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Highway roadside unit deployment under uneven distribution evolution of intelligent connected vehicles

Jiyuan Zhou[1*], Xiaolin Yu[2], Jian Geng[2], Ying Zhang[2], Luyu Zhang[3], Zhenhua Mou[1**]

1. School of Transportation Engineering, Shandong Jianzhu University, Jinan, Shandong 250101, China
2. Shandong Aobang Traffic Facilities Engineering Co., Ltd., Jinan, Shandong 250102, China
3. Qizheng New Energy Vehicle (Jinan) Co., Ltd, Jinan, Shandong 250101, China

Abstract: As the penetration rate of connected and autonomous vehicles (CAVs) increases on highways, their role as network nodes for communication tasks raises significant challenges. Spatial heterogeneity in node distribution creates density discrepancies that substantially impact network lifetime and stability, thereby constraining optimal deployment strategies for road side units (RSUs). This study introduces an enhanced low-energy adaptive clustering hierarchy (LEACH) clustering algorithm tailored for vehicular networks. By identifying dense and sparse regions through dynamic clustering, the algorithm categorizes node functions according to regional characteristics to balance energy consumption and improve network connectivity. MATLAB simulations validate the algorithm's performance under non-uniform vehicle distributions.The research further analyzes how vehicle node distribution patterns and CAV penetration rates affect optimal RSU deployment intervals. Key findings reveal that with consistent RSU-vehicle communication ranges: At a CAV traffic density of 0.01 and relative spatial density of 0.5 (uniform distribution), RSUs should be deployed at 641 m intervals. At a relative density of 0.9 (concentrated distribution), deployment intervals can expand to 1,887 m while maintaining high network connectivity. This adaptive strategy reduces communication blind spots by 32%, lowers deployment costs by 18%, and enhances vehicle-road coordination efficiency and traffic safety. The results provide critical technical support for intelligent vehicle-road collaboration systems.

Keywords: intelligent transport; heterogeneous traffic flow; vehicle grouping; RSU deployment; LEACH algorithm; uneven distribution

1 Introduction

With the popularization of connected and automated vehicles (CAVs) on highways, more CAVs serve as network nodes responsible for network communication [1−3]. However, owing to the rapid motion of vehicles on highways and the large count of vehicle nodes, investigating the movement of vehicles properties relying on a per-vehicle basis is not dependable. Vehicles are typically clustered [4], and research on highway vehicular sensing networks is conducted based on clusters. Intra-cluster vehicles communicate through single-hop or multi-hops [5], while vehicles not within the same cluster communicate between clusters [6−7]. Each vehicle cluster has at least one cluster leader, which acts as a data forwarding node responsible for transmitting relevant information to other member vehicles within the cluster. Vehicle clustering [8−11] is a manifestation of vehicle clustering on roads, and standard clustering techniques include partitioning clustering, density, and hierarchical clustering algorithms [12−13]. For example, Chen [14] proposed an optimized low-energy adaptive clustering hierarchy (LEACH) algorithm based on the block chain-based vehicle networking model, and carried out Partitioning and cluster leader election. Of road side unit (RSU) in BIoV, achieving good scalability while preserving the block chain's reasonable size. Choksi, et al. [15] a dynamic clustering algorithm (DCA) is introduced, leveraging fuzzy C-means (FM) machine learning, torecognize trusted vehicles for energy-efficient routing. This approach considers various mobility parameters and the residual energy in each vehicle node. Additionally, a novel variation of FM, termed distance and power-based fuzzy C-means (DP-FM), is presented. DP-FM utilizes distance affects residual power, metrics to determine stable cluster heads (CHs). Ren, et al. [16] The mobility and stability-based clustering algorithm (MSCA) is proposed, which predicts the mobile trend of vehicles, their geographical positions, and the duration of links, showing excellent performance in improving the average lifespan of cluster heads and optimizing the count of cluster heads. Zhao, et al. [17] an adaptive vehicle clustering algorithm, the fuzzy *c*-means algorithm serves as the foundation, is proposed. This method identifies the optimal cluster count to minimize overall vehicle energy usage and selects cluster heads considering vehicle movement direction, weighted mobility rate, and entropy to reduce power usage.

RSUs play a crucial role in vehicular cooperative systems.As Magsino, et al. [18] pointed out, the optimization of RSU deployment intervals must include dynamic parameters such as vehicle speed, data validity time, transmission range and deployment quantity. Their core function is to exchange information with mo-

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* *E-mail address*: 13066008197@163.com; ** *Corresponding author*: mouzhenhua@sdjzu.edu.cn
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tor vehicles: RSUs are responsible for providing real-time road environment data to vehicles while receiving traffic information transmitted by vehicles [19−20].Research on RSU deployment focuses mainly on several key dimensions: the design of deployment schemes, the selection of deployment locations, the determination of deployment quantities, and the optimization of deployment spacing. In addition, depending on the focus and objectives of the research,the problem of RSU deployment can be further divided into multiple sub-domains. In the design of RSU deployment schemes, researchers are committed to developing deployment models that meet communication requirements and are cost-effective. Fogue, et al. [21] a genetic algorithm is proposed for the Genetic algorithm-based roadSide unit deployment (GARSUD) system. Mao, et al. [22] proposed an RSU deployment scheme based on vehicle transmission demand and an RSU deployment algorithm based on evolutionary features, improved clonal algorithm-based evolutionary feature RSU deployment algorithm (ICA-EFRDA) algorithm, and Ghosh, et al. [23] proposed a new scheme for optimal RSU deployment, the immune-inspired algorithm for optimal RSU deployment (IIA-ORD), to deploy RSUs. The determination of deployment quantities aims to evaluate the required number of RSUs necessary to guarantee the stability of the communication network [24] and service quality. Gu, et al. [25] a network-based renormalization method, grounded in information flow is proposed and geographic location for layering Rsus on road networks, and Senouci, et al. [26] proposed an RSU-based heuristic clustering algorithm, HCAR for internet of vehicles (IoV), which needs to centralize clustering algorithms onto distributed RSUs. Heuristic clustering algorithm for RSUs (HCAR) introduces a novel mechanism to address the issue of CH unavailability. by using a weighting mechanism to select auxiliary CH. The selection of deployment locations mainly considers how to determine the optimal installation positions of RSUs based on the physical characteristics of roads, traffic flow distribution [27], and communication requirements [28−29] to achieve efficient communication coverage of vehicles. Sankaranarayanan, et al. [27] a proposal for an optimal RSU distribution planner has been put forward, ORDP, which provides feasibility based on user demand to determine appropriate parameter configurations for deploying RSUs at proper locations to maintain network connectivity and reduce installation costs within a specified region. Optimization of deployment spacing focuses on minimizing the distance between RSUs while ensuring communication quality [30−32], reducing the number of RSUs, and thereby reducing deployment and maintenance costs. Hao, et al. [33], a hybrid traffic flow speed control strategy is proposed,Considering factors such as RSU deployment spacing, interaction range, and communication latency. Research indicates that the proposed model maintains stability across various update frequencies.

