lane strategy from unleashing the two-dimensional benefits of CAVs in right-of-way conflict areas such as intersections. In contrast, the dedicated link strategy proposed in this paper can not only unleash the one-dimensional benefits of CAVs on the corresponding dedicated links, but also unleash the two-dimensional benefits of CAVs by partially deploying the cooperative driving approach at intersections.

B. Cooperative Driving at Signal-Free Intersection

One of the revolutionary impacts of CAVs on the traffic system is cooperative driving at intersections, which can turn signalized intersections to be signal-free and improve traffic efficiency by better organizing CAVs right-of-way assignments at intersections, also known as passing order. To address this problem, researchers have proposed various cooperative driving algorithms to solve the passing order. These algorithms can be broadly classified into four categories. The first category is the reservation based algorithm [32], [33], [34], [35], [36] that roughly follows the first-come-first-served (FCFS) principle. In each round of planning, the time for CAVs to arrive at the conflict zone is estimated, and then the passing order is arranged in ascending order of arrival time. The advantage of this category of algorithm is that it requires less computation cost, but the disadvantage is that there is a certain performance gap between its corresponding passing order and the optimal solution [30], [37], [38].

The second category is the mathematical programming based algorithms [36], [39], [40], [41], [42], [43], which formulate the right-of-way assignment problem as a constrained optimization problem and aim to solve the optimal passing order. However, since the problem is an *NP*-hard problem, the solution space grows exponentially with the number of vehicles, resulting in this category of algorithms not being able to meet the real-time requirements when the number of vehicles increases.

The third category is the tree search based algorithms [44], [45], [46], which formulate the right-of-way assignment problem as a tree search problem and guide the search process by designing heuristic rules, aiming to find near-optimal passing orders in a limited time budget. The tree search based algorithms have the advantage of being able to meet real-time requirements, but the performance may degrade as the number of vehicles increases further.

The fourth category is learning based algorithms [21], which formulate the right-of-way assignment problem as a combinatorial optimization problem and use deep neural networks to learn the mapping from intersection scenarios to the optimal passing order. Through offline learning and online fine-tuning search, the learning based algorithm can solve the cooperative driving problem for large-scale CAV swarms.

Compared to traditional traffic signal strategy, signal-free cooperative driving strategy can comprehensively improve the efficiency of the traffic system [30]. However, the cooperative driving strategy cannot be directly deployed into mixed traffic environments where HDVs exist. To this end, this paper proposes the dedicated link strategy and the corresponding intersection management approach, which can enable the deployment of the cooperative driving strategy in mixed traffic systems and thus unleash the two-dimensional benefits of CAVs [1].

III. Framework of Dedicated Link Strategy

This section introduces the framework for dedicated link strategy. As illustrated in Fig. 1, the implementation of the dedicated link strategy consists of macroscopic and microscopic levels, which will be presented in detail below.

A. Macroscopic Level

At the macroscopic level, the core issue is to determine which links within the road network should be set up as CAV dedicated links, i.e., the dedicated link deployment problem. The objective at the macroscopic level is to improve the travel efficiency of CAVs by optimizing the deployment of dedicated links. Simultaneously, the potential negative impact of dedicated links on HDVs must be considered to synergistically

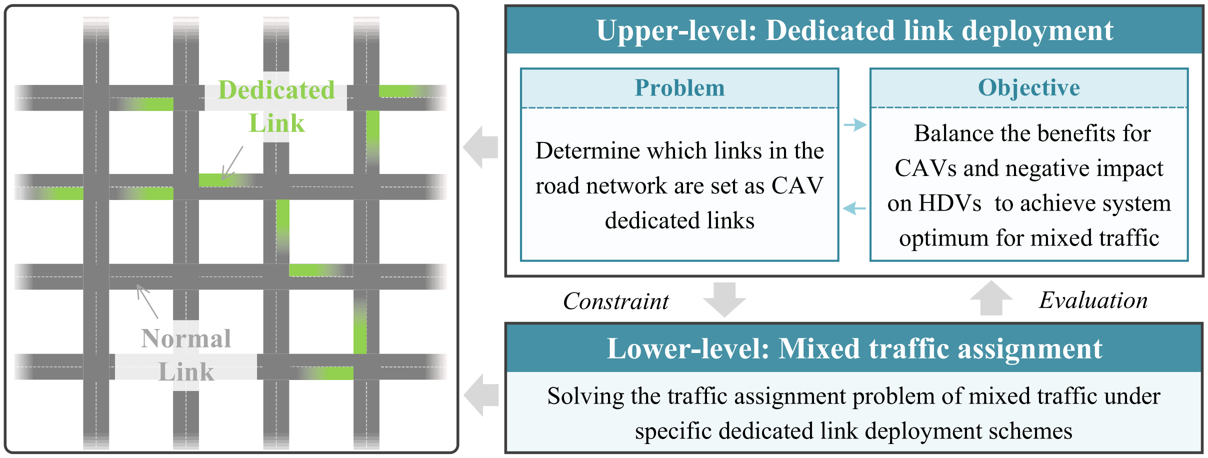

Fig. 2. The bi-level model for solving the dedicated link deployment problem. The upper-level issue is to determine which links are set as CAV dedicated links. The lower-level issue is to solve the corresponding traffic assignment problem. The results of lower-level traffic assignment can achieve an accurate evaluation of upper-level dedicated link deployment schemes.

improve the overall efficiency of the mixed traffic system. It should be illustrated that the dedicated link deployment problem is a computationally complex problem known as an *NP*-hard problem. With a road network comprising n links, the solution space of this problem is 2^n. For example, for a road network with a size of 7×7 (as shown in Fig. 6), the total number of links is 168, and the corresponding solution space size is $2^{168} \approx 3.73 * 10^{50}$.

To solve the optimal dedicated link deployment within a macroscopic road network, we propose a bi-level optimization model and develop an artificial bee colony based algorithm. Specifically, the upper level optimizes the dedicated link deployment scheme, while the lower level focuses on solving the corresponding traffic assignment problem. The results of lower-level traffic assignment provide an accurate evaluation of the upper-level dedicated link deployment scheme. The proposed artificial bee colony based algorithm aims to find the optimal dedicated link deployment scheme. Refer to *Section IV* for comprehensive details.

In essence, the deployment of dedicated links within the road network can achieve the separation of CAVs from mixed traffic flow at the macroscopic level and the formation of 100% CAV environments in dedicated links, providing favorable conditions for efficient management at the microscopic level.

B. Microscopic Level

At the microscopic level, the core issue is the effective management of intersections. Intersections act as bottlenecks that influence the traffic efficiency of the urban road network and, consequently, play a crucial role in unleashing the two-dimensional benefits of CAVs [30]. In a road network where the CAV dedicated links are deployed, we propose a novel intersection management approach that integrates the traditional traffic signal control strategies with the signal-free cooperative driving methods. The approach can improve the utilization of limited right-of-way resources at intersections, thereby unleashing the two-dimensional benefits of CAV.

Specifically, due to the deployment of CAV dedicated links, multiple links with only CAVs can be formed at intersections. Based on this, we are able to use the cooperative driving methods [20], [21], [44], [45] to optimize the motions of the CAVs on the dedicated links, allowing them to pass through intersections more efficiently. To achieve this, we propose emerging phase settings for intersections, which not only address the issue of right-of-way conflicts between CAVs and HDVs by sequential alternation of distinct phases, but also achieve the implementation of cooperative driving for CAVs. Furthermore, to address the emerging phase timing problem, we introduce a max-pressure based intersection timing method for assigning time to different phases. Refer to *Section V* for comprehensive details.

In essence, the microscopic intersection management approach resolves the issue of interaction between CAVs and HDVs in areas of right-of-way conflicts.

IV. Dedicated Link Deployment in Macroscopic Road Network

The problem of dedicated link deployment refers to setting some links in the road network as CAV dedicated links, which is the core issue of the dedicated link strategy. In the subsequent *Section IV-A*, we introduce the bi-level model for the dedicated link deployment problem. *Section IV-B* presents the artificial bee colony based dedicated link algorithm.

A. Problem Formulation

The mixed traffic system comprises two types of vehicles: connected and automated vehicles (CAVs) and human-driven vehicles (HDVs). According to the definition of the dedicated right-of-way, CAVs can use the dedicated links while HDVs cannot. In order to simultaneously unleash the one-dimensional and two-dimensional benefits of CAVs, we are committed to determining the optimal dedicated link deployment scheme. The goal of dedicated link deployment is to improve the travel efficiency of CAVs while minimizing the negative impact on HDVs caused by establishing dedicated links, thereby achieving system optimum of the network-wide mixed traffic.

