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Research Article

Signal-Vehicle Coordination Control Modeling and Roadside Unit Deployment Evaluation under V2I Communication Environment

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Signal-vehicle coordinated control holds substantial promise for enhancing urban transportation efficiency. However, its development faces notable challenges: (1) most existing studies have been conducted based on the assumption of perfect communication conditions. This assumption overlooks the significant impact of vehicle-to-infrastructure (V2I) communication quality on control performance, which leads to poor applicability in practice. (2) The evaluation of roadside unit (RSU) deployment for optimizing signal-vehicle control has not been well studied. Hence, the modeling of signal-vehicle coordination control and RSU deployment evaluation under V2I environment are studied in this paper. First, we introduce a communication model that characterizes the imperfections in communication between RSUs and connected vehicles (CVs). Second, we propose a model for signal-vehicle coordination control within this connected environment. This model integrates strategies from both signal control optimization and the speed optimization of CV platoons. Finally, to assess the impact of the RSU deployment parameters on the performance of signal-vehicle coordination control, we introduce a systematic evaluation method. The reduction in vehicle delays is introduced as the evaluation indicator for control performance. Six other indicators—the number of vehicles in the RSU communication domain, connectivity probability between the CV and RSU, number of vehicles whose speeds are successfully optimized, number of speed adjustments, green extension time, and overlap rate of the communication domains of multiple RSUs—are introduced as the observation indicators. The simulation experiments verify the effectiveness of the proposed model in implementing signal-vehicle coordination control under imperfect communication and environments in low-traffic, medium-traffic, and high-traffic scenarios. Furthermore, these experiments show the quantitative impact of RSU deployment parameters (communication distance, command transmission cycle, installation position, and number of RSUs) on control performance.

1. Introduction

Emerging vehicle-to-everything (V2X) technologies are a promising approach to addressing urban transportation network congestion. Owing to the limited computing capability of on-board units and the time-varying characteristics of vehicles [1], vehicle-to-vehicle (V2V) communication is insufficient for traffic control. To enhance the reliability of connected control, V2I communication technology has been incorporated, creating an extensive V2X communication domain through RSU deployment. RSUs receive real-time data from CVs and the signal controller and upload them to multiaccess edge computing (MEC) devices to generate control strategies. This facilitates signal-vehicle coordination control with a broader scope and more cooperative elements. Therefore, the scientific and efficient implementation of signal-vehicle coordination control has become a popular topic.

Current signal-vehicle coordination control strategies primarily concentrate on optimizing traffic indicators. Their goals include minimizing traffic pollution [2–4], enhancing traffic flow safety performance [5–7], and maximizing transportation efficiency [8–11]. These strategies compensate for the limited data resources and control range of traditional signal control methods [12, 13]. In particular, the vehicle platooning is an effective way to improve traffic capacity and energy consumption [14, 15]. Platoons are employed as control objects in studies to develop control strategies. To minimize the total travel time of connected autonomous vehicles (CAVs), Ding et al. [16–18] introduced an optimal phase allocation and trajectory control method for CAV platoons, assuming instant interaction between all CAVs and the control center. Based on real-time and lossless communication conditions, Feng et al. [19, 20] proposed a signal-platoon coordinated control strategy to enhance intersection throughput. Chen et al. [21] developed a multiplatoon trajectory optimization approach to achieve safe, fuel-efficient, and efficient operations. In scenarios with low CV penetration rates, Li et al. [22–24] proposed a real-time predictive coordination method based on vehicle-triggered platoon dispersion to enhance control performance. However, these studies were conducted based on the assumption of perfect communication conditions between RSUs and CVs. The impacts of V2I communication conditions on signal-vehicle control performance have been ignored. For instance, factors such as the communication distance of RSUs and the connectivity probability between CVs and RSUs can affect the number of CVs that can participate in signal-vehicle control. Finkelberg et al. [25] experimentally demonstrated that realistic communication distortion conditions worsen the performance of traffic control. Neglecting the influence of imperfect communication conditions in these studies may limit their practical applicability.

Modeling an imperfect V2I communication environment is essential for signal-vehicle coordination control. In the V2I environment, RSUs play a pivotal role in gathering essential information from CVs and signal controllers, calculating control strategies, and delivering control commands [26]. Thus, further exploring the impacts of RSU deployment on signal-vehicle control performance is a meaningful topic.

To date, several studies have discussed the impact of RSU deployment on V2I communication quality, such as communication coverage [27], communication connectivity [28, 29], and communication delays [30, 31]. Liang et al. [32] presented an RSU deployment method to guarantee that V2I communication delays would remain below a threshold with the lowest cost. However, this method lacks applicability to emerging technologies that include 5G. Sankaranarayanan et al. [26] proposed a fusion algorithm-based optimal RSU distribution planner (ORDP). The ORDP is capable of constructing an objective function by selecting parameters such as RSU deployment cost, RSU transmission capacity, and communication coverage to meet the requirements of the scenario. However, it disregards the communication performance parameters including connectivity probability and transmission delay. Consequently, these studies fail to thoroughly analyze the effects of communication quality resulting from specific RSU deployments on control performance. Thus, these studies still cannot determine the impact mechanism of RSU deployment on signal-vehicle control performance.

Most RSU deployment studies have optimized deployment parameters for better perception of urban traffic flow. Barrachina et al. [33] formulated a density-based RSU deployment approach. Li et al. [34] established a model to investigate the relationship between RSU deployment, vehicle travel time, and traffic capacity. Olia et al. [35] proposed an RSU deployment optimization model to minimize RSU estimation errors for vehicle travel time. Salari et al. [36] developed a mathematical model to identify optimal RSU deployment for path flow reconstruction. However, few RSU deployment studies have explored the impact of deployment parameters on signal-vehicle control performance. Fang et al. [37] and Du et al. [38] noted that changes in RSU deployment can lead to communication disturbances affecting control performance, but a comprehensive theoretical and experimental analysis of these mechanisms is lacking. To address this gap, our study delves into the impact mechanism of RSU deployment parameters on signal-vehicle control performance.

In conclusion, the development of signal-vehicle coordination control encounters several challenges: (1) most existing studies assume ideal communication conditions between RSUs and CVs. The impacts of V2I communication conditions on signal-vehicle control performance are ignored in these studies, which limits practical applicability. (2) The evaluation of RSU deployment for signal-vehicle control optimization has not been well studied. Hence, this paper focuses on modeling signal-vehicle coordination control and evaluating RSU deployment under V2I environment.

The main contributions are summarized as follows:

(1) This article proposes a model of signal-vehicle coordination control under V2I communication environment. The model integrates strategies for both signal control optimization and speed optimization of the CV platoon, providing a comprehensive control strategy for multiple vehicles. Furthermore, it incorporates communication conditions such as connectivity probability and command transmission cycle to characterize the imperfect communication environment between RSUs and CVs. This approach challenges the prevailing assumption of perfect communication in most related studies.

(2) This article presents a method of evaluating the impacts of RSU deployment parameters on the performance of signal-vehicle coordination control. Comprehensive experiments quantitatively reveal the impact mechanism of the deployment parameters (communication distance, command transmission cycle, installation position, and number of RSUs) on the control performance.