Intra-cluster vehicles form a network through wireless transmission as network nodes, enabling collaborative sensing, detection, and transmission of various complex environmental information within their coverage range to RSUs for data collection and processing. However, when vehicle nodes within a cluster are unevenly distributed, the node density significantly affects network lifetime and stability, thereby influencing the deployment of RSUs on highways. Large energy consumption of network nodes and premature energy depletion directly affect network connectivity. Connectivity is a metric that measures the strength of connections between nodes in a network, and premature node death leads to reducing the network's node count, disrupting the original network topology and reducing network connectivity.

Although the existing clustering algorithm can improve cluster stability, it does not fully consider the characteristics of highway vehicles' energy limitations and uneven distribution. The LEACH protocol is widely adopted for its dynamic cluster head election mechanism and energy equilibrium advantages, but its random election strategy can easily lead to premature depletion of cluster head energy when nodes are unevenly distributed. In response to this deficiency, this paper proposes an improved LEACH-improved with partition empowerment mechanis (LEACH-IM) algorithm to optimize energy consumption allocation through the partition empowerment mechanism.This paper is grounded in the concept of clustering mixed traffic flows on highways. Considers the impact of uneven vehicle distribution on vehicle networks, using an improved LEACH algorithm that considers distance control factors, residual energy factors, and density factors to divide unevenly distributed vehicles clusters into high and low-density areas. Ordinary nodes in dense areas are selected as relay nodes for data transmission, thereby balancing overall network energy consumption. The algorithm's effectiveness is substantiated through an examination of the network's residual energy and the count of surviving nodes. This study determines the ideal RSU deployment intervals, considering varying degrees of clustering among connected and automated vehicles (CAVs) and the penetration rate of CAVs. Furthermore, it scrutinizes relatively efficient and sensible RSU deployment strategies under different clustering intensities and CAV penetration rates.This paper innovates in two aspects: (1) Updating the threshold function $T(n)$ in the LEACH algorithm considering distance control factors, residual energy factors, and density factors, and dividing vehicle nodes in the LEACH algorithm into high and low-density areas for zoning. (2) This research analyzes the influence of irregular clustering patterns in mixed traffic flows on the spacing of RSU deployments along highways. It aims to offer viable and efficient RSU deployment strategies for varying clustering magnitudes, ensuring optimal coverage and network performance.

The ensuing structure of this article is sequenced as follows: Section 2 delineates the vehicular clustering challenges on highways and discusses pertinent literature. Section 3 Improves and augments the vehicle clustering algorithm for more efficient grouping. Section 4 corroborates the algorithm's efficacy via simulation experiments. Finally, Section 5 encapsulates the findings and anticipates future research trajectories 1.

1.1 RSU deployment strategy founded on vehicle clustering

Highway scenarios are noted for their simplicity, featuring low vehicle density and high velocity. In accordance with highway lane speed restrictions, vehicle velocities normally span from 60 to 120 km/h, adhering to a consistent trajectory. Owing to the swift motion of vehicles, owing to the transient nature of the traffic flows and the restricted coverage radius of RSU, vehicles are within the purview of only one RSU for a brief period [34]. Consequently, examining vehicle mobility attributes on an individual vehicle basis lacks dependability. As a corrective measure, vehicles are assembled into clusters, and investigations into highway vehicular sensing networks are undertaken at the cluster level. Intra-cluster vehicles communicate through single or multiple hops, while vehicles not within the same cluster communicate between clusters.

In addition, with the increasingly clear business needs of the Internet of vehicles, standards organizations and industry alliances worldwide are actively promoting the establishment and improvement of the end-to-end standardization system of the Internet of cars. In this process, platform-related standardization work is also proceeding in an orderly manner. 5GAA (5G automotive association) discussed the platform deployment issue in the early study of cellular vehicle-to-everything (C-V2X) network architecture, the association advocated for a stratified deployment strategy for the vehicle-to-everything (V2X) platform, tailored to diverse application needs. It subsequently introduced initiatives like the "V2X platform role" and "V2X application layer reference architecture", concentrating on delineating the platform's architectural design, functionalities, and interfaces.

In adopting the deployment strategy delineated in Fig. 1, predicated on vehicular clusters for RSU installation, it has been ascer-

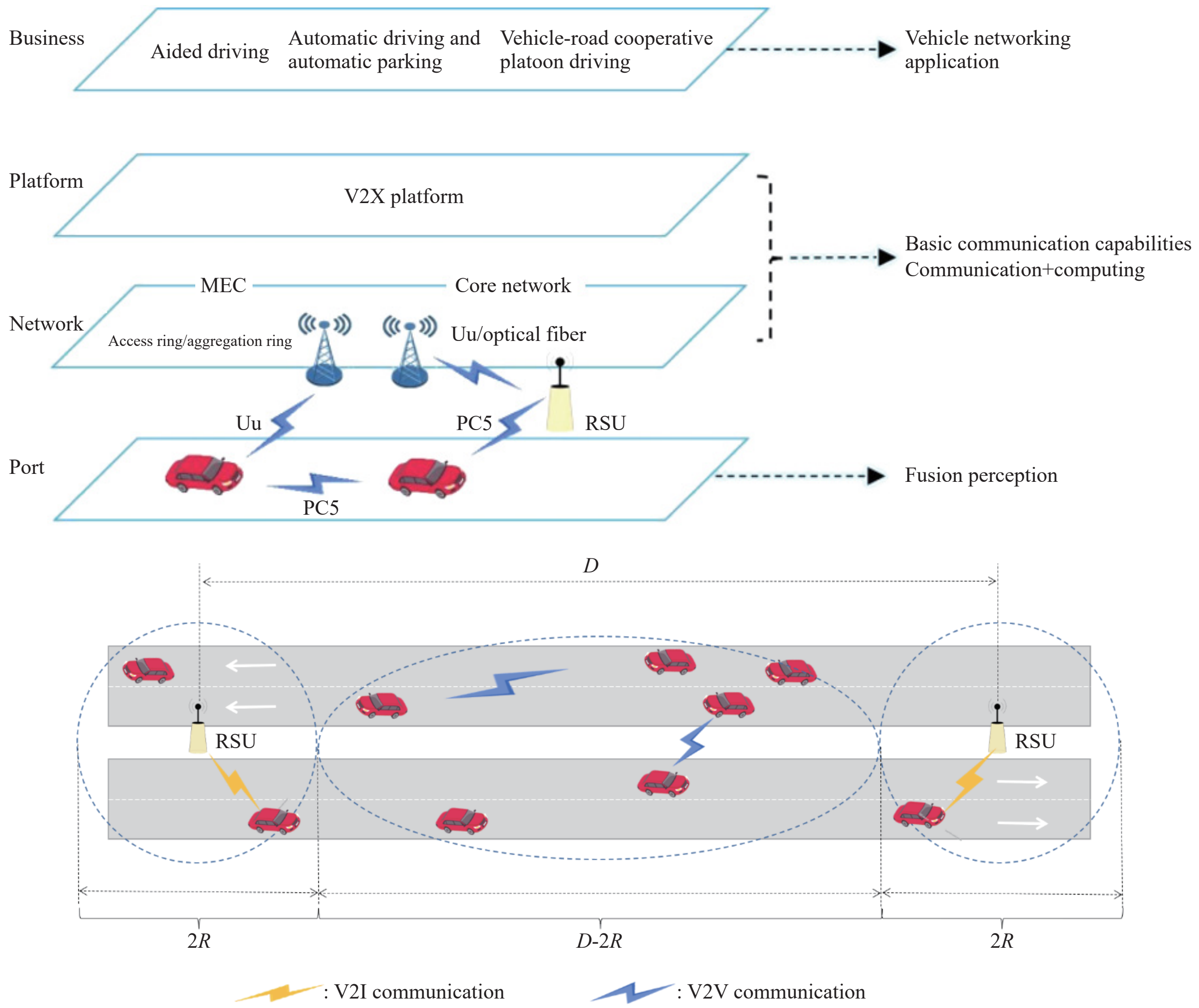

Fig. 1 Vehicle networking V2X overall architecture and communication diagram.

tained that setting the RSU spacing distance to the summation of the vehicular the length of the cluster, as well as twice the RSU communication. diameter. ($L(R) = E(C) + 2Rr$), this guarantees continuous communication between a vehicle cluster and an RSU throughout its journey. This not only solves the problem of network disruptions caused by excessively short vehicle cluster lengths.but also mitigates to some extent the energy consumption and mutual interference issues caused by excessively long vehicle cluster lengths or dense RSU deployments.

