



Available online at www.qu.edu.iq/journalcm
JOURNAL OF AL-QADISIYAH FOR COMPUTER SCIENCE AND MATHEMATICS
 ISSN:2521-3504(online) ISSN:2074-0204(print)



Energy and Mobility-based Routing Protocol for E-VANET

Ahmed Jawad Kadhim*

Ministry of Education, General Directorate for Education in Al-Qadisiyah, Al-Qadisiyah, Iraq. Email: ahmed_al_shaibany@yahoo.com

ARTICLE INFO

Article history:

Received: 23 /05/2026

Revised form: 22 /06/2026

Accepted : 24 /06/2026

Available online: 30 /09/2026

Keywords:

E-VANET

Electric Vehicles

Routing Protocol

Energy

Mobility

ABSTRACT

Electrical Vehicular Ad Hoc Network (E-VANET) is the future version of vehicular networks, which comprises a significant number of stopped and mobile electric vehicles connecting in a vast geographic area. It aims to exchange real-time information about weather, roads, accidents, traffic congestion, and other relevant details. The main issues that reduce the efficiency of routing in E-VANET are dynamicity due to the vehicle mobility and limitations of the vehicle's battery, which must be recharged frequently. In E-VANET, the vehicle's residual energy and energy consumption through path constructing and data forwarding affect the lifetime of electric vehicles and selected routes. Moreover, vehicle mobility affects the stability and lifetime of the selected route, and as a result, increases energy consumption during frequent route reconfiguration processes. Therefore, the data routing operations in E-VANET require a dedicated routing scheme that considers vehicle mobility, energy consumption, and battery limitations. Thus, a novel routing approach based on energy and mobility for E-VANET called REME is proposed in this paper. It depends on formulating the routing problem as an optimization mathematical model, which is focused on the mobility and energy factors in constructing the optimal routes. In this model, the mobility factors represent the average velocity and direction of each pair of connected vehicles. Moreover, the energy factors refer to the vehicle's residual energy and the total energy required to send data from the source to the destination. REME assigns a priority to each pair of connected vehicles with residual energy exceeding their thresholds and moves them at the minimum average velocity in the same direction, thereby maximizing the chance for them to function as intermediate nodes in the constructed route. From various simulation scenarios, we concluded that REME is superior to AH-SFLA and SANCV according to average route stability, energy consumption, network overhead, and number of dead electric vehicles.

<https://doi.org/10.29304/jqcm.2026.18.32923>

1. Introduction

Electric vehicles (EVs), which use electric engines for movement, are the future of the transportation sector. They depend completely on electricity, which is stored in rechargeable batteries [1, 2]. Now, many countries around the world, such as the United States, China, Japan, Germany, and Norway, have many manufacturers and big markets for buying and selling electric vehicles [3]. These vehicles are characterized by being environmentally friendly in terms of reducing CO₂ emissions compared to diesel vehicles, having lower operating costs due to cheaper electricity prices in most countries, and requiring less maintenance [4]. Connecting this type of vehicle to share information about various events creates a new network style named Electric Vehicular Ad-Hoc Network: E-VANET [5].

E-VANET is a future network inspired by the Vehicular Ad Hoc Network (VANET). It involves connecting electric vehicles and infrastructure (i.e., base station (BS), roadside unit (RSU)) to share information [5]. It can be used in various applications, such as safety monitoring, driving assistance, and transportation traffic management, to

*Corresponding author

Email addresses:

Communicated by 'sub editor'

enhance roadway safety, reduce traffic congestion, and support the energy-efficient transportation sector [3]. It uses vehicle-to-vehicle or vehicle-to-infrastructure (V2V, V2I, I2V, and I2I) connection modes to simplify the exchange operations of essential information and data between moving and stopping vehicles and fixed network nodes [6]. Like VANET, E-VANET suffers from several issues, such as bandwidth limitations, high vehicle mobility, frequent route and link breaks, and a highly dynamic topology [7]. They affect the efficacy and performance of routing, increase energy consumption, overhead, packet loss rate, and disconnection statuses, while reducing throughput, packet delivery ratio, delivery time, and vehicle lifetime [8, 9].

The problem that this paper tries to solve can be summarized as follows:

Mobility and battery limitations are the primary challenges in E-VANET, significantly impacting routing efficiency. Increasing the velocities of the intermediate vehicles that belong to the selected route maximizes the probability of disjointed links and, thus, negatively affects the stability and lifetime of that route. In addition, the direction of each pair of connected vehicles affects the stability of the link between them, so that vehicles moving in opposite directions may become disconnected after a short time. The unstable routes, which frequently experience broken links, increase the number of route maintenance processes and thus consume a significant amount of vehicle energy. On contract, the vehicles that move in the same direction stay connected for a long time. As a result, it is better to focus on the velocity and direction of each pair of connected vehicles. In addition to the vehicle movement, the data exchange operations among electric vehicles consume a large amount of energy and affect their lifetime, which ultimately impacts route stability and lifetime.