For ease of presentation, we employ a graph structure $G = (I, A)$ to represent the road network, where I is the set of intersection nodes and A is the set of links that connect

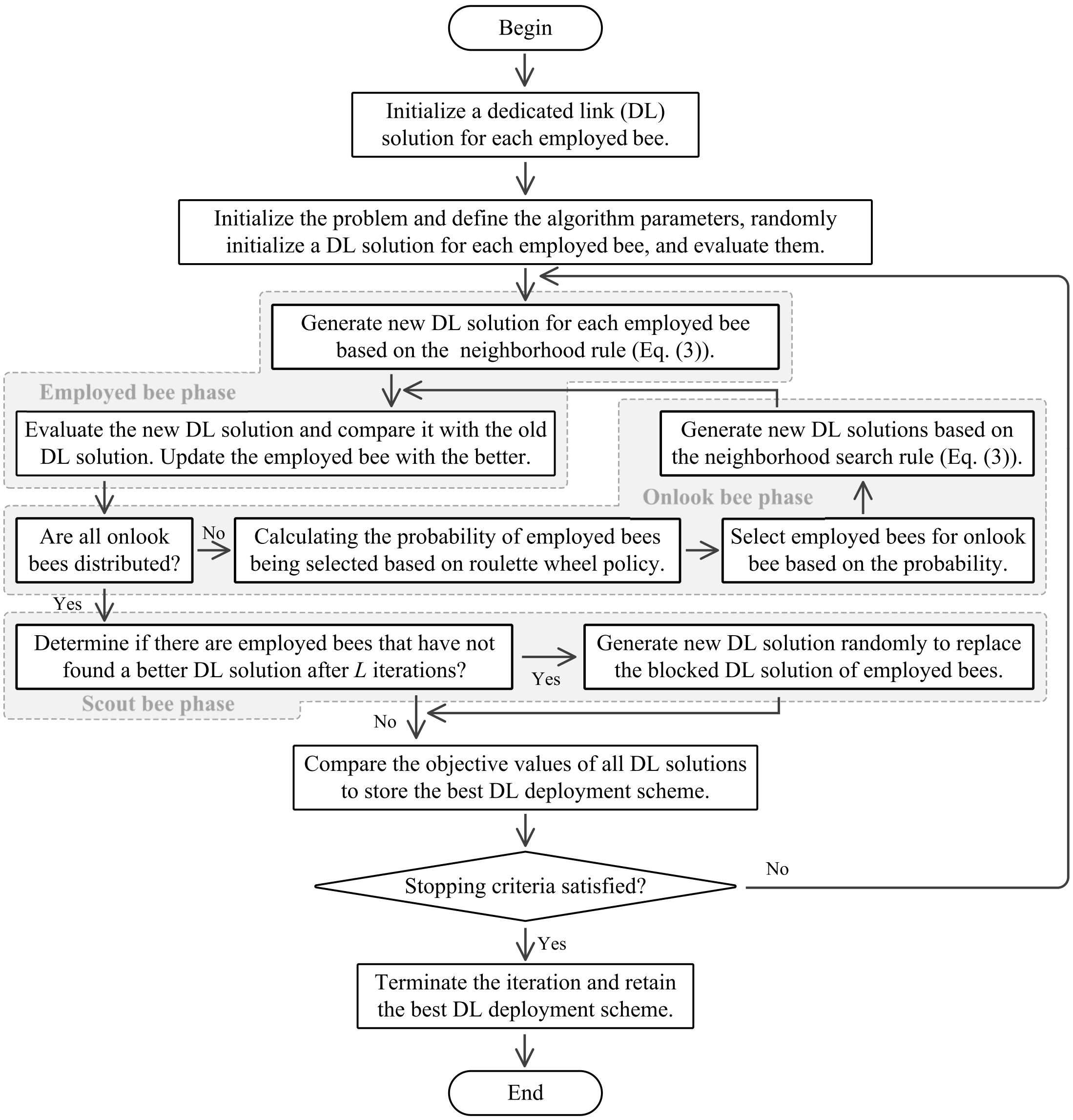

Fig. 3. Flowchart of artificial bee colony based dedicated link algorithm.

these intersections. The total number of links, denoted as n, corresponds to the set A. We denote the intersection nodes by $i, j = 1, 2, \cdots, n$, so the link can be represented as $(i, j) \in A$. We use $O \in I$ and $D \in I$ to represent the sets of origins and destinations, respectively. The set W denotes all origin-destination (OD) pairs. Therefore, an OD pair $w \in W$ connects an origin $o \in O$ with a corresponding destination $d \in D$. The value θ^w denotes the penetration rate of CAVs within OD pair $w \in W$. q^w denotes the total traffic flow between OD pair $w \in W$, where the traffic flow of CAVs is $q^w_{CAV} = \theta^w * q^w$ and the traffic flow of HDVs is $q^w_{HDV} = (1 - \theta^w) * q^w$.

To solve the optimal dedicated link deployment scheme, we propose a bi-level model as shown in Fig. 2. The upper level is to determine the deployment scheme for dedicated links, while the lower level is to solve the corresponding traffic assignment problem. The traffic assignment results at the lower level will realize a precise evaluation of the dedicated link deployment scheme at the upper level. The details are elaborated below.

1) Upper-Level: Dedicated Link Deployment Problem: Based on the above analysis, the deployment of the dedicated links in the network-wide mixed traffic system needs to balance the efficiency benefits for CAVs and the negative impact for HDVs. To this end, we set the following objective function to achieve the system optimum for mixed traffic:

$$f(X) = \min_{x_{ij}} \left\{ \sum_{(i,j)\in A} v_{ij} t_{ij} \left(1 - x_{ij}\right) + \sum_{(i,j)\in A} v_{ij} t'_{ij} x_{ij} \right\} + f_{\text{Enforceable}}(X) \quad (1)$$

$$\text{s.t. } x_{ij} \in (0, 1) \quad \forall (i, j) \in A \quad (2)$$

where $X = \{x_{ij}((i, j) \in A)\}$ is the decision variable. $x_{ij} = 1$ indicates that the link (i, j) is set to CAV dedicated link, and only CAVs can use. Conversely, $x_{ij} = 0$ indicates that the link (i, j) is a normal link accessible to both CAVs and HDVs. v_{ij} represents the traffic flow on link (i, j), which will be determined by the lower-level traffic assignment. t_{ij}

and t'_{ij} denote the travel time under different link settings, which are determined based on the classical Bureau of Public Roads (BPR) function [47] and the road flow capacity model considering CAV penetration parameters, as detailed in [48] and [49]. Additionally, considering that the setting of the dedicated links may cause HDVs to have no feasible route from their origin to their destination, we introduce the term $f_{\text{Enforceable}}(X)$ to assess the enforceability of the dedicated link deployment scheme $X = \{x_{ij}((i, j) \in A)\}$. If X results in HDVs having no feasible route to their destination, it indicates that the deployment scheme X is unenforceable and $f_{\text{Enforceable}}(X)$ will return a sufficiently large value; otherwise, it returns 0. The objective function represents the sum of travel time multiplied by the flow on each road link, which is the same as the objective function for the system optimum traffic assignment model [50], [51].

It is worth noting that in a road network with n links, there are 2^n possible deployment schemes for dedicated links. Consequently, the solution space of the dedicated link deployment problem grows exponentially with the number of links, making it an NP-hard problem. For any dedicated link deployment scheme, we can obtain its corresponding objective function value by solving the following traffic assignment problem.

2) Lower-Level: Traffic Assignment for Mixed Traffic Under Dedicated Link Strategy: After determining the dedicated link deployment scheme $X = \{x_{ij}((i, j) \in A)\}$, it is necessary to solve the corresponding traffic assignment problem in order to evaluate its performance. Similar to related studies [52], [53], [54], [55], the lower-level problem is addressed using the user equilibrium traffic assignment model [47], [48], [50], [56], i.e., no traveler can reduce travel time by unilaterally changing the route. According to the definition of the dedicated links, CAVs can pass through the dedicated link, while HDVs cannot. Under this constraint, we resolve the traffic flow on each link based on the user equilibrium traffic assignment model. It should be noted that other more complex traffic assignment models can also be used for addressing the lower-level traffic assignment problem. However, since the upper-level dedicated link deployment problem is an NP-hard problem, the computational time required for solving the lower-level problem will seriously affect the time needed to resolve the optimal dedicated link deployment scheme. As an evaluation module for the upper-level problem, the user equilibrium traffic assignment model is a choice that strikes a balance between computational complexity and evaluation accuracy.

B. Artificial Bee Colony Based Dedicated Link Deployment Algorithm

In this section, we elaborate on the proposed artificial bee colony based algorithm for solving the dedicated link deployment problem. Due to the exponential growth of the solution space for the dedicated link deployment problem, it is impractical to evaluate all dedicated link deployment schemes. Therefore, this paper presents the artificial bee colony based dedicated link algorithm, which aims to find a near-optimal dedicated link deployment scheme within a reasonable time.

The artificial bee colony algorithm [57] is a classical meta-heuristic optimization algorithm known for its excellent local search mechanism, and has achieved outstanding performance in many tasks [58], [59], [60]. The artificial bee colony algorithm emulates the intelligent foraging behavior of bees [61], [62]. It comprises three fundamental components: employed bees, onlooker bees, and scout bees. Employed bees and onlooker bees are used to implement the exploitation process within the solution space of a given problem, whereas scout bees are used to implement the exploration process across the full solution space. In the dedicated link deployment problem, we nest the lower-level traffic assignment into the search process of the dedicated link deployment schemes. The artificial bee colony algorithm conducts iterative searches to find better sources, i.e., better dedicated link deployment schemes, as illustrated in Fig. 3. The core steps are outlined below:

Step 1: Parameter initialization: Initialize the bee colony size L, set the global iteration number and the threshold T that represents the maximum number of iterations for a single solution.

Step 2: Initialize the employed bees: randomly assign a dedicated link deployment scheme to each employed bee and set the counter of each scheme to 0.

Step 3: Employed bee phase: Perform a neighborhood search around the dedicated link deployment solution of each employed bee. Unlike the neighborhood search rule in the original artificial bee colony algorithm, we have modified the neighborhood search rule since the decision variables of the dedicated link deployment problem $X = \{x_{ij}((i, j) \in A)\}$ are discrete $0-1$ integer variables instead of continuous variables. The improved neighborhood search rule is presented below:

$$X_j^{i'} = \begin{cases} X_j^i \ \text{if} \ X_j^i = X_j^k \\ X_j^i \ \text{if} \ X_j^i \neq X_j^k \ \text{and} \ \text{rand}(0,1) < \dfrac{f\left(X^k\right)}{f\left(X^i\right) + f\left(X^k\right)} \\ X_j^k \ \text{if} \ X_j^i \neq X_j^k \ \text{and} \ \text{rand}(0,1) \geq \dfrac{f\left(X^k\right)}{f\left(X^i\right) + f\left(X^k\right)} \end{cases} \tag{3}$$

where X_j^i denotes the j-th decision variable of the dedicated link deployment scheme X^i, and so on for X_j^k. $X^{i'}$ is the updated deployment scheme. X^k is a randomly selected solution different from solution X^i, i.e., $k \in \{1, 2, \cdots, L\}$ and $k \neq i$. $j \in \{1, 2, \cdots, n\}$ is a randomly selected index. $f\left(X^i\right)$ is the objective function value of X^i. The neighborhood search rule implies that the deployment scheme with a smaller objective function value has a higher probability of being selected as the updated solution. After obtaining the new solution $X^{i'}$, we solve for its objective function value. If the new dedicated link deployment scheme $X^{i'}$ has a smaller objective function value than that of X^i, we replace the old deployment scheme X^i with the updated solution $X^{i'}$ and reset the counter to 0. Otherwise, we keep the old dedicated link scheme X^i and increment its counter by one.