1.2 Vehicle mobility characteristics on highways

Due to the speed limits on highways, drivers typically control their speeds near the speed limit. Assuming that vehicle speeds are the same, the arrival process of vehicle nodes in a one-dimensional highway scenario follows a Poisson point distribution. The time intervals between vehicle arrivals follow an exponential distribution. Since we assume that vehicle speeds remain consistent, the distances between vehicles also follow an exponential distribution:

$$P_n = \frac{(\lambda L)^n}{n!} \mathrm{e}^{-\lambda L},\ n = 0, 1, 2, \cdots \tag{1}$$

where, λ is the varying vehicle congestion level. Then, the density of CAVs is defined as the concentration density of the vehicle in the RSU coverage area as $\lambda' = \lambda p$, the average count of vehicle nodes on the road segment is $N = L\lambda$, and the count of CAV nodes is $N' = L\lambda p = L\lambda'$.

On highways, speed restrictions influence drivers to maintain their vehicle speeds near the prescribed limit. Consequently, it is reasonable to assume uniform vehicle speeds. Vehicle spacing in mixed traffic adheres to an exponential distribution. CAVs engage in inter-vehicle communication, with the separation between CAVs also subject to an exponential distribution.

$$f(x') = \lambda' \mathrm{e}^{-\lambda' x} = \lambda p \mathrm{e}^{-\lambda x'} \tag{2}$$

Since vehicle communication spans considerably beyond lane width, the impact of lane width is overlooked in system analysis. Assuming vehicles have a circular communication range with radius R, communication probability between vehicles is determined when the separation between intelligent and networked vehicles is within R, formulated as:

$$P(x' < R) = \int_0^R f(x')\mathrm{d}x' = 1 - \mathrm{e}^{-\lambda p R} \tag{3}$$

Likewise, if the gap between intelligent and networked vehicles goes beyond the transmission range R, i.e., the probability that vehicles cannot communicate with each other is:

$$P(x' > R) = \int_R^\infty f(x')\mathrm{d}x' = \mathrm{e}^{-\lambda p R} \tag{4}$$

Taking into account the spacing between any two vehicles. operates independently, communication can be achieved through multi-hop links with a probability of P_{h}, when the multi-hop distance among two interlinked and sautomated vehicles exceeds the vehicle communication radius R.

$$P_h(x' > R) = \int_R^{\infty} f(x')\mathrm{d}x' = (1 - \mathrm{e}^{-\lambda pR})^h \tag{5}$$

where, h is the quantity of hops needed for in-cluster vehicle communications. As vehicles coalesce into clusters around the RSU, the vehicle cluster's length is established by counting neighboring mixed traffic flow cluster contains multiple vehicles, separated by less than the radius of vehicle communication. Consider a vehicle cluster with a CAV penetration rate of p and a total number of mixed traffic flow vehicles, resulting in CAVs within the cluster. Clustering mixed traffic flow vehicles means the first and last CAVs in the cluster are further from adjacent CAVs outside the cluster than the vehicle communication radius allows. Still all CAVs within the cluster are closer to each other than this radius. As a result, the likelihood of vehicle gaps in a cluster is:

$$g(n) = (\mathrm{e}^{-\lambda pR})^2(1 - \mathrm{e}^{-\lambda pR})^{n-1} \tag{6}$$

The expected extent of the vehicle cluster is:

$$E(C) = \lim_{n\to\infty} \frac{\sum_{i=1}^{n}(g(i)\sum_{j=1}^{i} d_j)}{\sum_{i=1}^{n} g(i)} = \frac{\lim_{n\to\infty}\sum_{i=1}^{n}(g(i)\sum_{j=1}^{i} E[x|x<R])}{(\mathrm{e}^{-\lambda pR})^2(1-\mathrm{e}^{-\lambda pR})}$$
$$= \frac{1 - \mathrm{e}^{-\lambda pR}(1 + \lambda pR)}{\lambda p\mathrm{e}^{-\lambda pR}(1 - \mathrm{e}^{-\lambda pR})} \tag{7}$$

Define χ as the relative density, representing the uneven distribution degree of vehicle nodes in dense areas of the highway. When the relative density of vehicle nodes in dense regions is χ, the uneven distribution of relative density of vehicle nodes in sparse areas is $1-\chi$. Define $1/\gamma$ as the vehicle aggregation index. When there is an uneven distribution of vehicle nodes on the highway, and vehicle nodes with a relative density χ are densely distributed within a length of L/γ section of the highway, while the remaining vehicle nodes with a relative density $1-\chi$ are sparsely distributed in the remaining area, the vehicle cluster length can be considered as the product of the sum of the lengths of the vehicle clusters in dense and sparse areas and the vehicle aggregation index. Then, we have:

$$\lambda_1 = \frac{N\chi}{\frac{1}{\gamma}L} = \frac{\gamma N\chi}{L} = \gamma\lambda\chi \tag{8}$$

$$\lambda_2 = \frac{N(1-\chi)}{(1-\frac{1}{\gamma})L} = \frac{\gamma N(1-\chi)}{(\gamma-1)L} = \frac{\gamma\lambda(1-\chi)}{(\gamma-1)} \tag{9}$$

$$E(C_M) = \frac{1}{\gamma}[E(C)_{\lambda_1} + E(C)_{\lambda_2}] \tag{10}$$

where, λ_1 and λ_2 are the vehicle node densities in the dense and sparse regions respectively, when the distribution density of vehicle nodes on the highway is uneven; $E(C)_{\lambda_1}$ and $E(C)_{\lambda_2}$ are the lengths of vehicle clusters in the dense and sparse regions respectively, under the same condition of uneven distribution of vehicle nodes on the highway; $E(C_M)$ is the overall length of the vehicle cluster.