Previous papers [10-35] focused on the routing problem in VANET and presented various types of routing and forwarding algorithms. However, they are not suitable for E-VANET because they do not pay close attention to energy consumption, as the batteries of diesel vehicles in VANET are automatically recharged during the vehicle's movement. Thus, E-VANET requires a new, efficient energy and mobility-aware routing approach to build routes that minimize energy waste and take into account the vehicle direction and velocity of the connected vehicles. This is the motivation that drives us to produce an efficient solution for the above problems in this research paper. To the best of our knowledge, it is the first paper of its kind to focus on the routing problem in E-VANET. The contributions of this research article are as follows:

- We produce a new routing scheme to construct the optimal route from source to destination. It searches among the available routes and selects the best one that contains a set of links that consume the minimum energy and have connected vehicles moving at the minimum speed. Moreover, it takes into account the vehicle direction and residual energy level of each pair of connected vehicles.
- We formulate the route problem as an optimization model that focuses on minimizing the impact of vehicle mobility and energy consumption. Moreover, it concentrates on the residual energy of the candidate intermediate nodes. It brings about the greatest change to nodes that move in the same direction and have residual energy exceeding the threshold, thereby increasing route stability and lifetime.
- In contrast to previous papers, which assign a fixed energy threshold for all types of electric vehicles, we calculate a specific threshold for each electric vehicle based on its battery capacity.
- We focus on the average velocity of each pair of connected vehicles, rather than the velocity of each vehicle, to reduce the probability of the link being broken.

The rest sections can be structured as follows: section 2 shows a set of previous routing strategies in the vehicular networks, section 3 outlines the system model, section 4 illustrates the designed routing algorithm, and section 5 displays the simulation scenarios and findings, while the conclusions and future plans are presented in the last section.

2. Related Works

Transmitting data from one point to another, whether in traditional or Software-Defined Network (SDN)-based VANET architectures, requires an efficient routing scheme. Thus, the researchers developed various routing techniques to transmit data with different quality of service (QoS) parameters in different VANET architectures. They can be classified as follows:

2.1. Traditional VANET

Many researchers in [10-26] have focused on the routing problem in traditional VANETs and have produced various novel, efficient schemes that depend on different ideas and solutions. They are as follows:

S. K. Bhoi et al. [10] produced a local traffic-aware routing algorithm to mitigate the negative effects of network fragmentation caused by mobility in VANET. It utilizes the available fixed nodes to transmit data and employs moving vehicles as virtual fixed nodes when there are no real fixed nodes in a geographical area. Moreover, the authors employed an efficient method that relies on exchanging information related to vehicle location to determine the best set of nodes to forward data with minimal delay. J. Wu et al. [11] introduced a reinforcement learning-based routing policy for VANETs, supported by roadside units, to reduce the impacts of vehicle movement. It collects road traffic information using the Q-learning policy to build the most reliable path. They assumed that data forwarding in the road segment is done using neighboring vehicles, whereas it is actually done using roadside units in the intersections. R. Sadakale et al. [12] proposed a routing algorithm that works reactively in VANET supported by infrastructure to send data to the destination with a high degree of resource utilization. They merged trustworthy routing with the group authentication keys policy to enhance performance and authentication levels. J. Nadarajan et al. [13] integrated secure 3D logistic chaotic with stochastic-based adaptive routing and produced an efficient routing approach to perform unicast transmission with low delay and high stability. It utilizes a robust deep learning algorithm called Boosted Long Short-Term Memory, which provides high prediction capabilities to construct the optimal route based on traffic knowledge. R. Ramamoorthy et al. [14] proposed a new routing protocol with the help of an improved version of ant colony optimization. First, it measures the distance between vehicles. After that, the source vehicle determines the best route, which has a minimum number of hops and a low communication cost, to forward data to the destination. A. J. K. Al-Shaibany [15] proposed a clustering technique that assigns a high degree to parked vehicles to serve as cluster heads. After that, a cluster-based routing method was proposed to compute the optimal path for transmitting safety messages quickly, with a high level of link stability, using a mathematical optimization model. O. Alzamzami et al. [16] focused on a set of parameters that are the queuing and retransmission delays, medium access control overhead, physical interference, and loss ratio, and designed a cross-layer model. After that, they utilized the proposed model to enhance geographic routing, selecting routes with a high level of reliability to minimize time cost and packet drops. M. A. Shah et al. [17] proposed a routing scheme that considers the distance and mobility parameters of the source and destination vehicles to efficiently determine and maintain the route in the VANET highway environment. It is designed to transmit warning messages with low delay, packet loss, and high throughput and reliability. R. K. Mahesh et al. [18] produced two contributions: the cluster formation technique and the smart forwarding approach for VANET. Former works depend on link features, such as signal-to-interference-plus-noise ratio and link consistency rate. The latter is determined by a probability routing protocol, which considers the signal strength when computing the optimal route. M. Sindhwani et al. [19] merged the support vector machine with the k-means clustering approach and produced an efficient context-aware routing scheme. It prioritizes clusters with high mean square error and selects the most reliable route as the optimal one for transmitting data content with the minimum delivery time. A. Naeem et al. [20] suggested a routing protocol to enhance the stability and lifetime of the cluster head and VANET throughput. They utilized the Sugeno model fuzzy inference framework to determine a set of metrics, including distance to fixed nodes, node degree, local distance, and concentration, during the cluster formation process and cluster head selection. B. Mehdi et al. [21] proposed a new intersection-based geographic routing approach for VANET in the smart city. Their proposed approach considers a set of parameters in the intersection, such as distance, direction, and traffic density, to compute the best route. L. Rui et al. [22] produced a new routing technique to enhance the route reliability and stability and solve the local optimization problem in VANET. It works depending on the connection quality and the delay incurred during the selection of the next intersection, utilizing reinforcement learning and greedy decision-making approaches. S. Ullah et al. [23] presented a routing approach to calculate a route with high stability and low beacon congestion for sending emergency messages in both low- and high-density VANETs using V2V and V2I connections. It predicts the relative positions of neighbors and determines the most reliable relay vehicle based on mobility metrics, such as speed, direction, and distance, to increase route stability. Moreover, the authors assumed that RSU can be used as a relay node to forward the messages using V2I when the number of vehicles is low. R. Ramamoorthy [24] combined two techniques to increase the reliability and security of data transmission in VANET. They are location-aided key management and ant colony routing. The former is used to discover the safest and shortest path, while the latter enhances the security and reliability of the whole network. A. K. Kazi et al. [25] presented an adaptive context-aware routing scheme to address the challenges of variable vehicle density, dynamic topology, and high mobility in urban VANET. Their presented scheme merges geographic forwarding, dynamic clustering, and context-aware routing to optimize QoS under various traffic conditions. R. Muthaiyan et al. [26] proposed a routing protocol depends on multi-objective optimized model to enhance the route reliability and transmission delay in VANET. In their proposal, they modeled the network in the first stage, and then designed a Meta heuristic algorithm, and finally wrote the routing algorithm.