Step 4: Onlooker bee phase: Select an employed bee for each onlooker bee based on the roulette wheel strategy. The

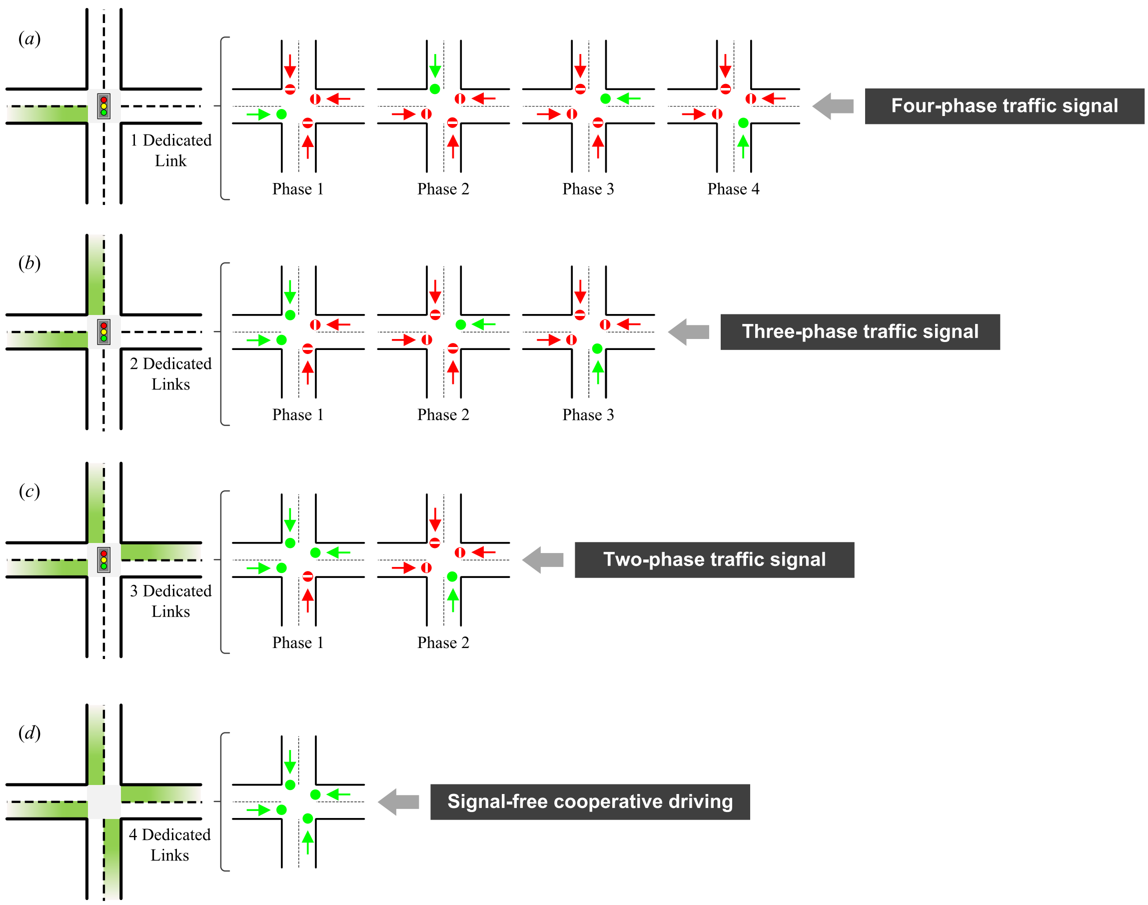

Fig. 4. An illustration of the phase settings for the intersection management approach under the dedicated link strategy.

probability of one employed bee X^i being selected is:

$$p_i = \frac{f\left(X^i\right)}{\sum_{\text{index}=1}^{L} f\left(X^{\text{index}}\right)} \tag{4}$$

And then conduct a neighborhood search on the dedicated link deployment scheme where the selected employed bee is located. The neighborhood search rule is the same as Eq.(3).

Step 5: Scout bee phase: If a dedicated link deployment solution indicated by an employed bee does not improve after T iterations of neighborhood searching, we abandon the solution, and the scout bee generates a new dedicated link deployment solution randomly.

Step 6: Compare the objective function values of all the dedicated link deployment solutions obtained so far and find the solution with the smallest objective function value, which is currently the best dedicated link deployment scheme.

Step 7: Increase the iteration count by one and then verify if the maximum number of iterations has been reached. If so, terminate the algorithm; otherwise, proceed to *Step 3*.

During the iterative process of the bee colony foraging, the current best dedicated link deployment scheme is continuously updated, and the entire bee colony will gradually converge towards the best deployment schemes. Once the maximum number of iterations is reached, the algorithm terminates and returns to the best dedicated link deployment scheme.

V. The Novel Management Approach for Microscopic Intersections

This section introduces the novel management approach for microscopic intersections under the dedicated link strategy. In order to unleash the two-dimensional benefits of CAVs, the novel approach integrates the traditional traffic signal strategies with the emerging signal-free cooperative driving methods.

Cooperative driving refers to the driving algorithm that coordinates driving behaviors and motion control of multiple CAVs with the support of V2X communication technology to improve traffic safety and efficiency and reduce energy consumption [63]. As mentioned above, at intersections, the cooperative driving method can turn signalized intersections to be signal-free and boosts traffic efficiency by better organizing the passing order of CAVs. Several studies [30], [32], [37] have demonstrated that the signal-free cooperative driving methods have significant efficiency advantages compared to traditional traffic signal strategies, making it the primary way for unleashing the two-dimensional benefits of CAVs.

The existing signal-free cooperative driving methods at intersections are designed for scenarios where all four directions at the intersection consist of CAVs, and all CAVs engage in cooperative driving planning simultaneously. Hence, under the dedicated link strategy, we can implement signal-free cooperative driving to enhance traffic efficiency in cases where all four links at an intersection are CAV dedicated links.

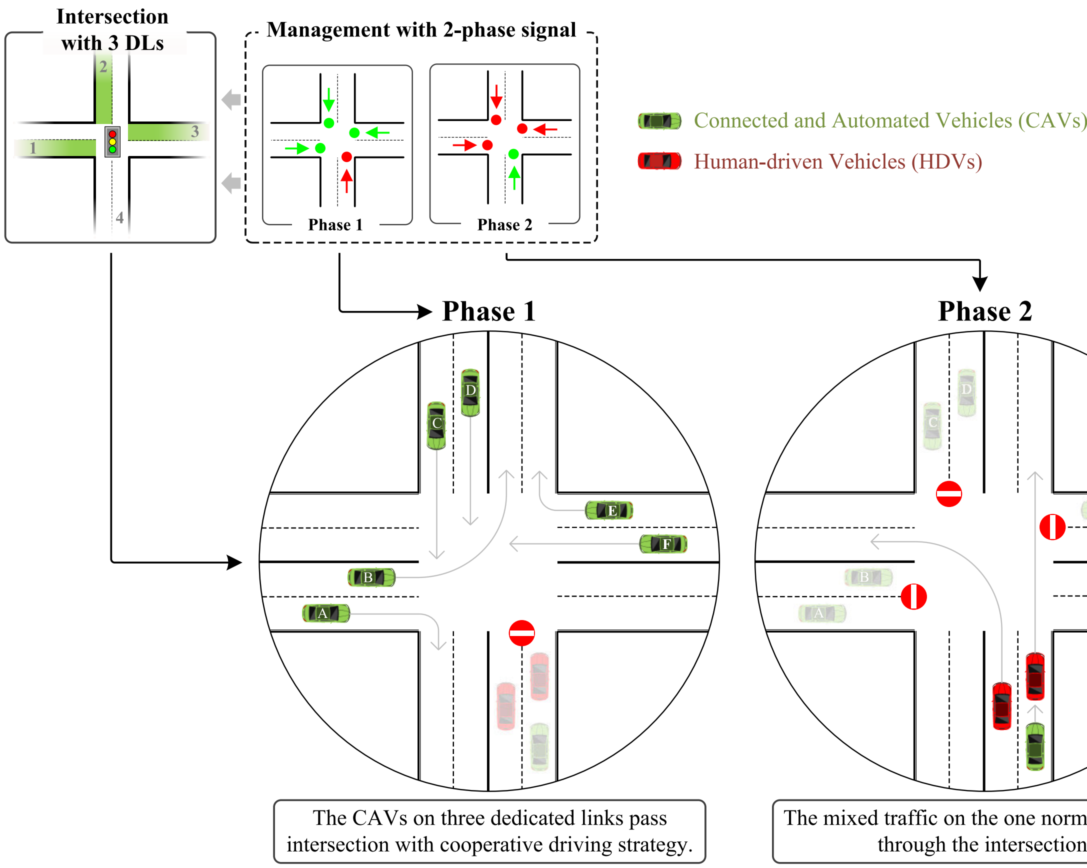

Fig. 5. An illustration of a two-phase management approach for the intersection with three dedicated links (DLs). In Phase 1, the CAVs on the three dedicated links pass through the intersection by using the cooperative driving method. For example, "*BACFDE*" is a feasible passing order for cooperative driving of these CAVs. When the paths of two CAVs conflict, the more front the CAV is in the passing order, the higher its priority. For example, the priority of *CAV B* is higher than the priority of *CAV D*.

However, the existing cooperative driving strategies are not capable of handling the normal links with a mixed traffic flow.