2. Methodology

2.1. Overview. As shown in Figure 1, the research framework includes three modules: the communication model of RSU and CV platoons, the signal-vehicle coordination control strategy under a connected environment, and the method to

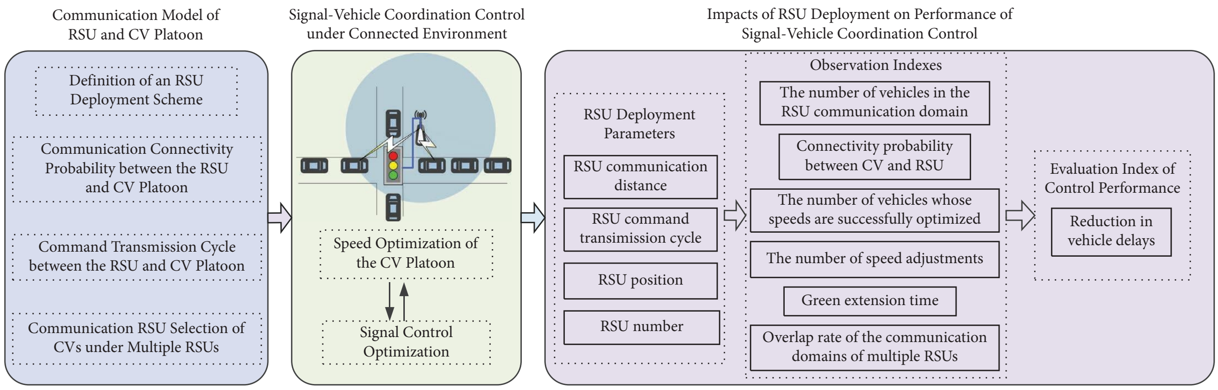


Figure 1: Overview.

evaluate the impacts of RSU deployment parameters on the performance of signal-vehicle coordination control. The function of the communication model is to develop an RSU deployment scheme, realize communication connection between the RSU and CV, and determine the command transmission cycle and the communication RSU selection of CVs under multiple RSUs. Based on the communication interactions of RSUs and CVs, a signal-vehicle coordination control strategy is formulated. The strategy includes the speed optimization of the CV platoon and the signal control optimization. In the third module, a method of evaluating the impacts of RSU deployment parameters on the performance of signal-vehicle coordination control is designed. The reduction in vehicle delays is used as the evaluation index of the control performance. Six other indicators—the number of vehicles in the RSU communication domain, connectivity probability between the CV and RSU, number of vehicles whose speeds are successfully optimized, number of speed adjustments, green extension time, and overlap rate of the communication domains of multiple RSUs—are employed as observation indicators. Simulation experiments under various RSU deployment parameters are conducted to demonstrate the impact mechanism of RSU deployment on the control performance.

The study scenario at an isolated signal intersection under V2I environment is shown in Figure 2.

Three assumptions are made in this paper.

(1) The communication between the RSU, the MEC server, and the signal controller is considered to be without transmission loss and delay. In addition, the signal controller executes the optimization strategy received from an RSU.

(2) All the vehicles are CVs, and all the vehicle members of a CV platoon are assumed to be within the communication range of the leading vehicle.

(3) Considering the CV platoon as a control unit, the complex behaviors between CV vehicles, such as decomposition and reorganization in the CV platoon, are not described. The RSU transmits information to the platoon's leading CV, and the following CVs always follow the commands from their preceding cars.

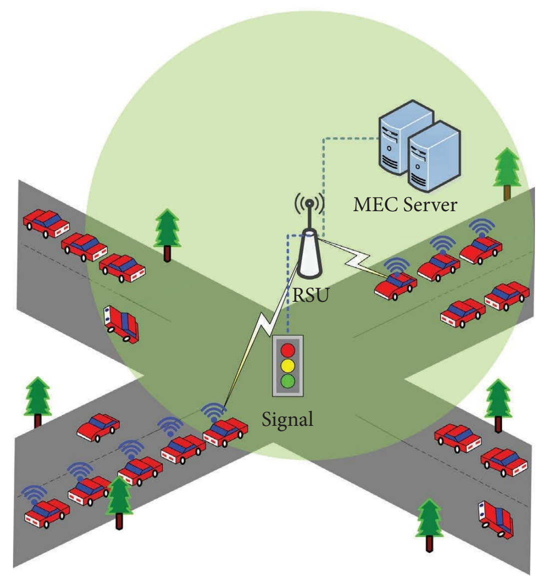


Figure 2: The study scenario at an isolated signal intersection under V2I environment.

2.2. Communication Model of the RSU and CV Platoon

2.2.1. Definition of an RSU Deployment Scheme. An RSU deployment scheme is defined as a quadruple $U = (D_{rsu}, T_{com}, X_{rsu}, N_{rsu})$, where D_{rsu} is the RSU communication distance, T_{com} is the RSU command transmission cycle, X_{rsu} is the RSU deployment position, and N_{rsu} is the RSU number.

The communication domain of an RSU is determined by its position and communication distance. Within the communication domain, an RSU can exchange information with CVs with a certain connectivity probability. The MEC server connected to the RSU subsequently generates a control strategy in response to the traffic flow and transmits it to the CVs in a regular cycle. Then, the communication topology between the RSU and the CV is updated.

2.2.2. Communication Connectivity Probability between the RSU and CV Platoon. The number of CVs and the number of RSUs are p and q, respectively. To establish a plane rectangular coordinate system, this paper sets the center of the intersection as the origin, east as the positive direction of the x-axis, and north as the positive direction of the y-axis. Let X_{rsu}^{j} represent the position of the RSU. D_{rsu}^{j} denotes the communication distance of RSU j, and X_{veh}^{i} represents the position of CV i. CVs interact with RSUs via shortwave communication.

$$d_{\text{vr}}^{\text{ij}} = \sqrt{X_{\text{veh}}^{i^2} + X_{\text{rsu}}^{j^2}}\,(i = 1, 2, \ldots p; j = 1, 2, \ldots q). \quad (1)$$

In equation (1), $d_{\text{vr}}^{\text{ij}}$ represents the distance between RSU j and CV i. If $d_{\text{vr}}^{\text{ij}} \leq D_{\text{rsu}}^{j}$, RSU j has the opportunity to establish a communication connection with CV i.

During information transmission, the information will undergo signal attenuation due to factors such as obstacle occlusion. An RSU and a CV are directly connected only when the received power P_r exceeds a predefined threshold P_{th}. The received power P_r and the communication probability $P(d_{\text{vr}}^{\text{ij}})$ between RSU j and CV i is given by the following equations [39]:

$$P_r = P_t - PL(d_0) - 10\alpha \lg\left(\frac{d_{\text{vr}}^{\text{ij}}}{d_0}\right) + Z_{\sigma}, \quad (2)$$

$$P\left(d_{\text{vr}}^{\text{ij}}\right) = P\{P_r \geq P_{\text{th}}\} = \frac{1}{2} + \frac{1}{2}\text{er}\, f\left(\frac{10\alpha \lg\left(r/d_{\text{vr}}^{\text{ij}}\right)}{\sqrt{2}\,\sigma}\right), \quad (3)$$

$$r = d_0 \cdot 10^{\left(P_t - \text{PL}\left(d_0\right) - P_{\text{th}}\right)/10\alpha}, \quad (4)$$

where P_t is the transmitted power, $\text{PL}(d_0)$ is the reference path loss at a critical distance d_0, α is the path loss exponent, and Z_{σ} is a Gaussian random variable with zero mean and standard deviation σ.