2.2. SDN-based VANET

Several routing protocols [27-35] that leverage the capabilities of SDN and its global network information to find the most effective routes in VANET have been proposed. They are as follows:

Y. Tang et al. [27] presented a routing policy for SDN-based VANET. Their policy applies an artificial neural network-based prediction method in the SDN controller to determine the mobility of vehicles depending on the collected information from the fixed nodes. After that, the SDN controller builds the optimal route for fixed nodes using this information to increase the stability degree. K. L. K. Sudheera et al. [28] applied the concept of SDN in VANET and produced a Tribrid routing scheme. The proposed protocol aims to select the shortest and most stable routes in both distributed and centralized manners to perform unicast, broadcast, and store-and-forward transmission modes with high-quality service. K. Eirini et al. [29] integrated the SDN concept with the named data networking connection approach. It focuses on the content of transmitted data by computing the route with a small number of connected intermediate vehicles. To achieve this, they assumed that a set of antennas is presented in roadside units and vehicles along the roads to participate in unicast data forwarding. D. Xinxin et al. [30] applied the concepts of SDN and forwarding separation approach to guarantee QoS in VANET. Moreover, they proposed a new routing algorithm, called the Adaptive Hybrid Shuffled Frog-Leaping Algorithm (AH-SFLA), to compute the optimal route. In this protocol, the arrived route requests are scheduled based on the deadline by the SDN controller. Finally, the controller exploits its global network information and VANET environment as input to AH-SFLA to determine the best route with high QoS for each request. H. Zhu et al. [31] designed an SDN and ant colony optimization-based routing protocol for VANET called SANCV. They suggested that each RSU node determines its neighbor RSUs and sends them ant packets during various periods. Depending on the received packets, each RSU computes information about the connection quality of the street segments that connect it with other neighbors. After that, it forwards this information to the SDN controller, which builds the optimal route to each destination based on the collected knowledge from all RSUs. P. Sehrawat et al. [32] focused on managing data traffic using random paths to the destination and proposed an efficient, secure and safe routing scheme for SDN-based VANET. It consists of route configuration, query control techniques, and route reconfiguration mechanisms, and operates based on the combination of information related to node position, speed, and mapping. Z. H. Ali [33] suggested an SDN-based routing method to optimize the delivery of emergency message with high reliability in VANET. It depends on the collected information by the SDN controller to reduce the possibility of a link failure and select the optimal next-hop. Moreover, it used a store-carry-forward policy to forward the data packet to the destination successfully with minimum network congestion. S. Ahmed et al. [34] designed a geographic cluster-based routing scheme for SDN-based vehicular network. In this proposed scheme, there are three stages, first, cluster formation using chaotic ant swarm optimization algorithm. Second, cluster head determination and finally, finding the closest neighboring vehicles using neighbor search method. S. J. Rajan et al. [35] exploited the benefits of SDN to improve the scalability and accuracy of routing of data in SDN-based VANET. Moreover, they used priority algorithms and the Zigbee protocol to increase quality of service of traffic flow.

Nonetheless, SDN-based architectures and routing schemes require the frequent exchange of information related to network links and vehicles with the SDN controller(s). They consume a large amount of link bandwidth and vehicle energy. Thus, the theoretical analysis explains that applying them in E-VANET negatively affects both the network and the electric vehicle's lifetime. Moreover, it will be proven practically in the simulation and evaluation section. On the other hand, traditional routing policies are not suitable for E-VANET because they do not take into account the energy consumption and residual energy of vehicles, which are crucial parameters in E-VANET. Moreover, they focused on the mobility factors such as the velocity and direction of each vehicle. However, they ignored the factors affecting the energy consumption of EVs and the lifetime of E-VANET for each pair of connected vehicles, and instead discovered and corrected routes. This motivates the development of a routing protocol called REME, which considers energy and mobility parameters, as discussed in the following sections. REME differs from previous protocols in that: i. focusing heavily on the battery capacity of electric vehicles. It considers both the vehicle's residual energy and the total energy required to send data. ii. It assigns a priority to each pair of connected vehicles with residual energy exceeding their thresholds and moves them at the minimum average velocity in the same direction. Therefore, this pair has the highest likelihood of working as intermediate nodes. iii. Instead of assigning a fixed energy threshold for all types of vehicles as used in the previous research works, the proposed protocol computes the energy threshold for each EV based on its battery capability. iv. Rather than the velocity of each vehicle, REME focused on the average velocity of each pair of connected vehicles to reduce the status of the failure links.