2 Clustered network and energy consumption model

2.1 LEACH protocol

The LEACH protocol operates as a cluster-oriented routing protocol, whose fundamental principle involves partitioning the CAV nodes into numerous groupings, with each grouping. is overseen by a cluster head node. This node is tasked with gathering data from the vehicle nodes within its cluster and summarizing it to be transmitted to the RSU nodes, thereby completing data collection and transmission. The algorithm randomly selects cluster head nodes in a cyclic manner, within each cluster, every cluster head has an equal chance of being chosen. As a result, energy consumption across the entire network is evenly distributed among the vehicle nodes, leading to a reduction in the network's overall energy consumption and an extension of the network's lifespan. The LEACH protocol is bifurcated into two principal phases: the cluster initiation phase and the sustained steady-state phase, with the combined duration of both phases constituting a single round. During the cluster setup phase, vehicle nodes produce a random figure ranging from 0 to 1. This number is subsequently juxtaposed with a threshold value. $T(n)$; if it is lower, the node chosen as the cluster leader employs the following formula to determine the threshold $T(n)$:

$$T(n) = \begin{cases} \dfrac{p}{1 - p\times(r \bmod \dfrac{1}{p})}, & n \in G \\ 0, \quad \text{else} \end{cases} \tag{11}$$

where, p *is* the established ratio of cluster heads, this recognizes the nodes that have not acted as cluster heads in the previous $1/p$ rounds; r *is* denotes the present round number; and n *is* the current node.

2.2 Energy consumption model

The power utilized by a vehicle node to transmit m bits of data towards neighboring vehiclesat a distance d is dependent on the transmission range d, as illustrated in the formula:

$$ETx(\mathrm{m}, d) = \begin{cases} m\cdot E_{\mathrm{elec}} + m\cdot\varepsilon_{\mathrm{fs}}\cdot d^2, \ d < d_0 \\ m\cdot E_{\mathrm{elec}} + m\cdot\varepsilon_{\mathrm{mp}}\cdot d^4, \ d \geqslant d_0 \end{cases} \tag{12}$$

The power needed for a vehicle node to receive m bits of data is calculated using the formula below:

$$E_{Rx}(m) = m\cdot E_{\mathrm{elec}} \tag{13}$$

where, E_{elec} is the energy required per bit for data processing by the vehicle node; and $\varepsilon_{\mathrm{fs}}$ and $\varepsilon_{\mathrm{mp}}$ are the communication energy parameter; d_0 is the threshold value that distinguishes between two modes. If the inter-node distance is under d, under the free space communication model, the multipath fading channel model is employed. The threshold value is calculated using the formula shown below:

$$d_0 = \sqrt{\frac{\varepsilon_{\mathrm{fs}}}{\varepsilon_{\mathrm{mp}}}} \tag{14}$$

2.3 Clustering network model

This paper introduces an enhanced LEACH-IM (LEACH-Improved) clustering algorithm, which builds upon the LEACH protocol to tackle the uneven distribution of CAV nodes on highways. It determines the density of nodes and divides nodes in different density areas into different functions, thereby balancing the overall network optimize energy reductions the number of node deaths due to uneven node distribution. The assumptions of the network model are as follows:

(1) The distribution of vehicle nodes on highways is uneven, with significantly higher densities in random areas and significantly lower densities in other areas.

(2) The positions of RSU nodes are fixed, and energy is sustainably supplied without considering their energy consumption.

(3) All initial energies of CAV nodes are the same, and the probability of being selected is the same; node energy cannot be replenished midway.

(4) Every vehicle node within the network possesses a unique identifier, and its computational and communication capabilities are equivalent.

(5) Wireless transmission power can be autonomously selected.

3 Description of LEACH-IM Algorithm

In the LEACH protocol, cluster head election is conducted through random selection, which may result in nodes with insufficient residual energy or unfavorable distribution locations being elected as cluster heads. Therefore, this algorithm first divides the CAV nodes on highways into dense and sparse areas, and then introduces three factors: distance factor, residual energy factor, and density factor. By improving the threshold $T(n)$ function comprehensively, the probability of vehicle nodes that do not meet the conditions being elected as cluster heads is reduced. Following the selection of cluster heads, data is transmitted to its corresponding relay node, and then the relay node transmits the data to the base station. This approach allows cluster heads in sparse areas to interact indirectly with the base station through relay nodes, thereby achieving energy consumption balance, reducing the overall network node energy consumption rate, balancing the network energy load, and minimizing premature node deaths due to uneven distribution in the network, which could lead to reduced network connectivity and increased RSU deployment costs.

3.1 Division of dense and sparse areas

Firstly, calculate the density of vehicle nodes on highways: each vehicle node transmits a single data packet to all nodes within its communication range, and the count of response data packets received by the node reflects the density of that vehicle node, denoted as D_{i}. Define the standard node density as:

$$D = \frac{N}{m} - 1 \tag{15}$$

where, m is the number of clusters; and N is the total number of CAV nodes in the network. If the density D_{i} of vehicle nodes is less than the standard node density D, then the area is defined as a sparse area; otherwise, it is a dense area.

3.2 Distance control factor

Considering that the distance between CAV nodes during communication with neighboring nodes and RSU affects the energy consumption of vehicle nodes, a distance control factor is set as:

$$\omega = \frac{d_i - d_{\max}}{d_{\max} - d_{\min}} \tag{16}$$

where, d_i is the spacing between the vehicle node and RSU; and $d_{\max}$ and $d_{\min}$ are the maximum and minimum distances between vehicle nodes and RSU in the network, respectively.

3.3 Residual energy factor

During the initial period of network cycles, the energy of each CAV node is relatively abundant. However, as the network cycles progress, some vehicle nodes are elected as cluster heads and consume a considerable amount of energy. If cluster head nodes are frequently chosen from this subset, it could precipitate an early depletion of node energy, thereby diminishing the overall network connectivity. To ensure the overall network connectivity, the interval between RSU deployments must be reduced, increasing deployment costs. Therefore, when selecting cluster heads, the residual energy of the nodes should be considered. The residual energy factor for a vehicle node is defined as:

$$E_{\mathrm{RE}} = \frac{E_{\mathrm{IE}}}{E_0} \tag{17}$$

where, E_{IE} *is* the node's current residual energy; and E_0 *is* the initial energy of the node at the start of the cycle.

3.4 Density factor

The density factor of a vehicle node reflects the count of neighboring nodes close to the node. This is determined by dividing the count of neighboring nodes within the node's maximum communication range by the number of nodes in a typical cluster proximate to the node. A node's density factor is represented by:

$$\rho = \frac{N_{i.\mathrm{nb}}}{\left(\frac{1}{p}\right) - 1} = \frac{p}{1-p} \cdot N_{i.\mathrm{nb}} \tag{18}$$

where, $N_{i.\mathrm{nb}}$ is the count of neighboring nodes within the maximum communication range R of the node; p is the percentage of cluster heads among all nodes; and $(1/p)-1$ is the number of neighboring nodes in the standard cluster.

3.5 Threshold formula

Therefore, after fully considering the distance control factor, residual energy factor, and density factor of each node, the threshold formula is updated as:

$$T(n) = \begin{cases} \dfrac{p}{1 - p\left(r \bmod \dfrac{1}{p}\right)}(\alpha E_{\mathrm{RE}} + \beta(1-\omega) + \delta\rho), & n \in G \\ 0, \quad \text{else} \end{cases} \tag{19}$$

where α, β and δ are weighting factors that vary with application scenarios and network scales, and must satisfy certain conditions $\alpha + \beta + \delta = 1$.