In this study, in order to fully unleash the two-dimensional benefits of CAVs, we present the approach to deploy cooperative driving methods when one, two, or three out of the four links at an intersection are CAV dedicated links. Below, we will first introduce the phase settings of intersections in *Section V-A*. Second, we will take an intersection with three dedicated links as an example to present the implementation details of the novel management approach in *Section V-B*.

A. Phase Settings of Intersections Under Dedicated Link Strategy

When one, two, or three out of the four links at an intersection are CAV dedicated links, it means that the remaining links are normal links with mixed traffic flow consisting of CAVs and HDVs. Consequently, the signal-free cooperative driving method cannot be directly applied at this intersection. Inspired by the phase setting in traditional traffic signal control strategies, we design the following phase settings to achieve cooperative driving of CAVs on the dedicated links. The core principle is to assign a single phase for all CAVs on dedicated links, enabling them to use cooperative driving to efficiently pass through the intersection. Meanwhile, each normal link is assigned a separate phase. The sequential activation of different phases not only enables CAVs to unleash two-dimensional benefits through cooperative driving, but also allows mixed traffic flows on normal links, especially HDVs, to pass through intersections independently and safely.

Based on the above principles, the phase settings for intersections under the dedicated link strategy vary depending on the number of dedicated links at each intersection. These phase settings are outlined below:

1) Intersection With 0 or 1 CAV Dedicated Links: When there are either no CAV dedicated links or only one CAV dedicated link, a four-phase traffic signal scheme is employed. In this scheme, each phase corresponds to the release of vehicles on a single link, as illustrated in Fig. 4(*a*).

2) Intersection With 2 CAV Dedicated Links: In the case where two links are designated as dedicated links, a three-phase traffic signal scheme is implemented, as illustrated in Fig. 4(*b*). In this scheme, Phase 1 consists of two dedicated links exclusively for CAVs. Consequently, in Phase 1, the CAVs on the two dedicated links can use the cooperative driving method to pass through the intersection efficiently. On the other hand, Phase 2 and Phase 3 correspond to two normal links with mixed traffic flow, each of which is assigned a separate phase.

3) Intersection With 3 CAV Dedicated Links: In the case where three links are designated as dedicated links, a two-phase traffic signal scheme is implemented, as illustrated in Fig. 4(*c*). In this scheme, Phase 1 consists of three dedicated links exclusively for CAVs. During Phase 1, CAVs on the three dedicated links pass through the intersection efficiently by using the cooperative driving method. Phase 2 corresponds to the normal link with mixed traffic flow and thus is assigned a separate phase.

4) Intersection With 4 CAV Dedicated Links: In cases where all four links are designated as dedicated links, the cooperative driving method can be fully deployed. At this case, intersections operate without the need for traffic signals to differentiate between phases, thus achieving signal-free intersection management, as illustrated in Fig. 4(*d*). From a road network perspective, this implies that the intersection has transformed into a dedicated intersection exclusively for CAVs.

B. Intersection With Three CAV Dedicated Links

In this section, we take the intersection with three dedicated links as an example to illustrate the implementation details of the emerging intersection management approach. According to the above phase settings, this intersection is configured with a two-phase signal scheme, as illustrated in Fig. 5. During Phase 1, CAVs on the three dedicated links pass through the conflict zone based on the passing orders and motion trajectories determined by the cooperative driving method, while the mixed traffic flow on normal links stops and waits. At the transition from Phase 1 to Phase 2, CAVs on the three dedicated links come to a halt, while the mixed traffic on the normal link starts to cross the intersection. Phases 1 and 2 are activated sequentially to ensure both efficient cooperative driving of CAVs and the safe passage of the mixed traffic through the intersection.

With the above phase settings, there are three key issues for the novel intersection management approach: (*1*) the traffic signal timing problem between Phase 1 and Phase 2; (*2*) the cooperative driving of CAVs on the three dedicated links in Phase 1; and (*3*) trajectory planning of CAVs on the normal link in Phase 2. The following sections introduce the methods for addressing these issues.

1) Traffic Signal Timing Problem: Similar to the conventional four-phase traffic signal strategy, this intersection operates under a two-phase signal control system. In this study, we improve the max-pressure based traffic signal timing method [64], [65] to address the emerging two-phase timing method. Max-pressure traffic control is fundamentally a phase selection algorithm that dynamically selects phases based on real-time traffic conditions. Due to its stability, adaptability, and distributed properties, max-pressure based traffic signal timing methods have been widely studied and applied [64], [65], [66]. Specifically, we define the pressure of Phase 1 as the maximum difference between the number of vehicles queuing on the three dedicated links and the number of vehicles queuing on the corresponding downstream links:

$$P_{\text{Phase 1}} = \max\left\{Q_1^{DL}, Q_2^{DL}, Q_3^{DL}\right\} \tag{5}$$

where $Q_i^{DL}(i = 1, 2, 3)$ is the difference between the number of vehicles queuing on the i-th dedicated link and the number of vehicles queuing on the corresponding downstream link. The link index is illustrated in Fig. 5. The pressure of Phase 2 is defined as the difference between the number of vehicles queuing on the normal link and the number of vehicles queuing on its downstream link, denoted as $P_{\text{Phase 2}} = Q_4$. During phase switching, the phase with the maximum pressure is assigned a "green" signal, while the other phases are assigned a "red" signal. Specifically, the current phase is compared with the phase with the maximum pressure. If the current phase remains the one with the maximum pressure, its duration is extended. Otherwise, if the current phase differs from the phase with the maximum pressure, it is switched to the phase corresponding to the maximum pressure. For other intersections with different phases presented in *Section V-A*, the max-pressure based signal timing method can be implemented similarly.

2) Cooperative Driving of CAVs on the Dedicated Links: A bi-level framework is employed to address the cooperative driving problem of CAVs on the three dedicated links. At the upper level, a centralized algorithm assigns the right-of-way of the conflict zone to the CAVs, while at the lower level, a distributed trajectory planning algorithm generates the motions of CAVs based on the output of the upper level. The output of the upper level is typically represented as a sequence of CAV indexes known as the passing order [21], [44], as depicted in Fig. 5. Notably, previous research has demonstrated that the passing order plays a dominant impact on the efficiency of the intersection system [30], [67]. Therefore, this paper focuses on resolving the passing order of CAVs on the three dedicated links.

In general, the right-of-way assignment is intended to optimize traffic efficiency by considering the delay of all vehicles passing through the intersection [21], [68]. Therefore, we take the delay of CAVs on the three dedicated links passing through the intersection as the optimization objective. Thus, if when there are m CAVs on the three dedicated links, the optimization problem can be formulated as follows:

$$\min_{t_{\text{assign},i}, b_{i,j}} \quad J = \sum_{i=1}^{m} (t_{\text{assign},i} - t_{\min,i}) \tag{6}$$

$$\text{s.t.} \quad t_{\text{assign},i} \geq t_{\min,i}, \quad i = 1, \cdots, m \tag{6a}$$

$$t_{\text{assign},i} - t_{\text{assign},p_i} \geq \Delta t_1, \quad i = 1, \cdots, m \tag{6b}$$

$$t_{\text{assign},i} - t_{\text{assign},j} + C \cdot b_{i,j} \geq \Delta t_2 \tag{6c}$$

$$t_{\text{assign},j} - t_{\text{assign},i} + C \cdot \left(1 - b_{i,j}\right) \geq \Delta t_2 \tag{6d}$$

$$b_{i,j} \in \{0, 1\}, \quad i, j = 1, \cdots, m \tag{6e}$$

where $t_{\text{assign},i}$ and $b_{i,j}$ are decision variables. $t_{\text{assign},i}$ is the assigned arrival time for *CAV i* to enter the conflict zone and $t_{\min,i}$ is the minimum arrival time. $b_{i,j} = 1$ means that *CAV i* has higher priority than *CAV j*; on the contrary, $b_{i,j} = 0$ means that *CAV j* has higher priority than *CAV i*. The constraints (6b) are the safety rear-end constraints for CAVs in the same lane, where t_{assign,p_i} is the assigned time for the preceding vehicle of *CAV i* and Δt_1 is the safety time headway between two CAVs in the same lane. The constraint (6c) and (6d) are safety lateral

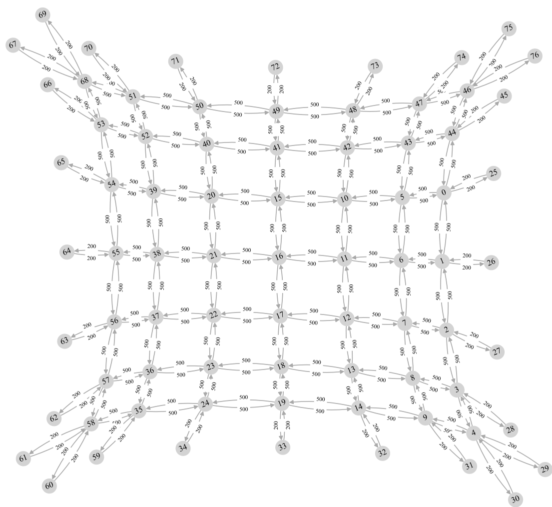

Fig. 6. The road network with a size of 7×7, where the number on the link is the length of the road segment, and the number on the node is its index name.

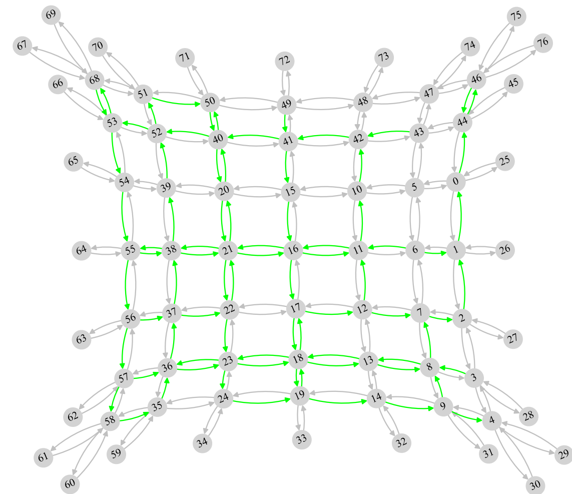

Fig. 7. The dedicated link deployment scheme, where the green links are set as CAV dedicated links, and the remaining links are normal links. The CAV penetration rate is 50%.