3. System Model and Problem Formulation

This paper focuses on pure E-VANET, where electric vehicles connect using V2V mode without any fixed nodes (see Fig. 1). To increase the realism of the used architecture, the battery capacity is not fixed in all electric vehicles. However, it depends on the vehicle's type and size. Moreover, the electric vehicles N move at different velocities and directions, and each vehicle has a GPS to determine its mobility direction and location at time t and $t-1$. This information is stored by the vehicle in the database and added to the route request ($RREQ$) before it is forwarded to its neighbors. Table 1 shows the notations used in this article.

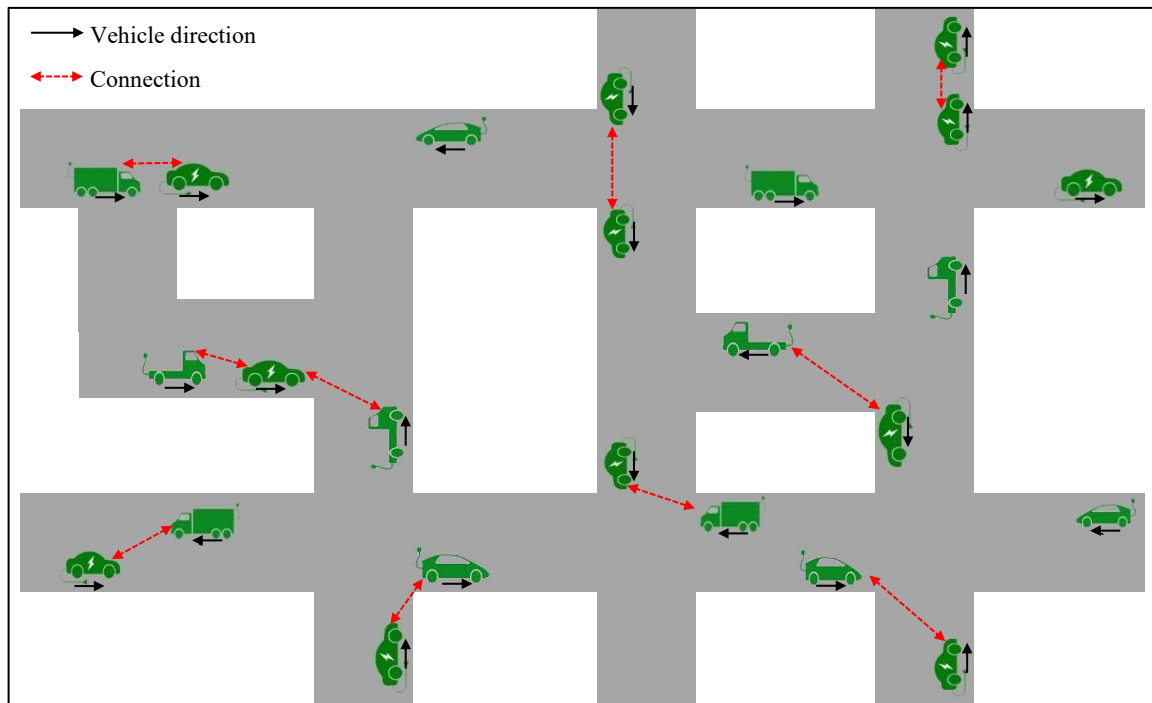


Fig. 1 – Pure E-VANET

Table 1 - Notations

Notation	Description
N	It is a set of all electric vehicles.
M	It represents a set of vehicles that forward the $RREQ$, and their information has been added to the $RREQ$ along with the destination vehicle.
L	It is a set of links.
λ_{ij}	Priority weight of the link between electric vehicles i and j . It is determined depending on the residual energy and energy threshold.
R_i	It is the residual energy of the electric vehicle i .
β_i	It is the energy threshold of the electric vehicle i .
C_i	Battery capacity of vehicle i .
W_{ij}	It is the direction weight of the link between the connected electric vehicles i and j . It is determined depending on the mobility direction and distances between these vehicles at different time slices.
μ_{ij}	It is the average velocity of electric vehicles i and j .
α_i	The average energy required to send one byte by the electric vehicle i .
D	It is the total data volume which must be forwarded to the neighboring vehicles.
γ_{ij}	It is the required energy to send the data D from vehicle i to j .
Max_v	It is the maximum value of the average velocity in the $RREQ$ information
Max_e	It is the maximum value of link energy consumption in the $RREQ$ information.
V_{ij}	It is the normalized measure of the average velocity of the vehicles i and j .