From Eq. (19), It is evident that the lower the residual energy value E_{RE} of a vehicle node, the smaller the threshold $T(n)$ value obtained by the node. Therefore, to be elected as a cluster head, the node needs to generate a smaller random number than before, thereby increasing the probability of nodes with more residual energy being selected as cluster heads. Similarly, when the distance between nodes and the RSU is far or the node density is sparse, the threshold value will decrease accordingly, reducing the probability of the vehicle node being designated as a cluster head.

During the initial period of network transmission, the energy of each vehicle node is relatively abundant, and the network is relatively insensitive to energy changes. Therefore, the weighting value α of the residual energy factor can be reduced at this time. As the network transmission cycle increases, the residual energy of each vehicle node approaches depletion. Therefore, in the later stage of network transmission, the weighting value α of the residual energy factor can be increased. Similarly, in scenarios where node density distribution is uneven, the weighting value δ of the density factor can be increased, as the density of vehicle node distribution has a greater impact on the election of cluster heads.

3.6 Algorithm flow

Step 1: RSU broadcast signals within the network area. Vehicle nodes calculate the distance between themselves and RSU based on the signal strength, using Eq. (16), to determine the distance control factor. Nodes then calculate the threshold based on their residual energy and node density.

Step 2: Each node produces a random figure ranging from 0 to 1. This generated number is then compared against the threshold value established by the Eq. (19). Should the random number be below the threshold, the node assumes the role of cluster head for that iteration; if not, it remains a standard node.

Step 3: Calculate the node density D_{i} and determine whether the node belongs to a dense or sparse area based on Eq. (15) and the standard node density D.

Step 4: Select the cluster head for each vehicle node based on the communication distance and the current energy of each cluster head.

Step 5: Among the regular nodes in dense regions, choose theAmong the regular nodes in dense regions, choose the cluster head in less dense areas choose the vehicle node closest to cluster head in less dense areas and with the most residual energy as the relay node for data transmission, thereby equalizing the overall network energy consumption.

Step 6: As the network cycle progresses, adjust the values of the weighting factors. When the node's energy is less than 50%, increase the weighting factor for residual energy α Other steps remain unchanged, and data transmission continues in cycles.

4 Simulation and result analysis

This paper uses MATLAB software to carry out simulation analysis on the scenario of two-way four-lane highway, where the communication modes coexist as V2V (Vehicle-to-Vehicle) and V2I (Vehicle-to-Infrastructure) in the highway, and the vehicle types in the heterogeneous traffic flow are CAV and HV (Human-driven Vehicles). In existing studies, the classic LEACH protocol tends to cause excessive energy consumption of some nodes due to the random cluster head election mechanism when vehicle nodes are unevenly distributed; although the LEACH-E algorithm introduces an energy factor, it does not consider the differences in node density and spatial distribution. Therefore, this paper conducts a comparison among the classic LEACH protocol, the improved LEACH-E algorithm, and the proposed LEACH-IM algorithm through 2,000 rounds of experiments, from the aspects of network residual energy and the number of surviving nodes.Additionally, the performance of the improved LEACH-IM algorithm was simulated under different penetration rates of heterogeneous traffic, The vehicle type is judged by the characteristics of the HV's large fluctuation and no continuity, while the CAV's front time distance is smaller and more uniform, the study examined how varying CAV penetration rates affect network connectivity, cluster sizes, and RSU spacing. Road simulation parameter settings in Table 1 below.

Table 1 Road simulation parameter settings.

Parameter	Value
Highway length	1,000 m
Heterogeneous traffic density λ	0.1–0.5 units/km
RSU transmission range	200 m
Lane width	20 m
RSU deployment coordinates	(1 000, 10) (1 deployed every 1 000 m, with a horizontal offset of 10 m)
Number of sensor nodes	0–40 veh

4.1 Configuration of simulation parameters

(1) Configuration of road environment parameters

In accordance with the *Technical Standard for Highway Engineering* (JTG B01—2017), the specifications for dual-direction, four-lane highway are set at dimensions of 3.75 m by 2 m. Considering the actual scenario of highways with emergency lanes and RSU installation widths, In this simulation, the width of the simulated highway is set to 20 m, RSU coordinates (1 000, 10) indicate that the first RSU is located at the end of the expressway (x=1 000 m) and 10 m from the center line of the road. In the simulation, an RSU is deployed every 1,000 m, and the lateral offset is fixed to 10 m. The specific road environment simulation parameters are shown in Table 2 below.

Table 2 Road environment simulation parameters.

Parameter	Value
Simulation area	1000 m × 20 m
RSU deployment coordinates	(1 000, 10)

(2) Network simulation parameter settings (Table 3)

Table 3 Communication environment simulation parameters.

Parameter	Data value
Network area	1000 m × 20 m
Number of sensor nodes	(0-40)
RSU coordinates (One is deployed every 1 000 m, with a horizontal offset of 10 m)	(1 000,10)
Data packet length (bit)	4 000
Initial cluster head probability p	0.05
Initial energy of each node E_0 (J)	25
Free space channel model signal amplifier power consumption E_{fm} (nJ/(bit·m^2))	10
Multipath fading channel model signal amplifier power consumption E_{mp}(pJ/(bit·m^4))	0.001 3

4.2 Simulation result analysis

Under the assumption that freeway vehicle arrivals conform to a Poisson process, we observe a traffic density of 0.04 veh/m, which translates to an average arrival rate λ=0.04 veh/s when considering the lane width. The time headway parameter h is set to 2 s, in line with the parameter specifications described in Section 4.1. Consequently, within the simulated highway segment, 40 vehicle nodes were randomly generated for the experiment, the upper right corner was set as the dense area, where the relative density of nodes is defined as the percentage of the number of vehicle nodes in the upper right corner to the total number of vehicle nodes in the experimental area. The distribution of vehicle node relative densities, ranging from 60% to 90%, is shown in Fig. 2.

4.3 Performance analysis of improved algorithm

Figs. 3 and 4 present a comparative simulation of the remaining power in the network and the count of viable nodes over time when employing the classical LEACH protocol, the improved low energy adaptive clustering hierarchy-enhanced (LEACH-E) algorithm, and the LEACH-IM algorithm proposed in this paper. These simulations are conducted under the condition of a 70% relative density of unevenly distributed vehicle nodes on a highway. Figs. 3 and 4 show the simulation results comparing the changes in remaining network energy and the number of surviving nodes when using the classic LEACH protocol, the improved LEACH-E algorithm, and the proposed LEACH-IM algorithm in scenarios where the relative density of uneven vehicle node distribution on expressways is 70%. The selection of 70% relative density (δ=0.7) is based on the sensitivity analysis in Fig. 5. When δ<0.7, connectivity increases significantly with density; when δ>0.7, the growth tends to flatten, so it is taken as the turning point for the deployment strategy. This density value not only ensures the basic connectivity of the network but also avoids resource waste caused by excessive deployment, providing a reasonable experimental premise for the subsequent performance comparison of algorithms.