2.2.3. Command Transmission Cycle between the RSU and CV Platoon.

Based on successful communication behaviors, the signal phase and timing (SPAT) message generated in the RSU, together with the real-time CVs' basic safety message (RSM), are sent back to the MEC, where the traffic control strategies are calculated. The strategies are sent to the CVs via the downlink according to the transmission cycle T_{com}. As the guidance command is distributed periodically, the successful transmission probability of the guidance information at time t is described by the following equation:

$$P_c^{\text{ij}} = \begin{cases} P\left(d_{\text{vr}}^{\text{ij}}\right), & \text{if } t \mid T_{\text{com}}, \\ 0, & \text{if } t \nmid T_{\text{com}}. \end{cases} \quad (5)$$

The RSU regularly sends guidance commands to CVs. In such a case, the probability that a CV receives command and updates its motion at any time t is P_c^{ij}.

2.2.4. Communication RSU Selection of CVs under Multiple RSUs.

Due to the constraints of channel resources, a CV interacts exclusively with one RSU upon entering the overlapping region of multiple RSU communication domains. To guarantee communication quality of communication, the CV selects its communication RSU based on the principle of maximizing connectivity probability. The communication connectivity probability between RSU k and CV i is given by the following equation:

$$P\left(d_{\text{vr}}^{\text{ik}}\right) = \max\left\{P\left(d_{\text{vr}}^{i1}\right), P\left(d_{\text{vr}}^{i2}\right), P\left(d_{\text{vr}}^{i3}\right), \ldots, P\left(d_{\text{vr}}^{\text{iq}}\right)\right\}. \quad (6)$$

2.3. Signal-Vehicle Coordination Control under Connected Environment.

Figure 3 illustrates the workflow of signal-vehicle coordination control under connected environment. The objective of signal-vehicle control is to minimize the total travel time of CVs.

The first step is to initialize the traffic state and the signal timing scheme. Subsequently, the RSU communicates with the CV platoon within its communication domain and estimates the time required by the CV platoon to pass the intersection. Combined with the SPAT, the RSU determines whether to transmit a suggested speed to the platoon. If the suggested speed is transmitted, the CV platoon will implement the speed adjustment command. Otherwise, the platoon will stop at the stop line to wait for the next green time.

2.3.1. Speed Optimization of the CV Platoon.

The RSU offers a suggested speed to the target CV platoon in the communication, with the aim of minimizing the total travel time of the CV platoon and enabling the platoon to cross the intersection within the green time (including the green extension time).

When an RSU communicates with the CV platoon, the remaining passing time for the platoon is T_l. To calculate the suggested speed, two scenarios are considered in this paper. The first scenario is that no vehicle is ahead of the target CV platoon. The objective function can be formulated as in the following equation:

$$f_1 = \min\left[\max\left(0, T_a^i\right)\right], \quad (7)$$

$$T_a^i = \rho\left[T_{\text{constant}}^i + T_{\text{acc}(1)}^i\right] + (1 - \rho)T_{\text{acc}(2)}^i, \quad (8)$$

$$\rho = \begin{cases} 1, & L^i \geq \left|\dfrac{v^2 - v_p^{i^2}}{2a_p^i}\right|, \\ 0, & L^i \leq \left|\dfrac{v^2 - v_p^{i^2}}{2a_p^i}\right|, \end{cases} \quad (9)$$

$$L^i = L_1^i + m^i L_{\text{car}} + \left(m^i - 1\right)L_{\text{in}}, \quad (10)$$

$$T_{\text{constant}}^i = \frac{L^i - \left|\left(v^2 - v_p^{i^2}/2a_p^i\right)\right|}{v}, \quad (11)$$

$$T_{\text{acc}(1)}^i = \left|\frac{v - v_p^i}{a_p^i}\right|, \quad (12)$$

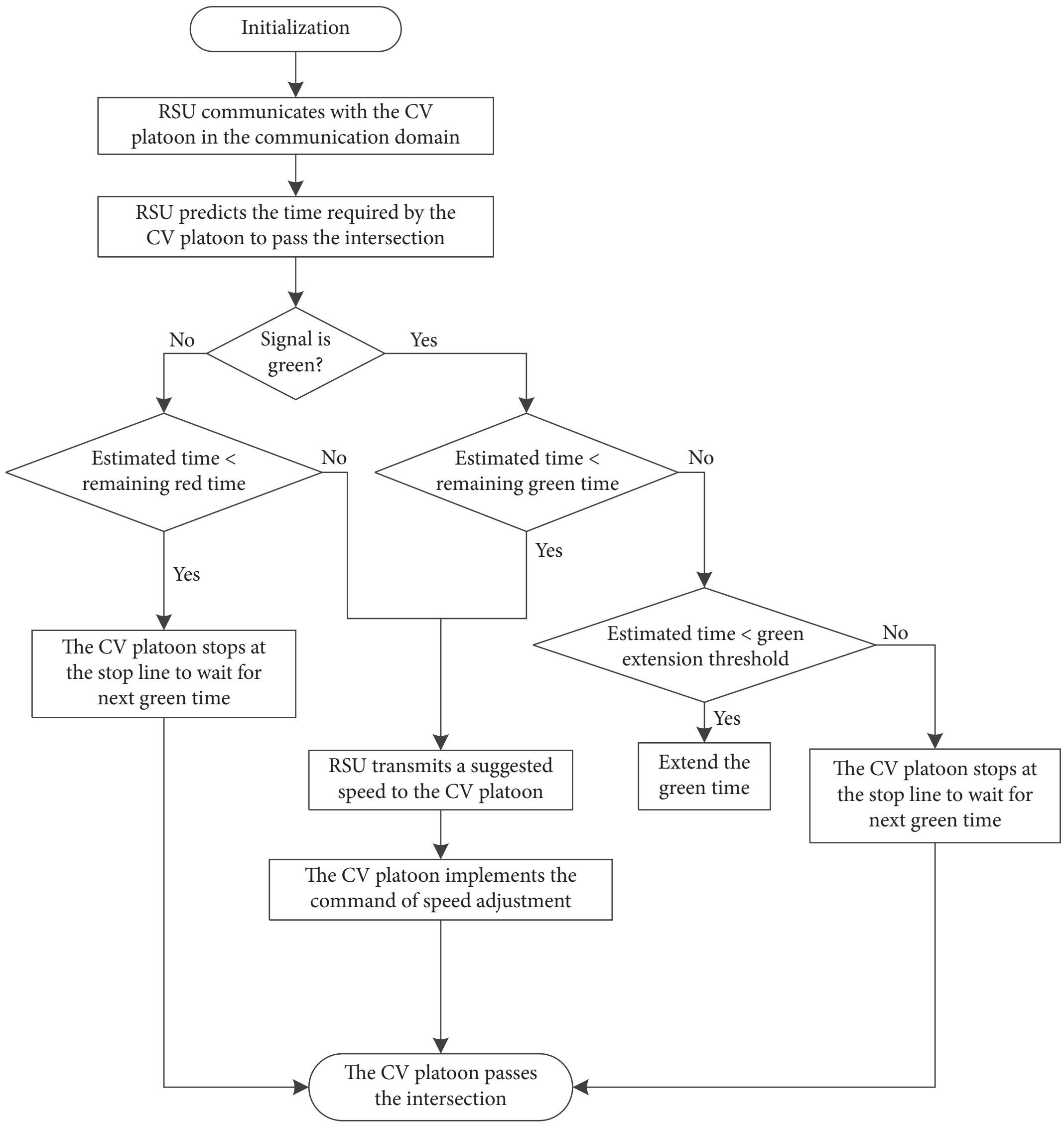


Figure 3: Workflow of signal-vehicle coordination control under connected environment.

$$T^i_{\text{acc}(2)} = \frac{-v^i_p + \sqrt{v^{i^2}_p + 2a^i_p L^i}}{a^i_p}. \quad (13)$$

Let T^i_a denote the travel time that the platoon i takes to pass the intersection from its current position. In equations (8) and (9), the parameter ρ indicates whether the platoon i is capable of crossing the intersection by accelerating from the current speed v^i_p to the suggested speed v. $T^i_{\text{acc}(1)}$ represents the time that platoon i takes to accelerate to the suggested speed. T^i_{constant} represents the time that platoon i takes to pass the intersection in a uniform velocity after the acceleration to the suggested speed. $T^i_{\text{acc}(2)}$ represents the time that platoon i takes to pass the intersection at the suggested speed. L^i represents the distance from the last vehicle in the platoon i to the stop line. In equation (10), L^i_1 denotes the distance from the leading vehicle in the platoon i to the stop line. L_{car} denotes the vehicle length. L_{in} is the distance between CVs within a platoon. m^i and a^i_p are the vehicle number and the acceleration of the platoon i, respectively.