E_{ij}	It is the normalized measure of the required energy cost to send data from vehicle i to vehicle j .
x_{ij}	It is a variable that represents the link from vehicle i to vehicle j and may takes the value 0 or 1.
K	It is the vehicle that sent or forwarded the route request $RREQ$ and its ID at the end of $RREQ$.
Q	It represents a set of neighbor vehicles that received the $RREQ$.
N_s	It represents a set of neighbor vehicles of the sender vehicle s and they received the $RREQ$ from it.
U	It is the number of vehicles in Q .
N_j	It represents a set of neighbor vehicles of vehicle j , and they received the $RREQ$ from it.

In this paper, route discovery is achieved at the destination vehicle, which initially extracts information from the received $RREQ$. After that, it computes the priority weight λ_{ij} , direction weight W_{ij} , average velocity V_{ij} , and energy cost E_{ij} of each link between each pair of connected vehicles as follows:

3.1. Residual Energy Weight

Energy threshold is one of the critical parameters, and computing it inaccurately affects the lifetime of the selected path and increases the number of dead electric vehicles. In the previous research works, the energy threshold is assigned as a fixed value. It is an irrational procedure because there are several types of electric vehicles, and each one has a different type and size of battery. Thus, it is best to rely on the battery capacity of each EV as a primary factor in calculating the energy threshold of that EV.

The vehicle with residual energy exceeding its energy threshold has the largest chance of functioning as an intermediate node compared to one with residual energy below the threshold. The destination determines the residual energy weight of the connection between vehicles i and j based on their residual energy. In this research work, we use "priority weight λ_{ij} " as a reference to the residual energy weight, which is determined as follows:

$$\lambda_{ij} = \begin{cases} 0.1, & \text{if } (R_i > \beta_i) \wedge (R_j > \beta_j) \\ 0.3, & \text{if } (R_i = \beta_i) \wedge (R_j = \beta_j) \\ 0.5, & \text{if } (R_i \geq \beta_i) \wedge (R_j < \beta_j) \text{ or } (R_i < \beta_i) \wedge (R_j \geq \beta_j) \\ 1, & \text{if } (R_i < \beta_i) \wedge (R_j < \beta_j) \end{cases} \quad \forall i, j \in M, \quad (1)$$

In equation (1), we assumed that the lowest value of λ_{ij} is assigned to the best case, as the objective function is minimized, as shown in equation (8). In contrast to previous papers, which assume a fixed energy threshold for all types of vehicles, we compute a specific energy threshold β_i for each electric vehicle, depending on its battery capacity. Thus, we assume that the value of β_i for each EV is equal to one-quarter of its battery capacity, because each one has a battery with some capacity and differs from the other vehicles. Each vehicle in E-VANET must compute its energy threshold and include it in the $RREQ$, as shown in Section 4. It can be calculated as follows:

$$\beta_i = C_i/4, \quad \forall i \in N, \quad (2)$$

3.2. Direction Weight

In most previous papers, each vehicle sends a *BEACON* message frequently, and the neighbor vehicles that receive it will send an *ACK* message as a response. Depending on the sending time of the *BEACON* message and the receiving time of the *ACK* message, the vehicle determines the nearest and farthest neighbors to be used in the routing procedure. However, sending these messages frequently increases energy loss, and as a result, it is not suitable for E-VANET. Thus, this paper avoids sending *BEACON* messages among electric vehicles to save energy.

To determine the priority of each link between each pair of connected vehicles i and j to be added to the selected route by taking vehicle directions into account, a direction weight W_{ij} is assigned for that link. Its value is determined depending on the mobility directions and distances between vehicles i and j at different time slices. To do that, let p_i be a variable that represents the vehicle's direction and takes the values 1, 2, 3, or 4 when the vehicle moves toward the north, south, east, or west, respectively. The value of W_{ij} is determined as follows:

$$W_{ij} = \begin{cases} 0.1, & \text{if } p_i = p_j \\ 0.3, & \text{if } (p_i \neq p_j) \wedge (d_{ij}^t < d_{ij}^{t-1}) \\ 1, & \text{otherwise} \end{cases} \quad \forall i, j \in M, \quad (3)$$

Where d_{ij}^t and d_{ij}^{t-1} are the distances between the electric vehicles i and j at t and $t-1$. The distances between each pair of connected vehicles are computed as in [15] after importing location information from $RREQ$.

In any vehicular network, the vehicles' direction can be one of the following cases:

Case 1: See Fig. 2(a). It occurs when the vehicles i and j move in the same direction (i.e., $p_i = p_j$). In this case, the stability of the link will persist for a long time, and as a result, it is the best case, with the optimal direction weight $W_{ij} = 0.1$.

Case 2: See Fig. 2(b). It occurs when the vehicles i and j don't move in the same direction (i.e., $p_i \neq p_j$) and the distance between the vehicles i and j at time t is less than the distance between them at time $t-1$. It is a good status, but it may change to case 3 over time. The value of direction weight is $W_{ij} = 0.3$.

Case 3: See Fig. 2(c). It occurs when vehicles i and j don't move in the same direction and the distance between vehicles i and j at time t is more than the distance between them at time $t-1$. This is the worst-case scenario, where the bad value of direction weight $W_{ij} = 1$.