(1) Network residual energy

Network residual energy denotes the entire network's unused energy, crucial when comparing operational durations, a higher amount of residual energy indicates better network performance. Fig. 3 illustrates the relationship between network residual energy and the network's cycle count composed of 40 CAV vehicle nodes communicating with one RSU through vehicle-to vehicle (V2V) and vehicle to infrastructure (V2I) communication. After 2,000 cycles of network operation, it is observed that the LEACH-IM algorithm proposed in this paper exhibits lower network energy consumption and higher residual energy compared to both the classical LEACH the enhanced protocol LEACH-E algorithm. This indic-

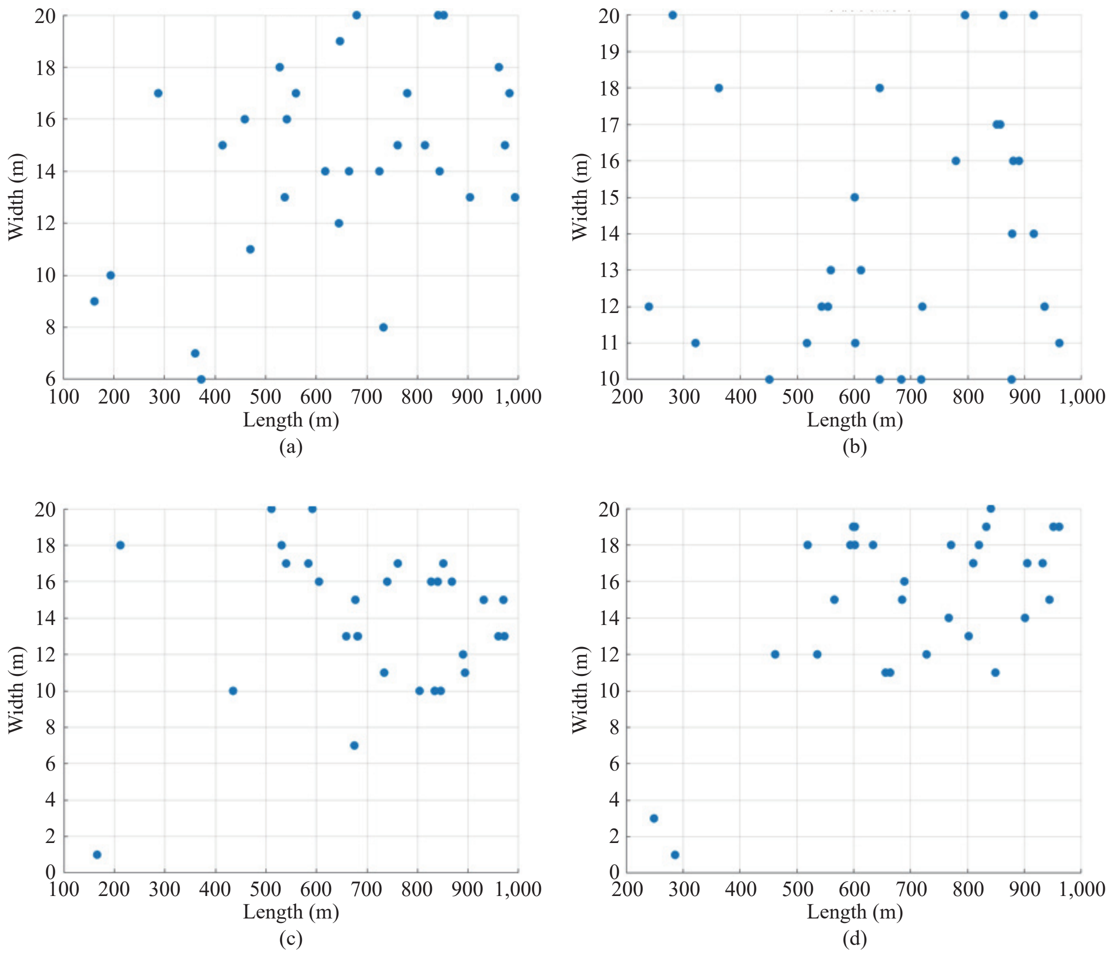

Fig. 2 Non-uniform distribution of vehicle nodes on the highway. (a) 60%vehicle node non-uniform distribution. (b) 70% vehicle node non-uniform distribution. (c) 80% vehicle node non-uniform distribution. (d) 90% vehicle node non-uniform distribution.

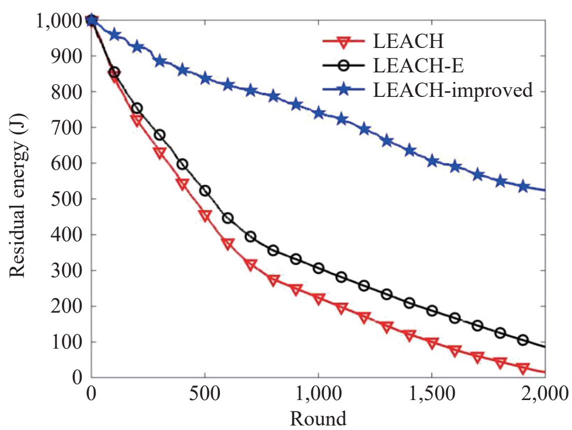

Fig. 3 Comparison of residual energy of the network.

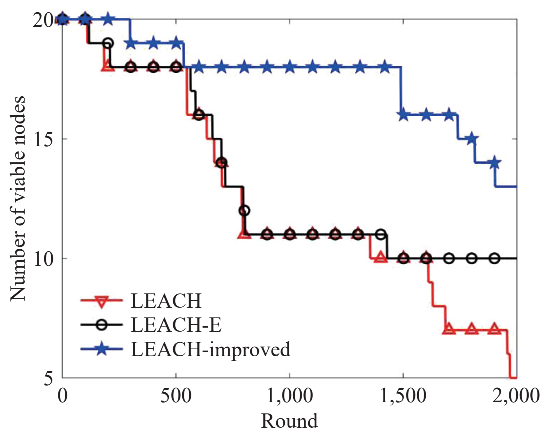

Fig. 4 Comparison of the number of viable nodes.

ates that the modified algorithm achieves more balanced energy consumption. The selection of cluster heads takes into account the current residual energy of nodes, the distribution of candidate nodes, and the density of nodes within the communication range of candidate nodes, thereby increasing the probability of selecting candidate nodes with higher residual energy, closer proximity to the RSU, and denser node density within their communication range as CHs.

(2) Number of viable nodes

The number of viable nodes refers to the number of nodes in the network that have not been depleted and remain active. The longevity of the network is intrinsically linked to the distribution of its nodes. If reasonable cluster head selection and energy consumption allocation are not properly conducted during network operation, uneven energy consumption among network nodes may occur, resulting in the premature depletion of certain nodes. A higher count of functional nodes signifies more equitable energy utilization within the network, extending its lifecycle. Fig. 4 depicts the correlation between the number of functional nodes and the number of cycles Observations reveal that, when contrasted with the conventional LEACH protocol and the LEACH-E algorithm, the algorithm presented in this research sustains a higher quantity of

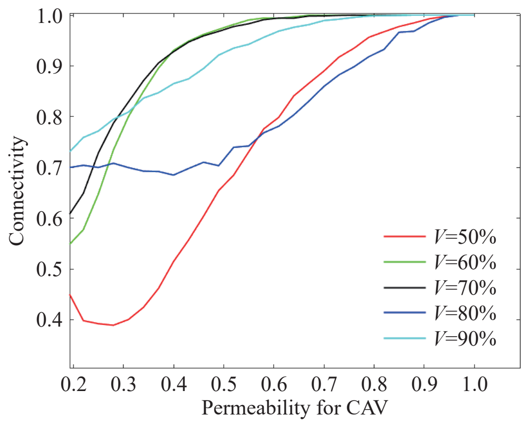

Fig. 5 Relationship between network connectivity and relative density at different CAV permeability.

active nodes. Those operated by the traditional LEACH protocol are exhausted at an accelerated rate, suggesting that the proposed algorithm fosters more balanced energy consumption among cluster nodes, even when node distribution is uneven.By introducing relay nodes from dense areas to alleviate the energy pressure caused by insufficient overall energy and long distances in sparse areas, the proposed algorithm reduces energy consumption within and between clusters, slows down the rate of node depletion, and extends the overall network lifetime more effectively.