In the second scenario, other CVs travel in front of the platoon i. To mitigate the interference of the vehicles ahead of platoon i, in addition to the target platoon, the RSU controls the CVs ahead of platoon i. If all vehicles ahead of the CV platoon i are in the RSU communication domain, the RSU incorporates the front vehicles into the target platoon i. The size of the platoon is expanded, and the first vehicle of the updated platoon becomes the leading vehicle. The RSU transmits the suggested speed to the leading vehicle of the updated platoon. The guidance strategy is calculated by the equations (7)–(13).

According to the speed v_l of the preceding platoon, RSU transmits the following speed v_g to the leading vehicle of the platoon i. The following model is utilized to calculate the speed v_g [40].

$$v_g = \min\left\{v_g + \frac{2a_{\max}(d_s + d_{\mathrm{lf}})}{(v_l + v_{\mathrm{free}})}, \frac{2a_{\max}L_1^i}{v_{\mathrm{free}}}\right\}. \quad (14)$$

In equation (14), v_{free} denotes the free-flow speed. $a_{\max}$ represents the maximum acceleration of the vehicle. d_s and d_{lf} are namely the safe distance and the distance between the follower and the leader.

Since a CV outside the RSU communication domain fails to receive guidance information, the motion of the target platoon i will be influenced. Therefore, the RSU steers all CVs within the communication range as a platoon, which follows the last CV inside the RSU communication domain. The speed data of the CVs outside the RSU communication domain is transmitted by a holographic detection device to the RSU. The RSU calculates the suggested speed according to equation (14). The travel time T_b of platoon i is given by the following equation:

$$T_b = \begin{cases} T_{\mathrm{lr}} + T_q + \dfrac{Q+M}{T_s}, & v_l = 0, \\ \dfrac{Q+M}{T_s}, & v_l \neq 0, \end{cases} \quad (15)$$

where Q and M denote the number of CVs outside and inside the RSU communication domain, respectively. T_{lr} represents the remaining red time, T_s represents the saturation flow rate, and T_q represents the vehicle start-up loss time.

The mentioned objective function is supposed to meet two constraints: (i) the suggested speed is within the range composed by the minimum speed $v_{\min}$ and the maximum speed $v_{\max}$ and (ii) the suggested speed is sufficient for the target platoon to pass the intersection within the remaining passing time. Hence, the constraints can be denoted as equation (16). $T \in \{T_a, T_b\}$ represents the time that the platoon takes to pass the intersection.

$$\text{s.t.} \begin{cases} v_{\min} \leq v \leq v_{\max}, \\ T < T_l. \end{cases} \quad (16)$$

Based on the estimated time of the platoon and the SPAT, the RSU evaluates the platoon's current motion status. When the platoon is capable of passing the intersection within the remaining travel time, the RSU transmits a suggested speed to the target CV platoon.

2.3.2. Signal Control Optimization. If the time required by the platoon to pass the intersection is greater than the current remaining green time T_{lg}, the RSU evaluates whether to execute a green extension strategy according to the following equation:

$$y = T - T_{\mathrm{lg}} - G_{\max}, \quad (17)$$

$$G_{\max} = T_{\mathrm{og}} - \frac{Q_c}{T_s}, \quad (18)$$

where $G_{\max}$ is the maximum green extension threshold. Q_c and T_{og} are the average vehicle queue length and green time of uncontrolled phases, respectively. If $y > 0$, the green extension time required by the platoon to pass the intersection exceeds the threshold. Thus, the platoon drives based on the car-following model and the signal timing scheme remains unchanged. If $y \leq 0$, the green extension time required by the platoon to pass the intersection lies within the threshold. In such case, the RSU transmits a command to the signal controller for the green extension. The green extension time T_{len} is presented as follows:

$$T_{\mathrm{len}} = T - T_{\mathrm{lg}}. \quad (19)$$

2.4. Impacts of RSU Deployment on the Performance of Signal-Vehicle Coordination Control. The RSU deployment scheme influences the implementation performance of the signal-vehicle coordination control strategy via communication interaction with CVs and signal controllers. Traffic delay is an essential index for evaluating the service level of an intersection [41]. Consequently, the reduction in vehicle delays is employed to evaluate the signal-vehicle coordination control performance, and six other indicators are selected as observation indexes to construct the evaluation index system for the RSU deployment scheme (see Table 1).

CVs are categorized into three types in the proposed scenario. (1) CVs geographically located in the RSU communication domain, whose average number per second is defined as C; (2) CVs in the RSU communication domain that may pass through the intersection without stopping via RSU control; and (3) CVs in the RSU communication domain that successfully execute the speed adjustment command and pass through the intersection without stopping during the corresponding signal cycle (including the green extension time), whose number is defined as K.

The number H of speed adjustments and the number K of vehicles whose speeds are successfully optimized are two indicators that quantify the changes in vehicle operation under the coordinated control. The green extension time G_{ext} is an indicator that quantifies the changes in signal parameters under coordinated control. Moreover, multiple RSUs may have an overlapping area of communication. The lower the overlap rate Z is, the higher the number C of vehicles in the communication domain is.

3. Simulation and Analysis

3.1. Scenario Description. We use simulation of urban mobility (SUMO) to build a four-approach signalized intersection, and the length of each approach is 1 km. The simulation time is 3600 s. The experimental parameter

Table 1: Relative indicators for impact analysis of RSU deployment on control performance.

Indicators	Types	Definitions
Reduction in vehicle delays R	Evaluation index of control performance	The difference between the total delays with and without the signal-vehicle coordinated control under CV-RSU communication
The number of vehicles in the RSU communication domain C	Observation index of CV-RSU communication	The average number of vehicles in the RSU communication domain per second
Connectivity probability between CV and RSU P_c	Observation index of CV-RSU communication	The average connectivity probability between CV and RSU
The number of vehicles whose speeds are successfully optimized K	Observation index of signal-vehicle coordinated control	The number of CVs whose speeds are successfully optimized and pass through the intersection without stopping during the signal cycle (including the green extension time)
The number of speed adjustments H	Observation index of signal-vehicle coordinated control	The number that CVs adjust their speed toward the suggested speed received from RSU
Green extension time G_{ext}	Observation index of signal-vehicle coordinated control	The total green extension time that the signal controller executes
Overlap rate of the communication domains of multiple RSUs Z	Observation index of CV-RSU communication	The ratio of the overlapping communication area of multiple RSUs to their total communication area

settings are shown in Table 2. For the threshold of received power and average distance between CVs within a platoon given in Table 2, refer to [42, 43], respectively.