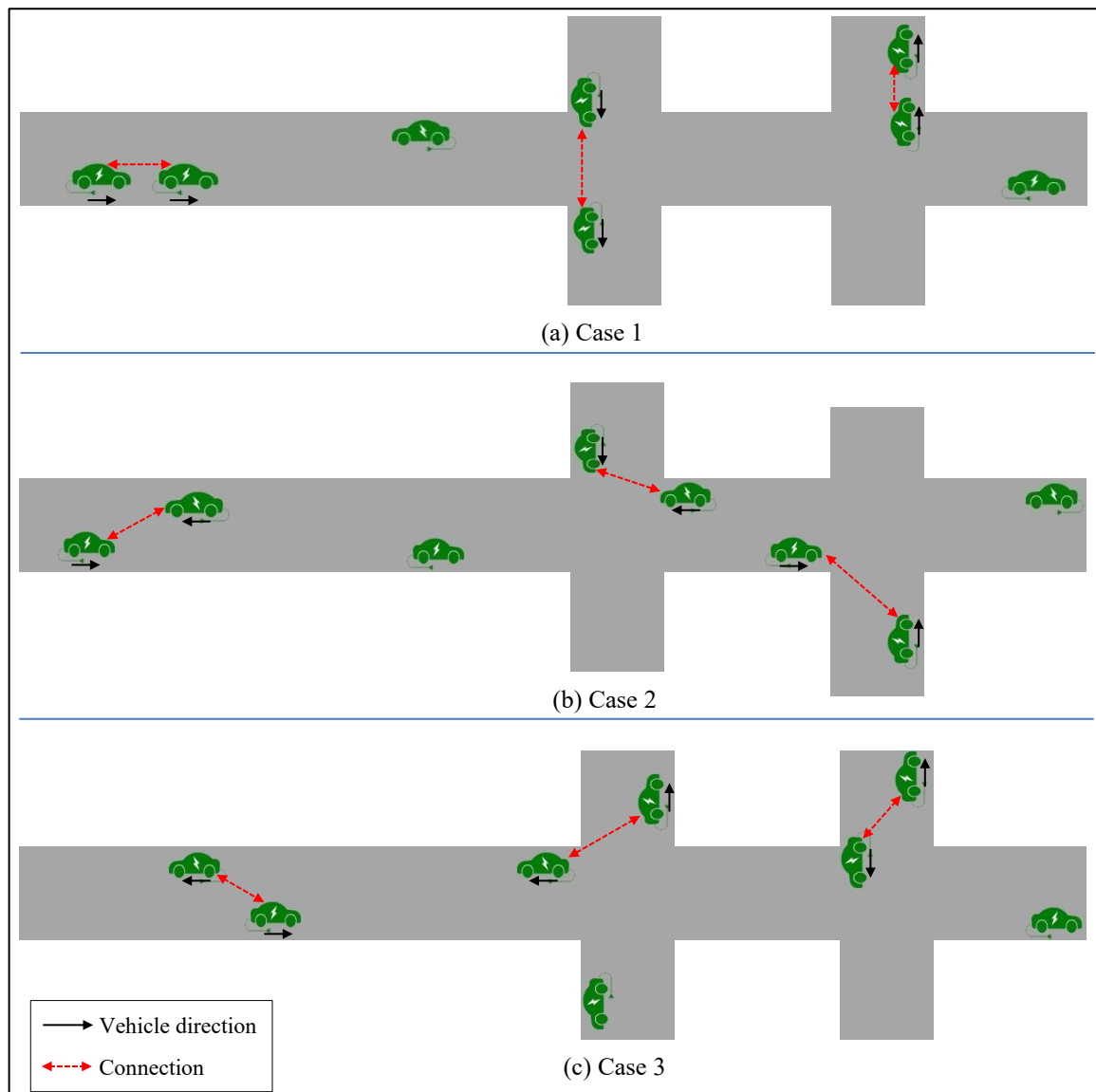


Fig. 2 - Cases of Vehicle Direction.

3.3. Average Velocity

The mobility of vehicles at different velocities has a significant impact on network and link stability, which requires a substantial amount of energy to maintain. However, previous papers focused on the velocity of each vehicle and did not consider the relationship between the velocities of the connected vehicles. Thus, the route stability of these

papers is low. However, we focus on the average velocity of each pair of connected vehicles to reduce the probability of the link breaking. The average velocity μ_{ij} can be computed as follows:

$$\mu_{ij} (s_i + s_j)/2, \quad \forall i, j \in M, \quad (4)$$

where s_i and s_j are the velocities of the electric vehicles i and j , respectively.

3.4. Energy Cost

To compute the energy cost, each vehicle sends three messages to its neighbors at different time intervals at the beginning of the network. The size of each message is one byte. Moreover, each vehicle computes the total energy consumed for these transmitted messages and divides it by 3 to calculate the average energy α_i required to send one byte.

When a vehicle receives *RREQ*, it extracts information about the size of data D (in bytes) that must be forwarded to its neighbors and applies the following equation to compute the required energy to send that data:

$$\Upsilon_{ij} = \alpha_i * D, \quad \forall i, j \in M, \quad (5)$$

After that, it adds information about the energy cost to *RREQ* before forwarding it to its neighbors.