4.4 Analysis of RSU deployment interval under the influence of relative density

4.4.1 RSU deployment: Permeability analysis

In accordance with the simulation setting detailed in Section 4.1, a diverse traffic concentration of 0.04 was established and following 2,000 simulations, the average communication radius for RSU and vehicles was set to 300 m. It is concluded that the network connectivity is affected by the permeability of CAV and the degree of non-uniform distribution, namely, relative density. From Fig. 5, it is evident that when the relative density of vehicle nodes on the highway remains constant, an increase in the permeability of CAV significantly enhances network connectivity. Meanwhile, as the relative density of vehicle nodes increases, indicating a more concentrated spatial distribution of vehicles, network connectivity also improves. When the relative density of vehicles exceeds 60% and the permeability exceeds 0.2, network connectivity exceeds 50%. Moreover, when the permeability exceeds 0.7, the connectivity under different relative densities exceeds 80%. These indicate that as more vehicles become network-enabled, the communication capabilities between vehicles are enhanced, contributing to the formation of a denser and more efficient communication network. In vehicle-dense areas, communication between vehicles is more frequent, contributing to the stability and reliability of the network.

Following the formulation analysis presented in Section 1.2, relationship between the average vehicle cluster in dense and sparse areas and the relative density and CAV permeability was obtained through MATLAB simulation analysis. To visually illustrate this relationship, the variations in vehicle cluster length in dense and sparse areas were presented in the same three-dimensional plot, as shown in Fig. 6. In Fig.6, the surface where vehicle cluster length increases with the increase of permeability and relative density represents the variation of vehicle cluster length in dense areas, while the other surface represents the variation of vehicle cluster length in sparse areas. The illustration shows that in congested zones, the average vehicle cluster length fluctuates in response to changes in the permeability of CAVs within the mixed traffic flow. With a constant vehicle density, an increase in CAV permeability results

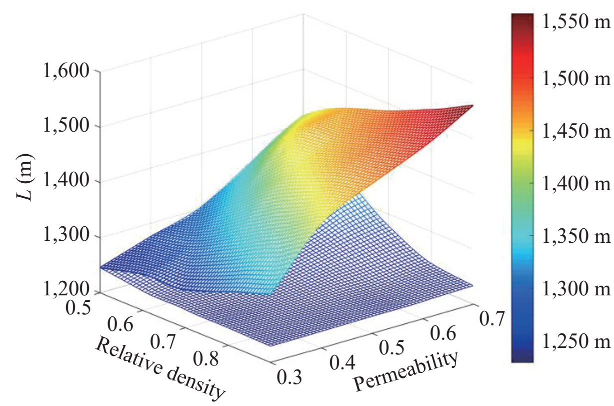

Fig. 6 Influence of permeability and relative density on the length of vehicle clusters in dense and sparse areas.

in reveals an extended average length of vehicle clusters. Likewise, a consistent CAV permeability yields an extended average vehicle cluster span when the vehicle density is higher. These findings resonate with real-world conditions.

As shown in the RSU deployment plan from Section 1.1, the interval between RSU deployments is determined by increasing the average vehicle cluster length significantly extends, reaching up to double the RSU transmission range, i.e., $L(R)=E(C)+2R$. From Fig. 7, observations indicate that in the mixed traffic flow, when the permeability of CAV is low at 0.3, the relative density of vehicles corresponds to 0.7, indicating a relatively concentrated distribution of vehicles, the RSU deployment interval is configured to be 1,851 m. According to Fig. 5, at this point, the network connectivity exceeds 80%. Conversely, when the CAV permeability is higher at 0.7 in the mixed traffic flow and the relative density of vehicles is 0.5, indicating a relatively uniform distribution of vehicles, the RSU deployment interval is configured to be 2,015 m. According to Fig. 5, at this point, network connectivity approaches 90%.

4.4.2 Analysis of RSU deployment considering vehicle density

Configuring the RSU and vehicle communication radius to 200 m, with a vehicle permeability of 1, and assuming that all vehicles have networking capabilities to participate in vehicle cluster formation, Fig. 8 the figure demonstrates the impact of highway traffic density and relative vehicle density on network connectivity. It is observed that with increasing traffic density, the network connectivity of vehicles increases. Moreover, under the same vehicle density, a higher relative density leads to greater vehicle aggregation and higher network connectivity. When the traffic density exceeds 0.01, the vehicle connectivity consistently exceeds 80%. Furthermore, when the traffic density exceeds 0.04 and the relative

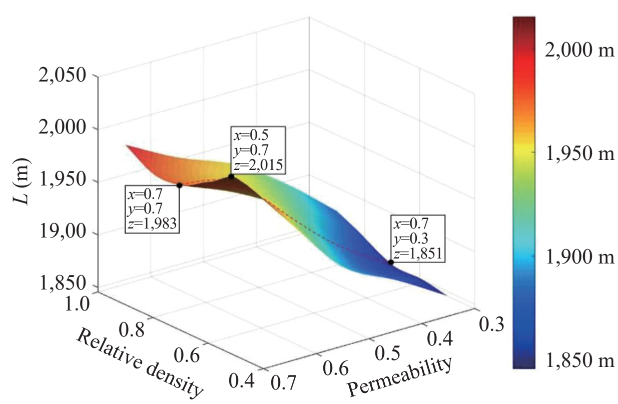

Fig. 7 Relationship between RSU deployment interval and traffic density and permeability.

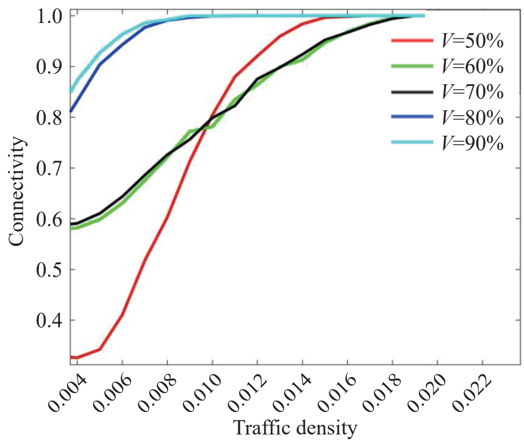

Fig. 8 Relationship between network connectivity and relative density at different traffic densities.

density exceeds 80%, network connectivity remains above 80%.