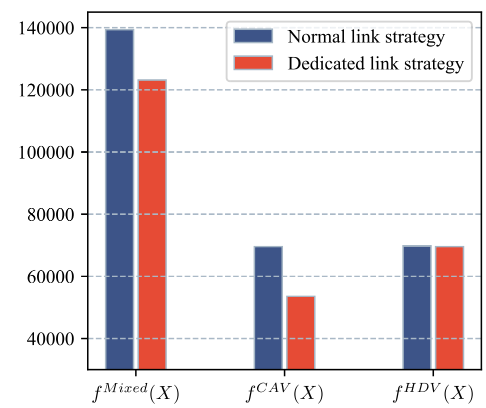

Fig. 8. The efficiency performance of vehicles under the dedicated link strategy and the normal link strategy. The normal link strategy refers to the scheme that does not set up any dedicated links. The performance metrics are defined in equations (7)-(9), the same below.

constraints for *CAV* i and j which have conflicting right-of-way, where Δt_2 is the safety time headway between two vehicles. C is a sufficiently large number. Different passing orders have different delays and our objective is to determine the passing order that minimizes delay. However, solving the optimal passing order is known to be an *NP*-hard problem [21], [45]. Considering the real-time requirement of traffic scenarios, it is not feasible to find the optimal passing order within the commonly used calculation time budget of $0.1s$ [45], [69]. Consequently, researchers have proposed various algorithms specifically designed to identify a better passing order in a limited time budget. In this paper, we employ the Monte Carlo tree search (MCTS) based algorithm [45] to solve the passing order since it has exhibited superior performance in comparative experiments [30], [69]. The MCTS based cooperative driving algorithm combines MCTS and some heuristic rules to guide the search process to traverse as many promising orders as possible in a limited time budget, which can search for a near-optimal passing order. Interested readers can refer to [21], [45], and [46] for more details regarding the implementation of signal-free cooperative driving method at intersections.

3) Trajectory Planning of CAVs on the Normal Links: On the normal links, CAVs coexist with HDVs. However, HDVs are unable to communicate and their driving behaviors often have unpredictable randomness. For this purpose, we use the typical eco-driving trajectory planning method to plan the trajectories of CAVs on normal links. Eco-driving is a classical vehicle trajectory planning method at signalized intersections. It is known for its ability to enhance driving comfort and reduce energy consumption, and has found extensive application in addressing the trajectory planning problem of CAVs in mixed traffic environments [70], [71], [72], [73]. Specifically, in this paper, we adopt the eco-driving trajectory optimization model introduced in [70]. The model employs model predictive control (MPC) to optimize the velocities of the CAVs based on the state of the preceding vehicles and the signal information of the intersection. The model assumes that the state of the preceding vehicle is collected by the onboard sensors of CAVs, while the signal information is obtained via vehicle-to-infrastructure communication technology. The objective function of the mode is the weighting of travel time, fuel efficiency, and driving comfort. Considering the length of the paper, interested readers can refer to the paper [70] for more details.

VI. Experiments

In this section, we verify the performance of the dedicated link strategy through two types of numerical experiments. First, in *Section VI-A*, we solve the dedicated link deployment scheme for a road network with a shape of 7×7, demonstrating the performance of the artificial bee colony based dedicated link algorithm and the performance compared to the normal link strategy. Second, in *Section VI-B*, we conduct microscopic traffic simulation experiments on a 3×3 road network to further verify the effectiveness of the dedicated link strategy and analyze its characteristics.

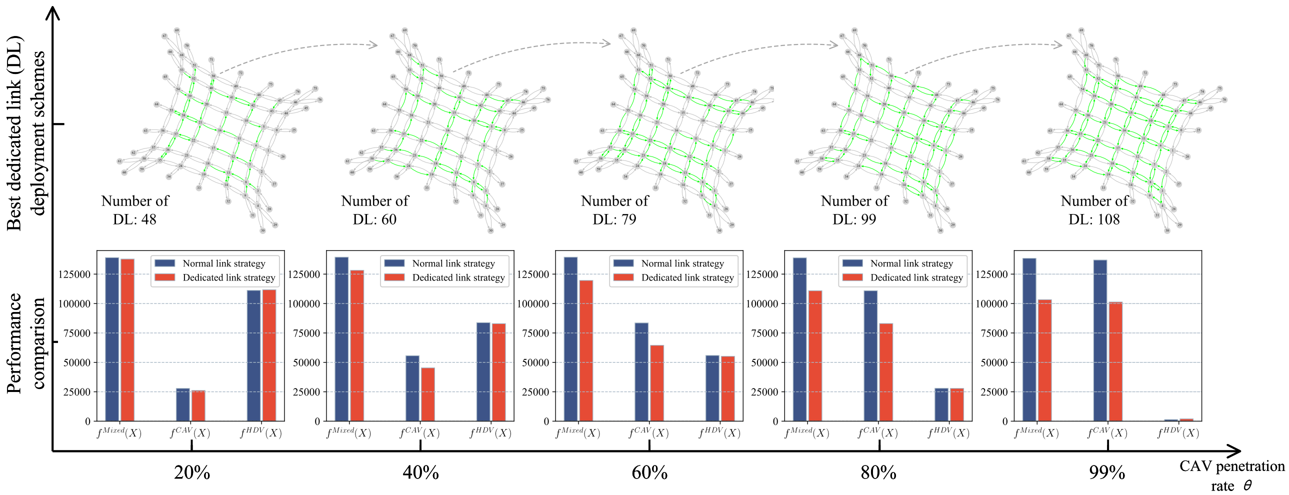

Fig. 9. The dedicated link deployment under different CAV penetration rates. The upper subfigures are the deployment schemes, where the green links are dedicated links. The lower subfigures are the corresponding performance comparison. DL is the abbreviation of dedicated link.

TABLE I
OD PAIRS AND THE CORRESPONDING TRAFFIC DEMANDS

(O, D)	Demand	(O, D)	Demand	(O, D)	Demand
(76, 61)	350*	(61, 76)	270	(45, 62)	300
(25, 63)	350	(63, 25)	320	(26, 64)	230
(27, 65)	330	(65, 27)	390	(28, 66)	320
(29, 67)	320	(67, 29)	350	(59, 74)	330
(60, 75)	330	(74, 59)	340	(34, 73)	390
(33, 72)	450	(72, 33)	360	(32, 71)	450
(31, 70)	490	(70, 31)	300	(30, 69)	400
(69, 59)	200	(70, 34)	200	(71, 33)	210
(74, 30)	120	(75, 30)	100	(76, 65)	170
(25, 63)	200	(25, 62)	130	(26, 66)	110
(28, 64)	100	(29, 61)	200	(33, 72)	100
(62, 45)	220	(64, 26)	340	(66, 28)	210
(66, 28)	210	(73, 34)	310	(71, 32)	340
(69, 30)	300	(72, 32)	230	(45, 64)	190
(27, 67)	135	(64, 26)	200		

*Unit: $veh/(h * lane)$.

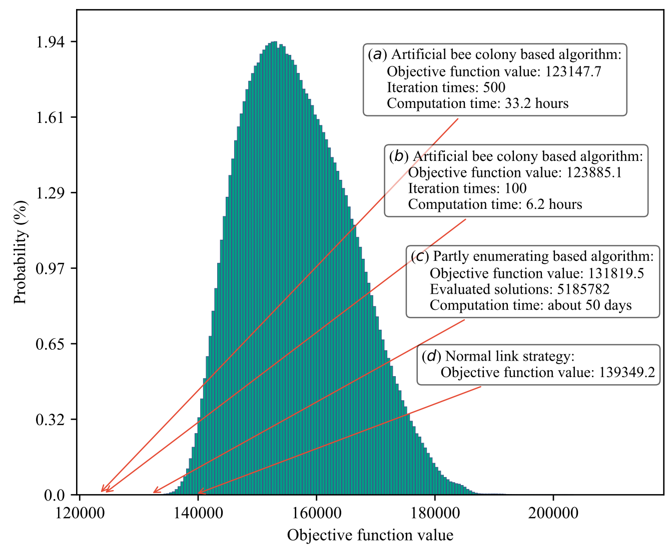

Fig. 10. The histogram of the objective function value for approximately 5 million dedicated link deployment solutions randomly sampled. The arrows refer to (a, b) the solution found by 500 and 100 iterations of the artificial bee colony based algorithm; (c) the best solution found by the partly enumerating based algorithm; (d) the solution corresponding to the normal link strategy.

A. Artificial Bee Colony Based Dedicated Link Deployment Solving

We verify the effectiveness of the proposed artificial bee colony based algorithm for solving the dedicated link deployment scheme on a 7×7 road network, as shown in Fig. 6. In the 7×7 road network, there are a total of 168 links that can be set up as dedicated links. Consequently, the dedicated link deployment problem involves 168 decision variables, resulting in a solution space of size $2^{168} \approx 3.73 * 10^{50}$. In subsequent experiments, the penetration rate is set to $\theta^w = 50\% (w \in W)$ when unspecified. The default traffic demand is shown in Table I. Each link has two lanes. For the artificial bee colony based dedicated link algorithm, we set the bee colony size $L = 300$. In the following, we will show the properties of the dedicated link strategy and the performance of the artificial bee colony based algorithm from three aspects.