The above weights were not selected randomly. Numerical analysis and several experiments were used to check which weights are suitable for each parameter and each status. In addition, from analyzing and investigating the values of average velocity, energy cost, priority weight, and direction weight, we noticed clear differences among them. The values of the required energy cost to send data over a link and the average velocity are large, while the priority weight and direction weight take values ranging between 0 and 1. These differences affect the accuracy of the results. Thus, it is better to normalize the values of average velocity and energy cost and convert them to values between 0 and 1 at the destination as follows:

$$V_{ij} = \mu_{ij}/Max_v, \quad \forall i, j \in M, \quad (6)$$

$$E_{ij} = \Upsilon_{ij}/Max_e, \quad \forall i, j \in M, \quad (7)$$

Finally, the destination models the information of *RREQ* and the outputs of the equations (1, 3, 6, and 7) as a weighted indirect graph $G = (M, L)$ where $M \subseteq N$. After that, it formulates the process of computing the best route as a Mixed Integer Programming (MIP) problem with an objective of a minimum effect of energy and mobility factors as follows:

$$Min \sum_{i,j \in M} E_{ij} \lambda_{ij} V_{ij} W_{ij} \quad (8)$$

S.T.

$$E_{ij} > 0, \quad \forall i, j \in M \quad (i)$$

$$\lambda_{ij} \in \{0.1, 0.3, 0.5, 1\}, \quad \forall i, j \in M, \quad (ii)$$

$$1 \geq V_{ij} \geq 0, \quad \forall i, j \in N, \quad (iii)$$

$$W_{ij} \in \{0.1, 0.3, 1\}, \quad \forall i, j \in M, \quad (iv)$$

$$x_{ij} + x_{ji} = 1, \quad \forall i, j \in N, \quad (v)$$

$$x_{ij} \in \{0, 1\}, \quad \forall i, j \in M, \quad (vi)$$

Equation (8) represents the objective function. The objective function can be evaluated using $O(N^2)$ time. The problem is NP-hard, and its memory complexity is $O(N^2)$. First constraint (i) indicates that the value of the necessary energy to transmit data from vehicle i to vehicle j must be more than 0. Second constraint (ii) explains that the priority weight of the link between the connected vehicles i and j must be 0.1, 0.3, 0.5, or 1, which is determined based on equation (1). Third constraint (iii) indicates that the normalized value of the average velocity of the connected vehicles i and j must be between 0 and 1. Fourth constraint (iv) is the direction weight, and its value must be 0.1, 0.3, or 1. Fifth constraint (v) is used to prevent data from entering a loop problem, ensuring that the data sent from vehicle i to vehicle j cannot be sent in the opposite direction from j to i . The final constraint (vi) indicates that the variable x_{ij} involves the value 1 if the connection between vehicles i and j has been chosen as part of the best route to the destination. Otherwise, it takes the value 0.

The above mathematical model has been tested and solved manually, as well as using CPLEX software, with several examples featuring various networks composed of different numbers of nodes. For instance, Fig. 3 represents a

graph formulated by the destination vehicle, EV_7 , to send data from the sender, EV_1 , to EV_7 . Each link in this graph is pointed with information about the needed energy cost (E_{ij}) to transmit data from vehicle i to vehicle j , average speed (V_{ij}), direction weight (W_{ij}) of the vehicles i and j , and priority weight (λ_{ij}) of the link from i to j . This information was input into CPLEX software to solve the proposed model and determine the optimal route to EV_7 . In this example, there are six available routes to send data from EV_1 to EV_7 , as shown in Table 2. The optimal route, with the minimum value, is $EV_1 \rightarrow EV_3 \rightarrow EV_6 \rightarrow EV_7$.

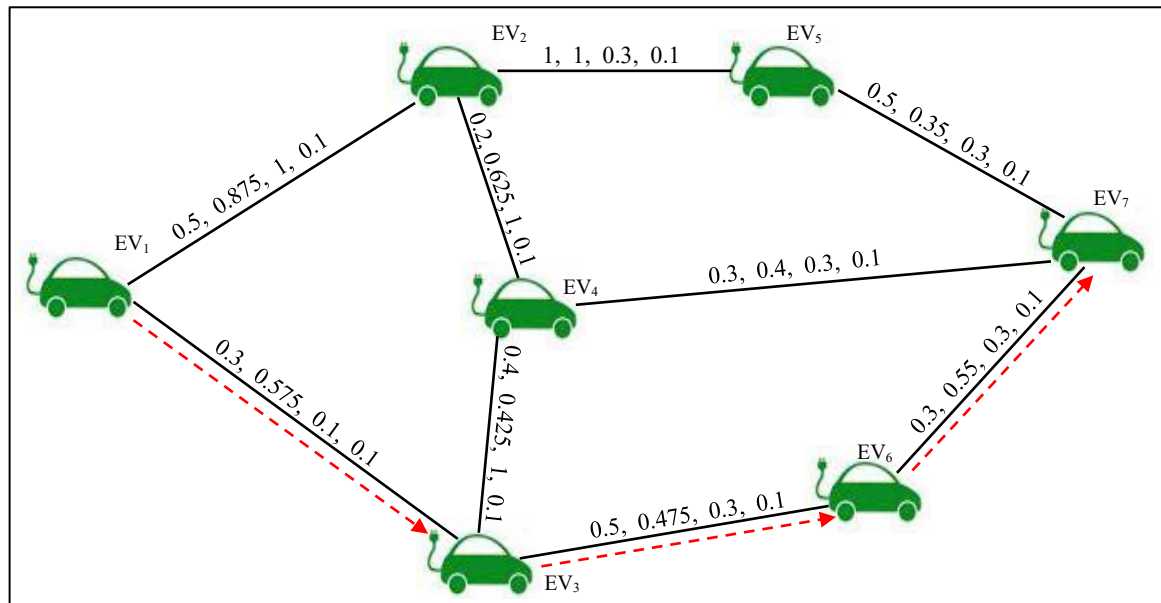


Fig. 3 - Example

Table 2 - Available Routes from EV_1 to EV_7 .