We consider three different traffic flow modes: low, medium, and high traffic flows, represented by traffic flows of 400 veh·h^{-1} · lane^{-1}, 800 veh·h^{-1} · lane^{-1}, and 1200 veh·h^{-1} · lane^{-1}, respectively. Under these three modes, the intersection saturation values are approximately 0.3, 0.6, and 0.9, respectively. The ratio of north-south traffic flow to east-west traffic flow is 4 : 3, and the north-south traffic flow is the major traffic flow. In this paper, we focus on the north-south traffic flow as the RSU control target. In the single-RSU deployment scenario, the RSU is positioned at the south approach of the intersection. In the multiple-RSU deployment scenarios, RSUs are installed at the south and north approaches of the intersection. The parameters of the RSU deployment schemes are presented in Table 3.

In order to investigate the impacts of RSU deployment parameters on performance of signal-vehicle coordination control, RSU deployment scheme for different analysis is shown in Table 4.

As shown in Figure 4, the RSU is designed on SUMO, and the blue area is the communication range of the RSU.

Table 2: Experimental parameters.

Parameters	Values
Threshold of received power (dB)	50
Low traffic flow (veh·h^{-1} · lane^{-1})	400
Medium traffic flow (veh·h^{-1} · lane^{-1})	800
High traffic flow (veh·h^{-1} · lane^{-1})	1200
Average velocity (km·h^{-1})	40
Maximum velocity (km·h^{-1})	60
Maximum acceleration (m·s^{-2})	1.5
Minimum acceleration (m·s^{-2})	−4
Platoon size (veh)	10
Average distance between CVs within a platoon (m)	5
Minimum distance between CVs within a platoon (m)	1.5
Vehicle length (m)	4
Phase number	2
Signal cycle (s)	90
Green time (s)	42
Yellow time (s)	3

3.2. Impact Analysis of a Single-RSU Deployment

3.2.1. Impacts of RSU Communication Distance on Control Performance. As illustrated in Table 4, this section utilizes the RSU deployment schemes of U1–U5 for low, medium, and high traffic flows, where the RSU number, position, and command transmission cycle are unchanged. A single RSU with a communication distance of $D_{\text{rsu}} = \{100,200, 300,400,500\}$ is deployed at the roadside location of stop line on the south approach.

Figure 5(d) presents the impacts of RSU communication distance D_{rsu} on the reduction in vehicle delays R in the north-south direction. Under different traffic flows, R tends to increase and then decrease, as D_{rsu} increases. From Figure 5(a), it is clear that as D_{rsu} increases, the control range of the RSU expands, and C increases. Figure 5(b) shows that, given the characteristics of wireless transmission, P_c drops as D_{rsu} increases. This reduces the number of CVs that can successfully receive RSU commands. As shown in Figure 6(c), combining the above two effects, K tends to increase and then decrease as D_{rsu} increases, and R tends to increase and then decrease.

The peak of vehicle delay reduction is observed at an RSU communication distance of 200 m, because the number of vehicles in the RSU communication domain C has the largest growth, and the connectivity probability between a CV and RSU P_c remains at a high level. C increases slowly and P_c decreases dramatically when D_{rsu} is larger than 200 m. The analysis results for the two indicators show that the best choice of RSU communication distance is 200 m.

Overall, the RSU communication distance D_{rsu} affects both the number of vehicles in the RSU communication domain C and connectivity probability between CV and RSU P_c. The combination of two indexes influences the number of vehicles whose speeds are successfully optimized K, which ultimately changes the reduction in vehicle delays R.

3.2.2. Impacts of the RSU Command Transmission Cycle on the Control Performance. As shown in Table 4, this section utilizes RSU deployment schemes of U2, U6–U9 for low, medium, and high traffic flows, where RSU number, position, and communication distance are unchanged. Considering that the travel distance of CV within the cycle needs to be less than the minimum communication distance of RSU, the command transmission cycle is selected as $T_{\text{com}} = \{1, 3, 5, 7, 9\}$.

From Figure 6(c), under different traffic flows, the reduction in vehicle delays R for the north-south traffic flow follows a decreasing trend as the RSU command transmission cycle T_{com} increases. Further insight into the impacts of the RSU command transmission cycle is provided below. As shown in Figures 6(a) and 6(b), as T_{com} increases, H and G_{ext} decrease. Therefore, R decreases. As T_{com} increases, the number of issued control strategies decreases rapidly. This influences the optimization of the signal-vehicle control performance.

To summarize, the RSU command transmission cycle T_{com} affects both the number of speed adjustments H and green extension time G_{ext}, which eventually influences the reduction in vehicle delays. As T_{com} expands, H and G_{ext} both display a downward trend, which leads to a decrease in R.

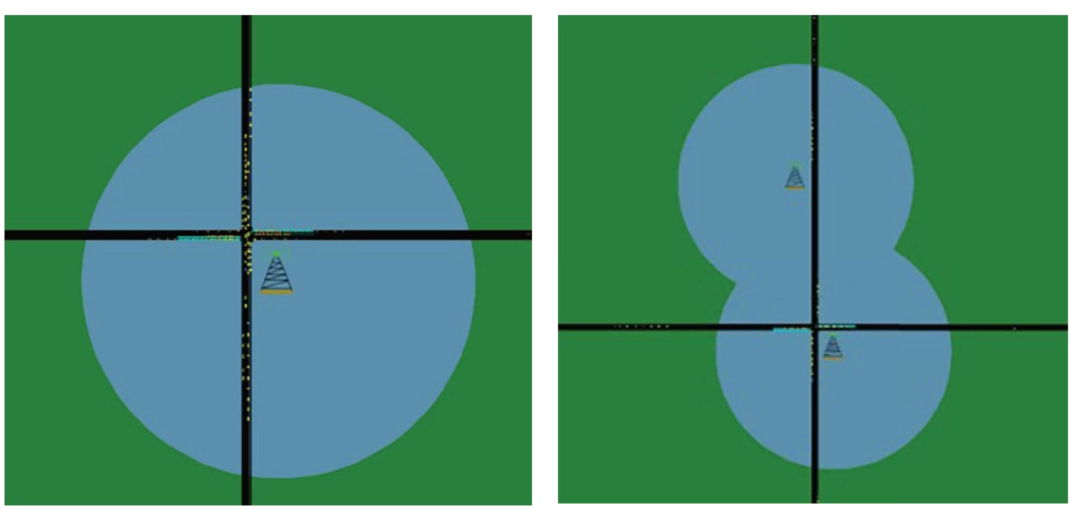
3.2.3. Impacts of the RSU Position on the Control Performance. As illustrated in Table 4, this section utilizes RSU deployment schemes of U6, U10–U12 for low, medium, and high traffic flows, where RSU number, communication distance, and command transmission cycle are unchanged. A single RSU under different positions is deployed to explore the impacts of the RSU deployment position on the control performance.

Table 3: Parameters of RSU deployment schemes.

Schemes	D_{rsu} (m)	T_{com} (s)	N_{rsu}	X_{rsu} (m)
U1	100	1	1	0 m from the stop line of the south approach
U2	200	1	1	0 m from the stop line of the south approach
U3	300	1	1	0 m from the stop line of the south approach
U4	400	1	1	0 m from the stop line of the south approach
U5	500	1	1	0 m from the stop line of the south approach
U6	200	3	1	0 m from the stop line of the south approach
U7	200	5	1	0 m from the stop line of the south approach
U8	200	7	1	0 m from the stop line of the south approach
U9	200	9	1	0 m from the stop line of the south approach
U10	200	1	1	100 m from the stop line of the south approach
U11	200	1	1	200 m from the stop line of the south approach
U12	200	1	1	300 m from the stop line of the south approach
U13	200	1	2	RSU 1 is 0 m from the stop line of the south approach, RSU 2 is 100 m from the stop line of the north approach
U14	200	1	2	RSU 1 is 0 m from the stop line of the south approach, RSU 2 is 200 m from the stop line of the north approach
U15	200	1	2	RSU 1 is 0 m from the stop line of the south approach, RSU 2 is 300 m from the stop line of the north approach
U16	200	1	2	RSU 1 is 0 m from the stop line of the south approach, RSU 2 is 400 m from the stop line of the north approach

Table 4: RSU deployment scheme for different analysis.