1) Case Study: We solve the dedicated link deployment scheme with 50% penetration rate by employing the proposed artificial bee colony based algorithm, and the results are shown in Fig. 7. The deployment scheme shows that a total of 77 links (accounting for 45.8% out of 168) are designated as CAV dedicated links. Specifically, in terms of intersections, there are 18 intersections with one dedicated link, 15 intersections with two dedicated links, 7 intersections with three dedicated links, and 2 intersections with four dedicated links. The results demonstrate that the dedicated link strategy not only takes advantage of the one-dimensional benefits of CAVs through isolated dedicated links but also unleashs the two-dimensional benefits of CAVs at the intersections by setting $2-4$ ded-

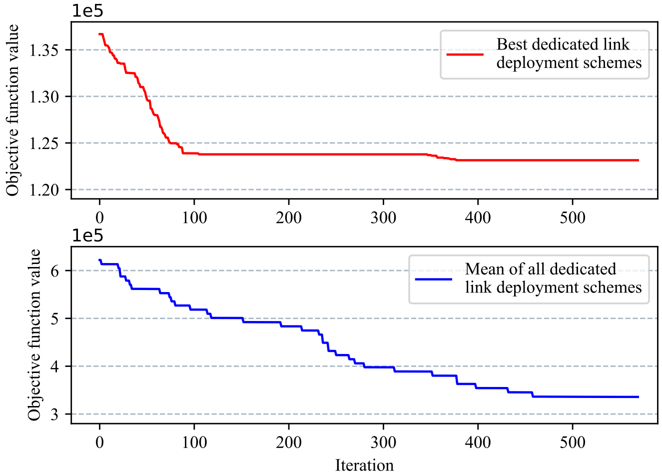

Fig. 11. The convergence process of the artificial bee colony based algorithm, where the upper sub-figure is the performance of the best dedicated link deployment scheme during the search process, and the lower sub-figure is the mean performance of all dedicated link deployment schemes for the entire bee colony.

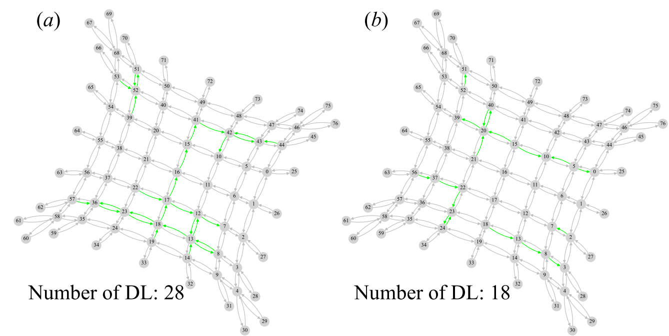

Fig. 12. The dedicated link deployment schemes under low CAV penetration rate. (*a*) The CAV penetration rate is 10%; (*b*) The CAV penetration rate is 5%. DL is the abbreviation of dedicated link.

icated links, thereby enhancing the overall efficiency of the network-wide mixed traffic system.

Moreover, the results depicted in Fig. 7 demonstrate that the dedicated link strategy exhibits a prominent characteristic of sequentially establishing multiple dedicated links along the connected routes, creating an effect comparable to that of a CAV dedicated route. This attribute offers opportunities for further exploiting the one-dimensional benefits of CAVs within mixed traffic flow.

Furthermore, the performance comparison between the dedicated link strategy and the conventional normal link strategy is illustrated in Fig. 8. The normal link strategy refers to a scheme that does not establish any dedicated right-of-way. Similar to Eq.1, we define the following metrics for evaluating the efficiency performance of the overall mixed traffic system within the road network (the same below), as follows:

$$f^{\text{Mixed}}(X) = \sum_{(i,j)\in A} v_{ij} t_{ij} \tag{7}$$

$$f^{\text{CAV}}(X) = \sum_{(i,j)\in A} v_{ij}^{CAV} t_{ij} \tag{8}$$

$$f^{\text{HDV}}(X) = \sum_{(i,j)\in A} v_{ij}^{HDV} t_{ij} \tag{9}$$

where v_{ij}^{CAV} is the CAV traffic flow on link $(i, j) \in A$ and v_{ij}^{HDV} is the HDV traffic flow on link $(i, j) \in A$. t_{ij} is the travel time cost of link $(i, j) \in A$, which is derived from the BPR function and the road flow capacity model considering CAV penetration parameters, and interested readers can refer to [47], [48], and [49]. The results indicate that compared to the normal link strategy, the proposed dedicated link strategy enhances the efficiency of the entire mixed traffic system. Among them, the efficiency of CAVs shows a significant improvement. Although the setting of the dedicated links may restrict the selection of travel routes for HDVs, the results in Fig. 8 demonstrate that the efficiency of HDVs is basically not affected and is equivalent to the performance under the normal link strategy.

2) Dedicated Link Strategy Under Different Penetration Rates: We solve the dedicated link deployment schemes under different penetration rates, and the results are shown in Fig. 9. The results show that as the penetration rate increases, the number of dedicated links in the road network will gradually increase. For example, when the CAV penetration rate is 20%, a total of 48 links are set up as CAV dedicated links. When the CAV penetration rate is 80%, 99 links are set up as CAV dedicated links. Meanwhile, the results also show that even at high penetration rates, the dedicated link strategy still preserves feasible routes for HDVs. At 99% penetration rate, a total of 108 links are set up as dedicated links while the remaining 60 links are normal.

Moreover, the performance comparison results demonstrate that the dedicated link strategy enhances the efficiency of the mixed traffic system across all penetration rates, and the improvement becomes more significant as the penetration rate increases. Especially, the travel efficiency of CAVs has been significantly improved without weakening the efficiency of HDVs.

3) Performance of Artificial Bee Colony Based Dedicated Link Algorithm: In order to demonstrate the performance of the artificial bee colony based dedicated link algorithm, a comparison is made between the objective function values of different deployment schemes, as illustrated in Fig. 10. Due to the huge solution space and the impracticality of complete enumeration, we spend 50 days randomly sampling about 5 million enforceable deployment schemes (called partly enumerating based algorithm) within the solution space, and their histogram distribution is displayed in Fig. 10. The results indicate that the solution found by the artificial bee colony based algorithm outperforms both the normal link strategy and even the best solution found by the partly enumerating based algorithm. The solution solved by the artificial bee colony based algorithm in 100 iteration steps (taking about 6.2 hours) has a 6.02% performance improvement over the solution found by the partly enumerating based algorithm (taking about 50 days) and has a 11.10% performance improvement over the solution corresponding to the normal link strategy. Furthermore, the histogram distribution of the solution space reveals that the deployment scheme solved by the artificial

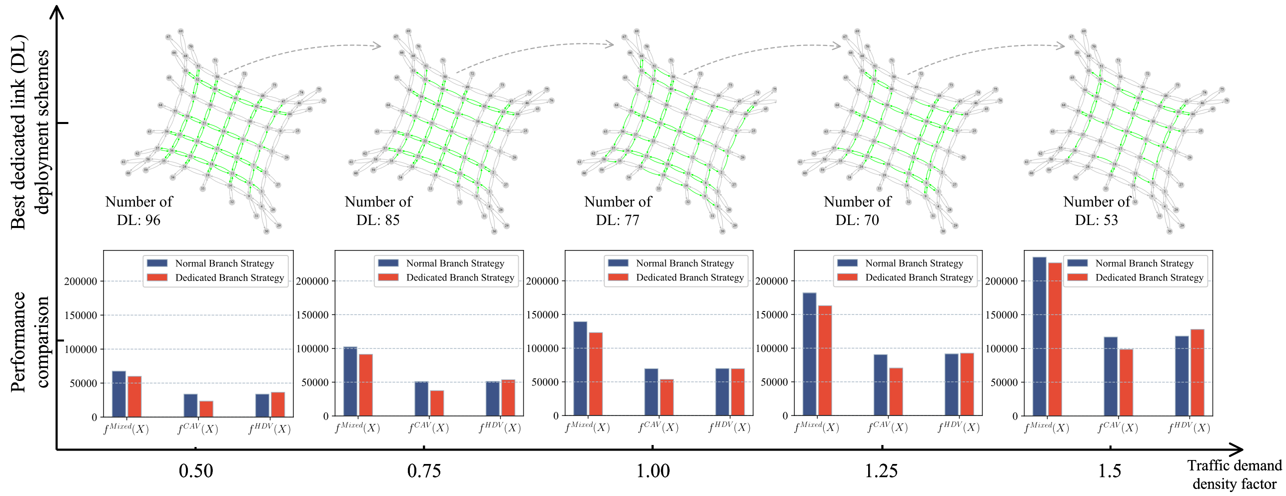

Fig. 13. The dedicated link deployment schemes under different traffic densities. The upper subfigures are the deployment schemes, where the green links are dedicated links. The lower subfigures are the corresponding performance comparison. DL is the abbreviation of dedicated link.

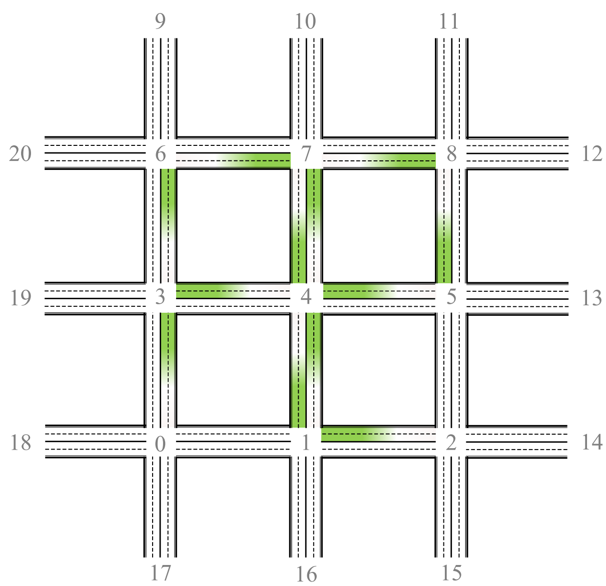

Fig. 14. The road network used for microscopic traffic simulation, where the green links are set to CAV dedicated links. Intersection 4 has three dedicated links, therefore a two-phase traffic signal scheme is deployed; Intersections 1, 3, and 7 have two dedicated links, thus deploying a three-phase traffic signal scheme. The rest intersections are deployed with conventional four-phase traffic signal scheme.