Exploring how the vehicle cluster length changes with variations in relative density and traffic density, Fig. 9 presents the changes in cluster length in dense and sparse areas. The plane represented by the red curve in Fig. 9 indicates the trend of vehicle cluster length increasing with the rise of relative density and traffic density in dense areas. Specifically, the red curve indicates that when the traffic density in dense areas is fixed at 0.01, the length of the vehicle cluster is adjusted with the change of the relative density. It is observed that in areas with relatively concentrated vehicles, the size of vehicle clusters expands as vehicles further aggregate, and the rate of growth in vehicle cluster length accelerates with increasing traffic density. This suggests that even a slight increase in relative density in areas with many vehicles leads to a significant increase in vehicle cluster length. In contrast, the plane represented by the green curve indicates the opposite trend of decreasing vehicle cluster length with increasing relative density in sparse areas. Specifically, the green curve indicates that when traffic density in sparse areas is fixed at 0.01, the decrease in vehicle cluster length with changes in relative density is shown. This may be due to the fact that in areas with fewer vehicles, the relative density has increased, there are fewer vehicle nodes instead, and the actual distance between vehicles is further, which limits the expansion of vehicle clusters. At the same time, the decreasing trend of vehicle cluster length becomes more obvious with the promotion of traffic density, which indicates that the increase of traffic density does not lead to significant expansion of vehicle clusters when there are fewer vehicles.

As shown in Fig. 10, the variation of vehicle cluster length with changes in relative density and traffic density is observed. In this

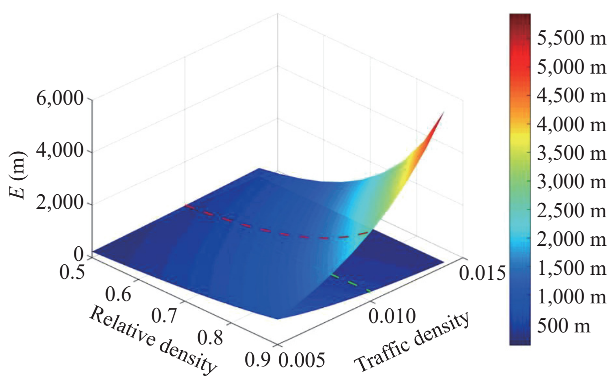

Fig. 9 Impact of traffic density and relative density on vehicle cluster length in dense and sparse areas.

figure, the red curve specifically shows how the cluster length changes with variations in relative density when the traffic density remains at 0.01. The overall length of the cluster increases with increasing relative and traffic densities. Furthermore, under the same traffic density conditions, an increase in relative density leads to a significant increase in cluster length, indicating a direct impact of vehicle aggregation on cluster size. It is noted that when the traffic density on the highway is 0.01 and the relative density is 0.5, indicating a relatively uniform distribution of vehicles, the RSU deployment interval is configured to be 641 m. According to Fig. 8, at this point, vehicle network connectivity approaches 80%. Conversely, when the relative density is 0.9, indicating a more concentrated distribution of vehicles, the RSU deployment interval is configured to be 1,887 m. According to Fig. 8, at this point, vehicle network connectivity approaches 100%.

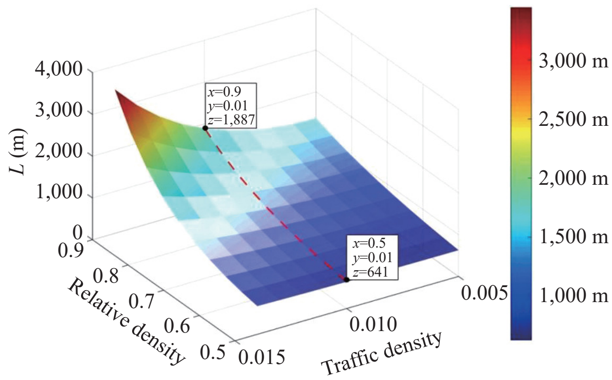

Fig. 10 Relationship between RSU deployment interval and relative density and traffic density.

5 Conclusion

This paper examines the mobility traits of vehicle clusters, the clustering tendencies of vehicles, and the uneven aggregation patterns observed in mixed traffic flow on highways. Aiming at the influence of uneven distribution degree deployment of RSUs on highways with mixed traffic flow, this paper takes into account elements like mixed traffic density and CAV permeabilityand relative density, and improves LEACH algorithm. The LEACH algorithm is improved by updating the threshold function considering the distance control factor, residual energy factor, and density factor. The algorithm divides vehicle nodes into high and low density areas, assigns energy to each area, and paper examines different elements such as mixed traffic density and CAV permeability. and employs clustering of vehicles using the enhanced LEACH clustering algorithm proposed herein. A comparative evaluation of the network performance is conducted among the traditional LEACH protocol, the advanced LEACH-E algorithm, and the LEACH-IM algorithm introduced in this study. The subsequent conclusions are derived:

(1) The Em-LEACH algorithm proposed in this paper consumes less network energy and retains more residual energy, indicating a more balanced energy consumption after the improvement. The selection of cluster heads fully considers the current residual energy of nodes, the distribution of candidate nodes, and the density of nodes within the communication range, increasing the probability of selecting candidate nodes with more residual energy, closer to the RSU, and with greater node density within the communication range as cluster heads.

(2) The proposed algorithm retains more active nodes in the network, indicating a more balanced energy consumption of intra-cluster nodes when facing unevenly distributed nodes. By adding relay nodes from dense areas to share the pressure of sparse areas due to insufficient total energy and long distances, the energy consumption within and between clusters is reduced, slowing down the

node death rate, effectively enhancing network lifespan and stability.

Through MATLAB software simulation, the relationship between varying levels of CAV permeability, vehicle uneven distribution degree and mixed vehicle flow density on network connectivity, the analysis of vehicle cluster span and RSU deployment period within mixed traffic flow provides the following insights:

(1) With a diverse traffic density of 0.04, with an average RSU and the vehicle communication radius of 300 m, CAV permeability at 0.3 is notably low, and the relative density of vehicles is 0.7, indicating a relatively concentrated distribution of vehicles, the RSU deployment interval is configured to be 1,851 m. When the permeability of the CAV is elevated at 0.7 and the relative density of vehicles is 0.5, indicating a relatively uniform distribution of vehicles, the deployment interval for the RSU can be set at 2,015 m.

(2) Given a communication radius of 200 m for both the RSU and the vehicles, and a vehicle permeability of 1, when the highway traffic density is 0.01 and the relative density of vehicles is 0.5, indicating a relatively uniform distribution of vehicles, the deployment interval for the RSU can be adjusted to 641 m. However, when relative density of vehicles reaches 0.9, signifying a more densely distributed vehicle pattern, the deployment interval for the RSU should be set to 1,887 m.

These deployment strategies guarantee the maintenance of high-level network connectivity.This research offers a theoretical foundation for establishing fair and efficient measures restricted stock units deployment intervals based on future highway CAV permeability and vehicle uneven distribution.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Author contribution statement

Jiyuan Zhou: Conceptualization, Writing-review. Xiaolin Yu: Formal analysis, Investigation. Jian Geng: Visualization. Ying Zhang: Data curation. Luyu Zhang: Writing - original draft. Zhenhua Mou: Methodology.All authors have reviewed and approved the final version of the manuscript.

Data availability statement

The datasets generated during and analyzed during the current study are not publicly available due to privacy or ethical restrictions but are available from the corresponding author on reasonable request.

Use of AI statement

During the preparation of this work, the authors used ChatGPT to generate initial code snippets for data analysis.The output was subsequently modified and integrated by the authors. The authors take full responsibility for the final content.

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