Analysis	Scheme
Impacts of RSU communication distance on the control performance	U1–U5
Impacts of RSU command transmission cycle on the control performance	U2, U6–U9
Impacts of single-RSU position on the control performance	U2, U10–U12
Impacts of dual-RSU position on the control performance	U13–U16
Impacts of RSU number on the control performance	U2, U12, and U16



(a) (b)

Figure 4: Simulation of signal-vehicle coordination control under CV-RSU communication. (a) The scene with a single-RSU located at the south approach, where the deployment position, communication distance, and command transmission cycle of the RSU are variable. (b) The scene with two RSUs located at the south approach and north approach, respectively, where the deployment positions of two RSUs are variable.

From Figure 7(c), under low traffic flow, the reduction in vehicle delays R for the north-south traffic flow decreases gradually as the RSU position X_{rsu} increases. Under medium and high traffic flows, the reduction in vehicle delays R for the north-south traffic flow increases as the RSU position X_{rsu} increases.

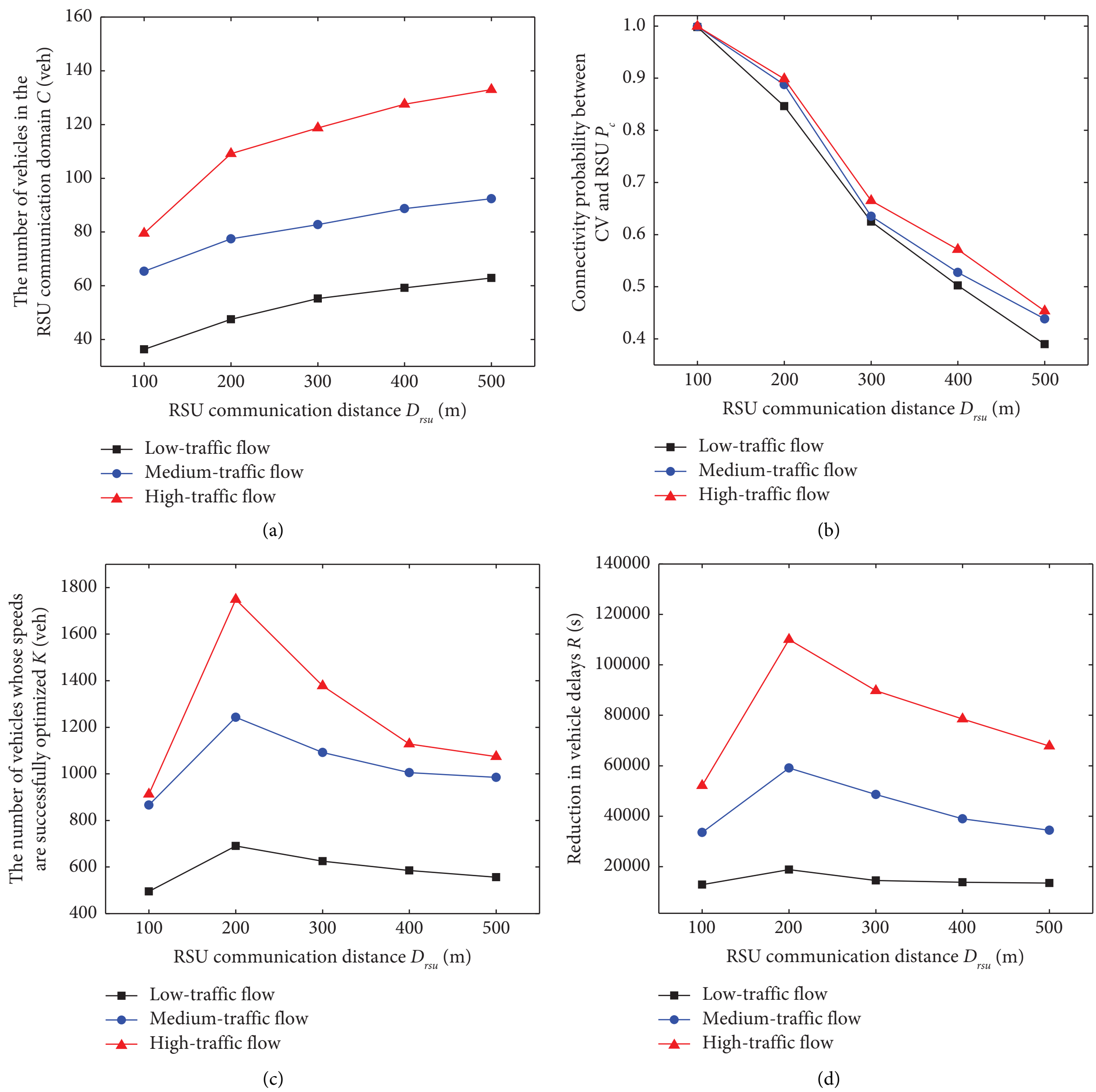


FIGURE 5: Impacts of RSU communication distance D_{rsu} on the analysis indicators.

Since the number of vehicles at the intersection is the largest, C tends to decrease as X_{rsu} increases in Figure 7(a). As shown in Figure 7(b), under low traffic flow, the vehicles are free to travel, the control space is large, and P_c remains unchanged. When the RSU is located closer to the intersection, C increases. The coordination control considers a broader range of traffic flows, which leads to an increase in K and R. Therefore, installing a single RSU close to the intersection is effective for reducing vehicle delays in low traffic flows.

Under medium and high traffic flows, queuing vehicles pass through the intersection with a saturation flow rate when the signal turns green. These vehicles lack guided space and value. As X_{rsu} increases, the proportion of queuing vehicles in the RSU communication domain is reduced. The number of vehicles with guided space grows. Consequently, K increases and eventually R displays an upward trend. Further analysis finds that considering only a static traffic flow is not sufficient for RSU deployment; the behavior and demands of dynamic traffic flow need to be addressed as well.

The position X_{rus} of an RSU influences the number of vehicles in the RSU communication domain C. This will influence the number of vehicles whose speeds are successfully optimized K. Consequently, the reduction in vehicle delays R is affected.