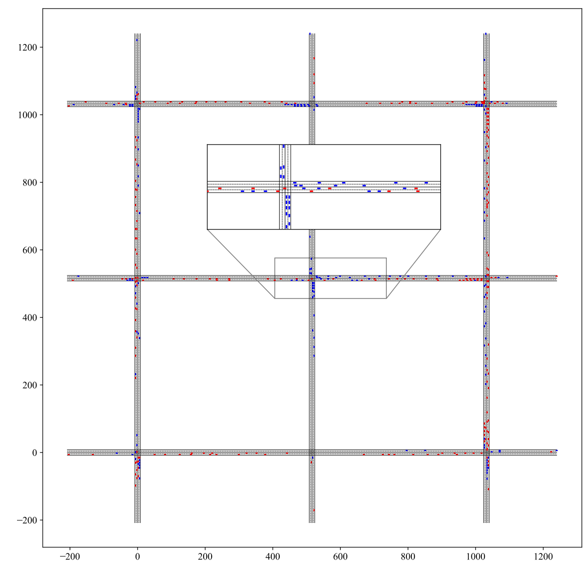

Fig. 15. Snapshot of the microscopic traffic simulation under the dedicated link strategy. The blue vehicles are connected and automated vehicles (CAVS) and the red vehicles are human-driven vehicles (HDVs).

bee colony based algorithm has a significantly low probability within the solution space, which further verifies the superiority of the algorithm.

Moreover, we present the search process of the artificial bee colony based algorithm in Fig. 11. The results show that the proposed artificial bee colony based algorithm can find deployment schemes that are closer to the convergence solution in fewer iterations (100 iterations). This makes it efficient in addressing the NP-hard problem of dedicated link deployment, as it can find a near-optimal deployment scheme within a reasonable time.

4) Deployment Scheme Under Low Penetration Rate: Here, we further solved the dedicated link deployment schemes under lower CAV penetration rates, as illustrated in Fig. 12. The results show that at a CAV penetration rate of 10%, 28 links are deployed as dedicated links, accounting for 16.7% of the total links. While at 5% penetration, only 18 links are deployed as dedicated links, accounting for only 10.7%. That is, in mixed traffic systems with low CAV penetration rates, the number of dedicated links is relatively small. This is reasonable because setting up dedicated links at low penetration rates will negatively affect the overall performance of the mixed traffic system. Therefore, when the penetration rate is low, the proposed algorithm tends to set few dedicated links in the road network.

5) Effect of Traffic Density: To further evaluate the performance of the proposed dedicated link strategy, we solved the dedicated link deployment schemes under different traffic densities. Here, we take the traffic demand listed in Table I

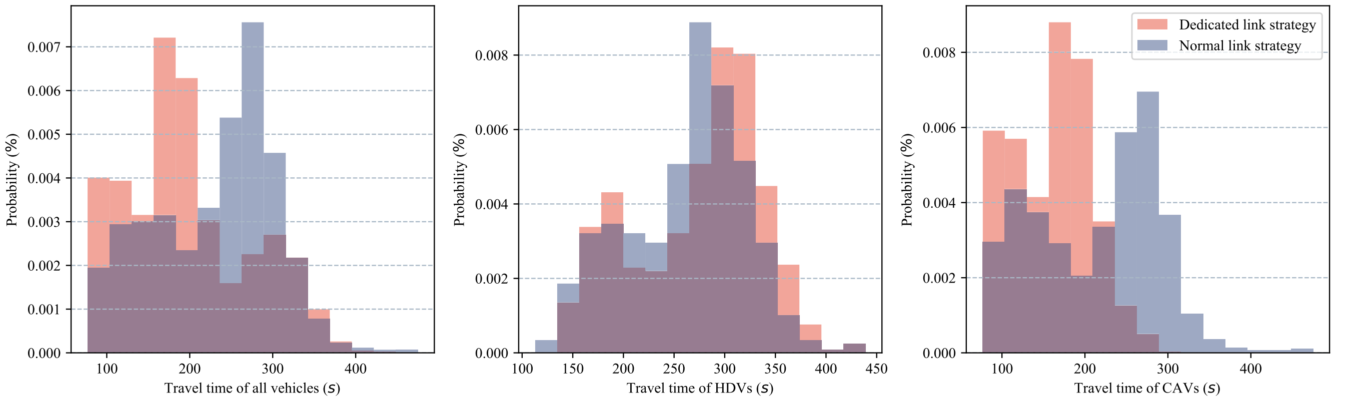

Fig. 16. Distribution of the travel time under the dedicated link strategy and the normal link strategy. (*Left*) All vehicles; (*Middle*) HDVs; (*Right*) CAVs.

as a basis and then scale the traffic demand using a density factor, which ensures that the heterogeneity of traffic demand between different densities is similar. For example, a factor of 1.5 indicates that the traffic demand is the demand in Table I multiplied by 1.5. The rest are similar. The CAV penetration rate is 50%. For different traffic densities, we solved the corresponding dedicated link deployment schemes and the corresponding performance comparisons, and the results are shown in Fig. 13.

The results show that the proposed dedicated link strategy can improve the efficiency of the mixed traffic system under any traffic conditions by adaptively solving the corresponding dedicated link deployment schemes. Moreover, there are differences in the dedicated link deployment scheme under different traffic densities. The number of dedicated links decreases as traffic density increases. At a density factor of 0.5, 96 links are set up as dedicated links (accounting for 57.1% of the total links), while at a density factor of 1.5, only 53 links are set up as dedicated links (accounting for 31.5% of the total links). From the performance comparison shown in the bottom subfigures of Fig. 13, it can be seen that the main reason is that the proposed deployment algorithm can adaptively balance the benefits for CAVs and the adverse effects on HDVs. At lower traffic densities, there are fewer vehicles in the road network. Concentrating HDVs on a portion of the links has a modest impact on their travel efficiency, so more links can be set as dedicated links. On the contrary, at higher traffic densities, the traffic flow in the road network is relatively congested. The deployment of dedicated links has an increased adverse impact on HDVs, so the number of dedicated links in the solved deployment schemes decreases.

B. Performance Evaluation via Microscopic Traffic Simulation

In this section, we perform microscopic traffic simulation experiments using the CAVSim simulator [74], [75] to further evaluate the performance of the dedicated link strategy. The road network employed in the experiments is a network with a shape of 3 × 3, as shown in Fig. 14. With the artificial bee colony based dedicated link algorithm, we solve the corresponding dedicated link deployment scheme, represented by the green links in Fig. 14. Considering the characteristics

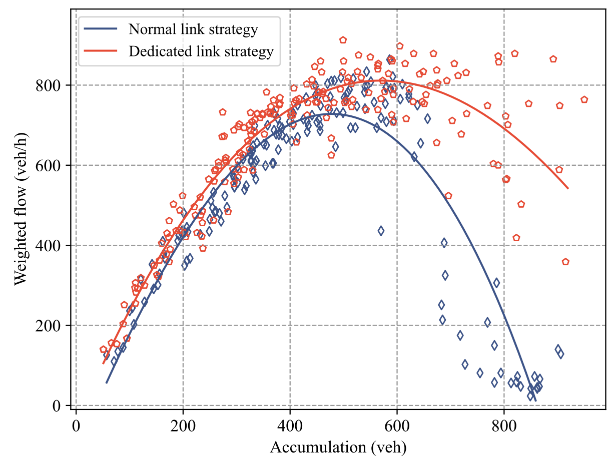

Fig. 17. Macroscopic fundamental diagram (MFD) results of the network traffic under the dedicated link strategy and the normal link strategy.

of cooperative driving, we set up a range centered on the intersection with a radius of 200 meters and the vehicles within this range are considered to have arrived at the intersection and are used to calculate the pressure of the traffic signal phase. The pressure values of links are updated every 2 seconds and the max-pressure traffic signal control strategy is set with a minimum green signal time of 15 seconds. The classic intelligent driver model (IDM) model [76], [77] is used for HDVs, while a modified IDM model proposed in [78] is used for CAVs, see related literature [1], [74] for more details. A snapshot of the microscopic traffic simulation is depicted in Fig. 15. To provide a benchmark, we compared the proposed dedicated link strategy with the normal link strategy. Based on the simulation results, the following metrics are analyzed for the local mixed traffic system: (*1*) vehicle travel time distribution, (*2*) macroscopic fundamental diagram (MFD), and (*3*) the vehicle trajectories at local intersections under different strategies. The results are as follows.

1) Travel Time Distribution: First, we analyze the distribution of travel time for individual vehicles, and the corresponding results are depicted in Fig. 16. Travel time serves as a performance metric to evaluate the effectiveness of the network-wide management approach for individual vehi-