3.3. Impact Analysis of Dual-RSU Deployment

3.3.1. Impacts of the RSU Position on the Control Performance. As illustrated in Table 4, this section adopts the RSU deployment schemes of U13–U16 for low, medium,

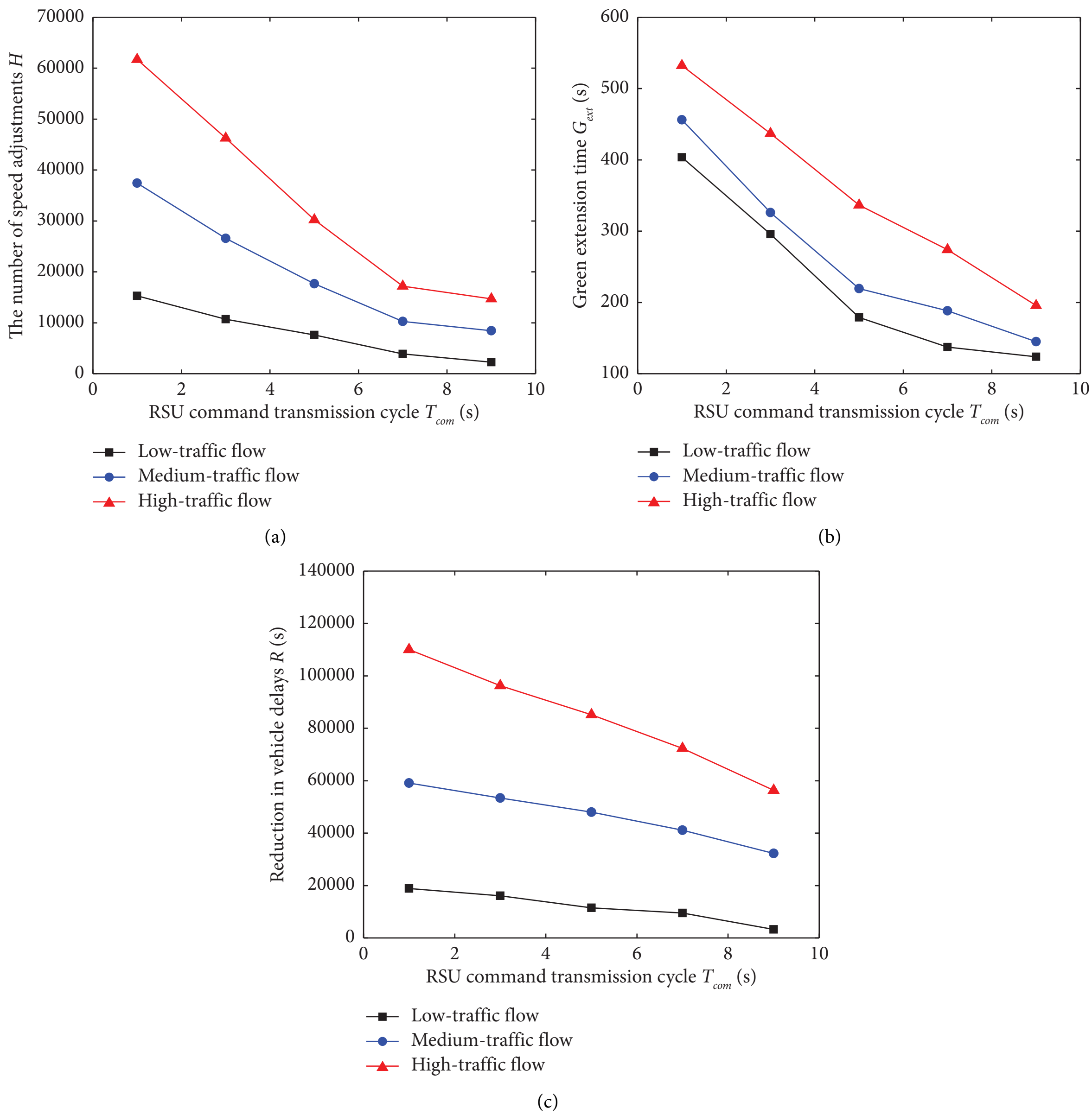


Figure 6: Impacts of the RSU command transmission cycle T_{com} on the analysis indicators.

and high traffic flows, where the RSU number, communication distance, and command transmission cycle are unchanged. Double RSUs are deployed at different positions on the north approach and south approach.

As shown in Figure 8(d), the reduction in vehicle delays R increases as the dual-RSU position X_{rsu} increases.

Under different traffic flows, as indicated in Figure 8(a), increasing the distance between the RSU located at the north approach and the intersection can reduce Z and expand the effective coverage of double RSUs. As a result, in Figure 8(b), C increases as X_{rsu} increases. Since the RSU-CV platoon connectivity probability P_c is unchanged, as presented in Figure 8(c), K increases and R increases accordingly.

The dual-RSU position X_{rsu} affects the overlap rate of the communication domains of multiple RSUs Z. This will influence the number of vehicles in the communication domain C, which in turn influences the number of vehicles whose speeds are successfully optimized K and ultimately changes reduction in vehicle delays R.

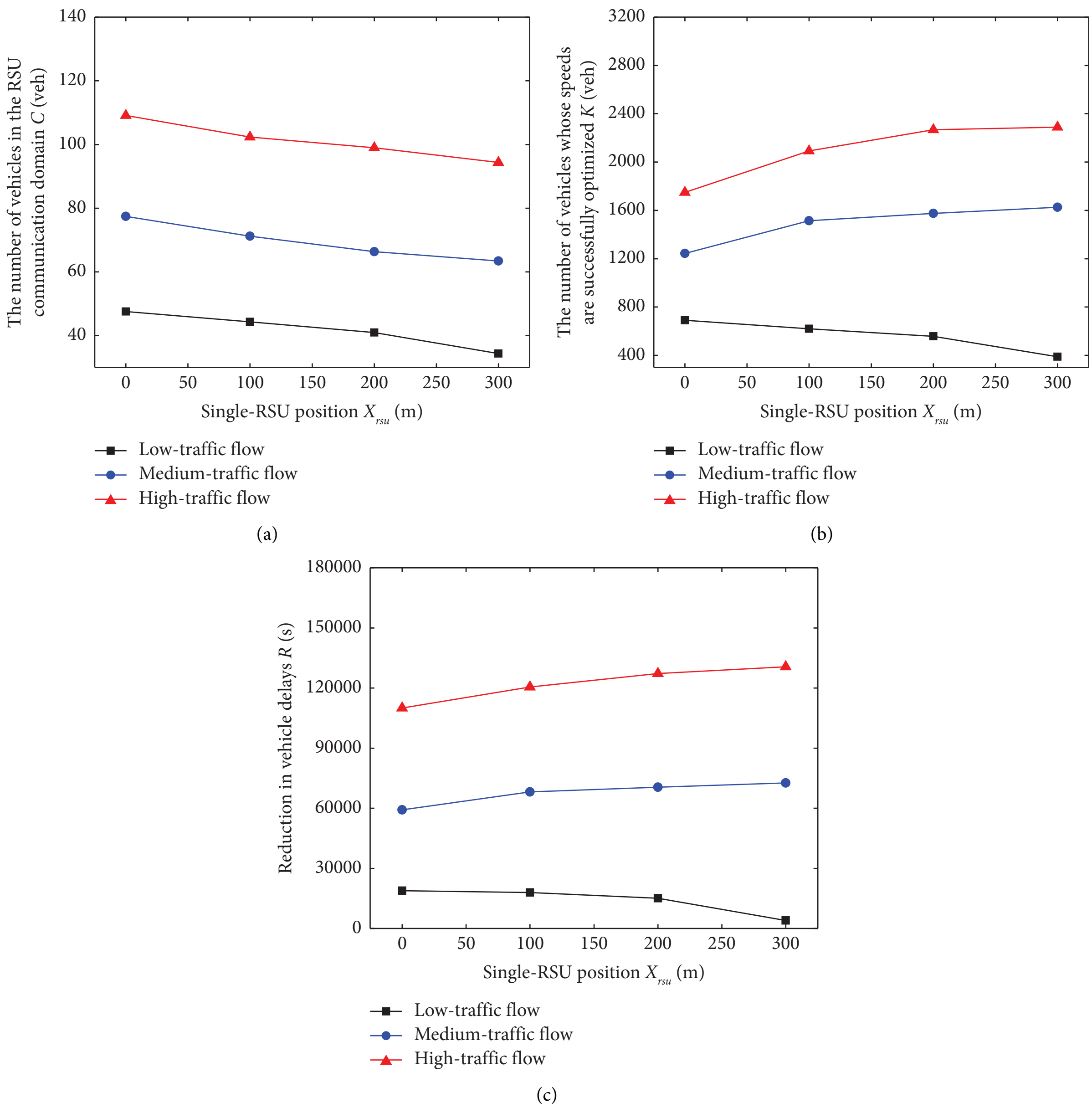


Figure 7: Impacts of the single-RSU position X_{rsu} on the analysis indicators.