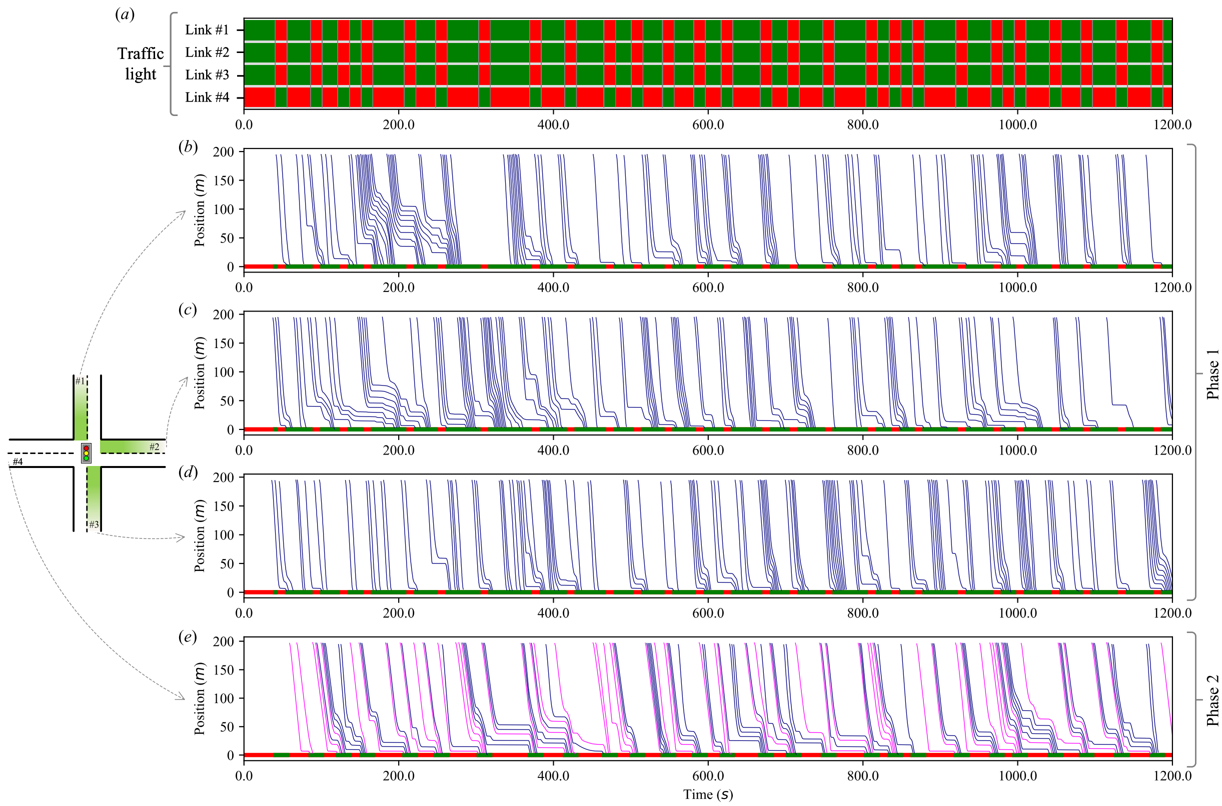

Fig. 18. Vehicle trajectories under the dedicated link strategy. The intersection has 3 dedicated links (corresponding to Intersection 4 in Fig. 14) and the traffic signal is the proposed two-phase management scheme. (*a*) Traffic signals for different links. (*b*)∼(*e*) Trajectories on Link #1 ∼ #4. The blue trajectories are for CAVs. The red trajectories are for HDVs.

cles. The results demonstrate that the implementation of the dedicated link strategy can reduce the travel time of vehicles within the mixed traffic system, as illustrated in Fig. 16(*Left*). Among them, Fig. 16(*Right*) shows that the travel time of CAVs is significantly reduced. Fig. 16(*Middle*) indicates that the travel time of HDVs is roughly consistent with the normal link strategy. This finding aligns with the experimental results presented in *Section VI-A*.

2) Macroscopic Fundamental Diagram (MFD): Second, we count the MFD results of the microscopic traffic simulation under different strategies, as shown in Fig 17. The MFD provides a comprehensive evaluation of the strategy's performance under different traffic conditions and serves as a powerful tool for evaluating the impact of the microscopic driving behavior of vehicles on the macroscopic network-wide traffic system [30], [79]. The results demonstrate that the dedicated link strategy significantly enhances the overall efficiency of the network-wide mixed traffic system. Under the same traffic density, the dedicated link strategy can improve the traffic flow. The benefits of the dedicated link strategy become evident at medium and high traffic densities, resulting in considerable improvements in traffic flow and overall network-wide traffic efficiency. This can be attributed to two factors. On the one hand, the dedicated rights-of-way effectively separate CAVs from mixed traffic, thereby reducing the disruption caused by HDVs to CAVs. On the other hand, the novel intersection management approach reduces the time consumption of CAVs when passing through intersections, and thus the traffic efficiency is improved at microscopic intersections, which subsequently enhances the network-wide efficiency of the mixed traffic system.

3) Further Look Into the Dedicated Link Strategy: Finally, we analyze the vehicle trajectories at the local intersection to further demonstrate the benefits associated with the dedicated link strategy. As shown in Fig. 18 and Fig. 19, we have drawn the trajectories of the intermediate intersection presented in Fig. 14, under the dedicated link strategy and the normal link strategy. Under the dedicated link strategy, the intersection has two phases (corresponding to Phase 1 and Phase 2 in Fig. 5). Conversely, under the normal link strategy, the intersection comprises four phases.

The vehicle trajectories depicted in Fig. 18 and Fig. 19 demonstrate that under the dedicated link strategy, the trajectories are smoother and there are fewer blocking waves. On the contrary, under the normal link strategy, i.e., the four-phase traffic signals, there will be a lot of blocking waves, which reduces traffic efficiency. The reason for this is the two-dimensional benefits that cooperative driving methods bring to CAVs. By coordinating CAVs on multiple dedicated links, conflicts are eliminated, enabling them to pass through the conflict zone in the same phase. Consequently, this approach minimizes the need for vehicles to wait in queues at intersections, thereby improving traffic efficiency of microscopic intersections.

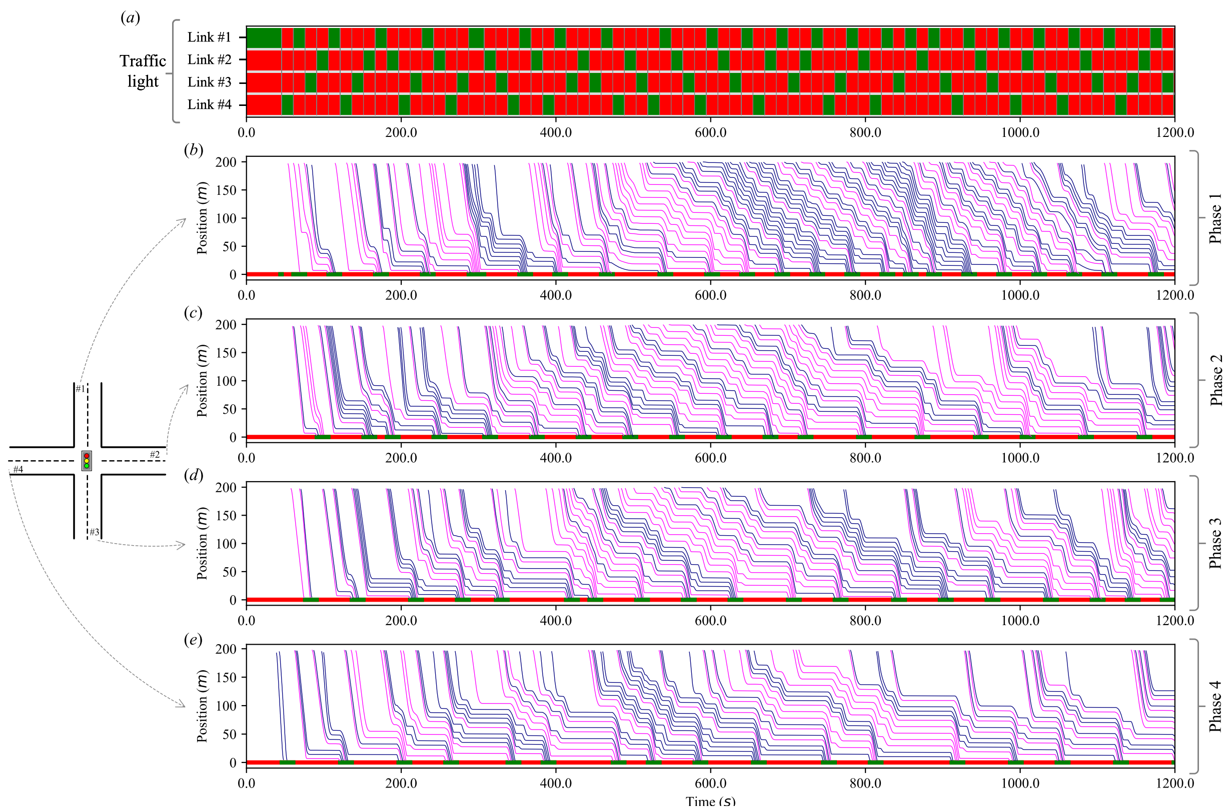

Fig. 19. Vehicle trajectories under the normal link strategy. The traffic signal is the traditional four-phase management scheme. (a) Traffic signals for different links. (b)∼(e) Trajectories on Link #1 ∼ #4. The blue trajectories are for CAVs. The red trajectories are for HDVs.

VII. Conclusion

In this paper, we introduce a novel dedicated link strategy for the management of the network-wide mixed traffic system. By separating CAVs from mixed traffic, the dedicated link strategy can not only promote the deployment of CAV technologies but also fully unleash the benefits of CAVs. Specifically, at the macroscopic road network level, the core of the dedicated link strategy is the deployment of dedicated links. To achieve this, we propose a bi-level dedicated link deployment model, along with an artificial bee colony based dedicated link algorithm. The proposed algorithm can find near-optimal dedicated link deployment schemes within a reasonable time. As for the microscopic intersection level, we introduce an innovative management approach for intersections under the dedicated link strategy. This approach integrates traditional traffic signal control strategy with the signal-free cooperative driving method, thereby fully unlocking the potential of two-dimensional benefits associated with CAVs and enhancing the efficiency of intersections. Numerical experiments demonstrate that macroscopic and microscopic methods complement each other, and the dedicated link strategy yields substantial improvements in the overall efficiency of the mixed traffic system.

This paper introduces the concept and roadmap of the dedicated link strategy, as well as the intersection management approach that integrates the traditional traffic signal control strategy with the signal-free cooperative driving method. Although we use the common implementation methods, the experiments have demonstrated the performance superiority of this strategy. As a new mixed traffic management strategy, we believe that improving deployment methods will further enhance the performance of the dedicated link strategy. In future work, we will further investigate the following key issues. First, the current dedicated link deployment is static. In order to improve the flexibility and timely response of the strategy, future work will focus on proposing a dynamic dedicated link deployment approach that adapts to real-time traffic conditions. Second, the dedicated link deployment problem is an NP-hard problem with a huge solution space, and we will work on proposing better algorithms for solving the dedicated link deployment scheme in order to improve the optimality of the solution. Third, we will further improve the emerging intersection management approach, especially the traffic signal timing problem under the emerging phase settings, aiming to achieve seamless integration between traffic signal strategies and signal-free cooperative driving methods.

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