3.3.2. Impacts of the RSU Number on the Control Performance. As illustrated in Table 5, to determine the impacts of the RSU number on the control performance, we adopt RSU deployment schemes U2 and U16 for low traffic flow and U12 and U16 for medium and high traffic flows. In Table 5, compared with the single-RSU deployment scheme, the deployment of two RSUs yields better performance in reducing vehicle delays. The experiments confirm that increasing the number of RSUs is crucial for enhancing the signal-vehicle coordination control performance.

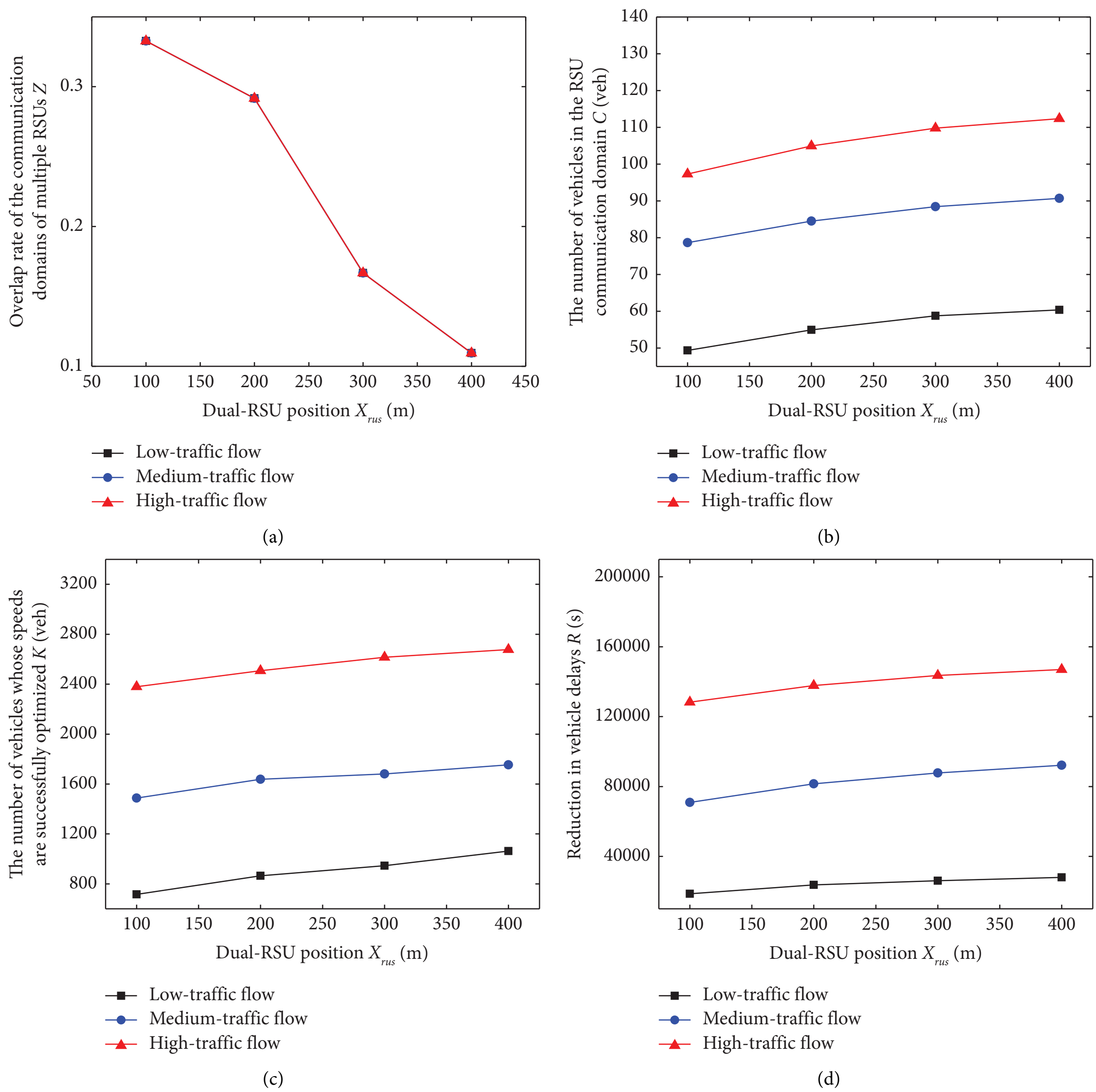


FIGURE 8: Impacts of the dual-RSU position X_{rsu} on the analysis indicators.

TABLE 5: Reduction in vehicle delays under different numbers of RSU.

Number of RSU	R under low traffic flow(s)	R under medium traffic flow(s)	R under high traffic flow(s)
1	18829.21	72609.29	130619.15
2	28012.40	92139.53	147001.35

TABLE 6: The influence of different RSU deployment parameters on the control performance.

Parameters	Observation indexes	Impact on the control performance
D_{rsu}	C, P_c, and K	The reduction in vehicle delays displays an upward trend and then a downward trend as the RSU communication distance increases
T_{com}	H and G_{ext}	The reduction in vehicle delays decreases as the RSU command transmission cycle increases

Table 6: Continued.

Parameters	Observation indexes	Impact on the control performance
X_{rsu} of a single RSU	C and K	Under low traffic flow, the reduction of vehicle delays decreases as the RSU position moves away from the intersection. Under medium traffic and high traffic flows, the reduction in vehicle delays increases as the RSU position moves away from the intersection
X_{rsu} of dual-RSU	Z, C, and K	The reduction in vehicle delays increases as the RSU position moves away from the intersection

3.3.3. Experiment Summary. In conclusion, Table 6 shows the influence of different RSU deployment parameters on the control performance. It reveals the impact mechanism of RSU deployment on the control performance. This provides theoretical support for the modeling and RSU deployment optimization algorithm under signal-vehicle coordination control.

4. Conclusions

In this paper, we investigate the modeling of signal-vehicle coordination control and RSU deployment evaluation under V2I environment. First, we develop a communication model of RSU and CV platoons under imperfect communication conditions. Second, a signal-vehicle coordination control strategy is designed to minimize the travel time of the CV platoon. Ultimately, we propose a method of evaluating the impacts of RSU deployment parameters on the performance of signal-vehicle coordination control. Through simulations, we reveal the impact mechanism of the RSU deployment parameters on the control performance.

The major conclusions are summarized as follows: (1) The reduction in vehicle delays tends to increase and then decrease as the RSU communication distance increases. (2) The reduction in vehicle delays decreases as the RSU command transmission cycle increases. (3) Under low traffic flow, the reduction in vehicle delays decreases as the distance between the intersection and RSU position increases. Under medium and high traffic flows, the reduction in vehicle delays increases as the distance between the intersection and RSU position increases. (4) The reduction in vehicle delays increases as the position of dual RSUs moves away from the intersection.

This article presents initial experimental research on the number of RSU deployments. Future research will integrate the installation cost and the number of RSUs to develop an RSU deployment optimization method. Moreover, future research aims to incorporate resource scheduling, communication delay, and other communication models to obtain a more realistic cosimulation model for both transportation and communication networks.

Data Availability

The data used in this study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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