No.	Route	Value of applying equation (7)
Route 1	$EV_1 \rightarrow EV_2 \rightarrow EV_5 \rightarrow EV_7$	0.079
Route 2	$EV_1 \rightarrow EV_2 \rightarrow EV_4 \rightarrow EV_7$	0.05985
Route 3	$EV_1 \rightarrow EV_2 \rightarrow EV_4 \rightarrow EV_3 \rightarrow EV_6 \rightarrow EV_7$	0.085325
Route 4	$EV_1 \rightarrow EV_3 \rightarrow EV_6 \rightarrow EV_7$	0.0138
Route 5	$EV_1 \rightarrow EV_3 \rightarrow EV_4 \rightarrow EV_7$	0.022325
Route 6	$EV_1 \rightarrow EV_3 \rightarrow EV_4 \rightarrow EV_2 \rightarrow EV_5 \rightarrow EV_7$	0.066475

4. Suggested Routing Protocol

When a vehicle (let's s) has data and wants to transmit it to a different vehicle, it must find a route. The route construction and data forwarding processes require a large amount of energy. Moreover, due to vehicle mobility, the frequent correction operations of unstable links consume an amount of vehicle energy. In E-VANET, the energy and mobility of EVs are important factors. They play a big role in determining the stability and lifetime of the entire selected routes. Therefore, this paper proposes a novel mobility and energy-based routing scheme for E-VANET named REME. It aims to build the route with minimal energy and maximum stability. In addition to the energy cost of the links from the source to the destination, the residual energy in the vehicles is also taken into account when computing the route. Moreover, the stability of the links depends on the vehicle's velocity and direction.

In REME and at the beginning, the sender vehicle s broadcasts a route request $RREQ$ containing the source ID, destination ID, and data volume. **Algorithm 1** and Fig. 4 illustrate how the optimal route is discovered. Each of its neighbors that receives this $RREQ$ will check the destination ID and, if it is the intended destination, will send a route reply $RREP$ to s . Otherwise, it will rebroadcast the $RREQ$ after adding its ID and information about its location at times t and $t-1$, which is imported from GPS, including velocity, direction, residual energy, and energy threshold. Moreover, it sends back an ACK message. However, EV that has residual energy less than its energy threshold ignores the received $RREQ$. But when it receives the same $RREQ$ from the same vehicle, it understands that there is no neighbor for this vehicle and must forward this $RREQ$ and send back an ACK message.

This procedure reduces the likelihood of using EVs with minimal remaining energy as forwarding nodes, thereby decreasing the number of dead vehicles. **Note** that each vehicle receiving the same *RREQ* from more than one vehicle will be manipulated with one of them has residual energy more than the threshold, and the rest will be ignored to reduce network flooding, energy consumption, and loop problems.

When the destination receives this *RREQ* from one or more vehicles, it extracts the information about the residual energy, direction weight, average speed, etc., of all links and vehicles that received and forwarded the *RREQ*, as shown in [Section 3](#). After that, it applies the proposed mathematical optimization model ([Section 3](#)) to compute the best route. Then, it sends back the route as an *RREP* to *s*, which finally starts the data transmission session. After computing the route, if this destination receives the same *RREQ* from another vehicle, it will ignore this *RREQ* to reduce the redundant energy wastage.

During data transmission, if an error occurs and a link breaks, it is corrected locally at the location where the error occurred, depending on the residual energy, energy cost, and mobility speed and direction of the neighboring vehicles. The path is updated from the failure point to the destination using the objective function shown in equation 8 and the constraints (i.e., equation (i) to equation (vi)), presented in [Section 3](#).

Algorithm 1: Route Discovery in REME

Input

Source ID, destination ID, data volume

Output

Optimal path from the source to destination

```

1)  $s \leftarrow$  sender electric vehicle
2)  $s$  broadcasts a RREQ
3)  $N_s \leftarrow$  a set of neighbor electric vehicles delivering RREQ
4)  $k \leftarrow s$ 
5)  $Q \leftarrow N_s$ 
6)  $i \leftarrow 1$ 
7) The vehicle  $i$  ( $v_i$ ) stores ID of  $k$ 
8) If (ID of  $v_i ==$  ID of  $k$ ) then
9)  $v_i$  calculates the optimal route
10)  $v_i$  sends RREP back to  $s$ 
11) Else
12)  $v_i$  updates RREQ
13)  $v_i$  sends ACK to  $k$ 
14) If ( $i < U$ ) then
15)  $i \leftarrow i + 1$ 
16) Go to Step 7
17) Else
18) For  $j \leftarrow 1$  to  $U$  do
19) The vehicle  $j$  ( $v_j$ ) broadcasts RREQ to  $N_j$ 
20) End For
21)  $k \leftarrow j$ 
22)  $Q \leftarrow N_s$ 
23)  $i \leftarrow 1$ 
24) Go to Step 7
25) End If
26) End If
27) Return optimal path

```

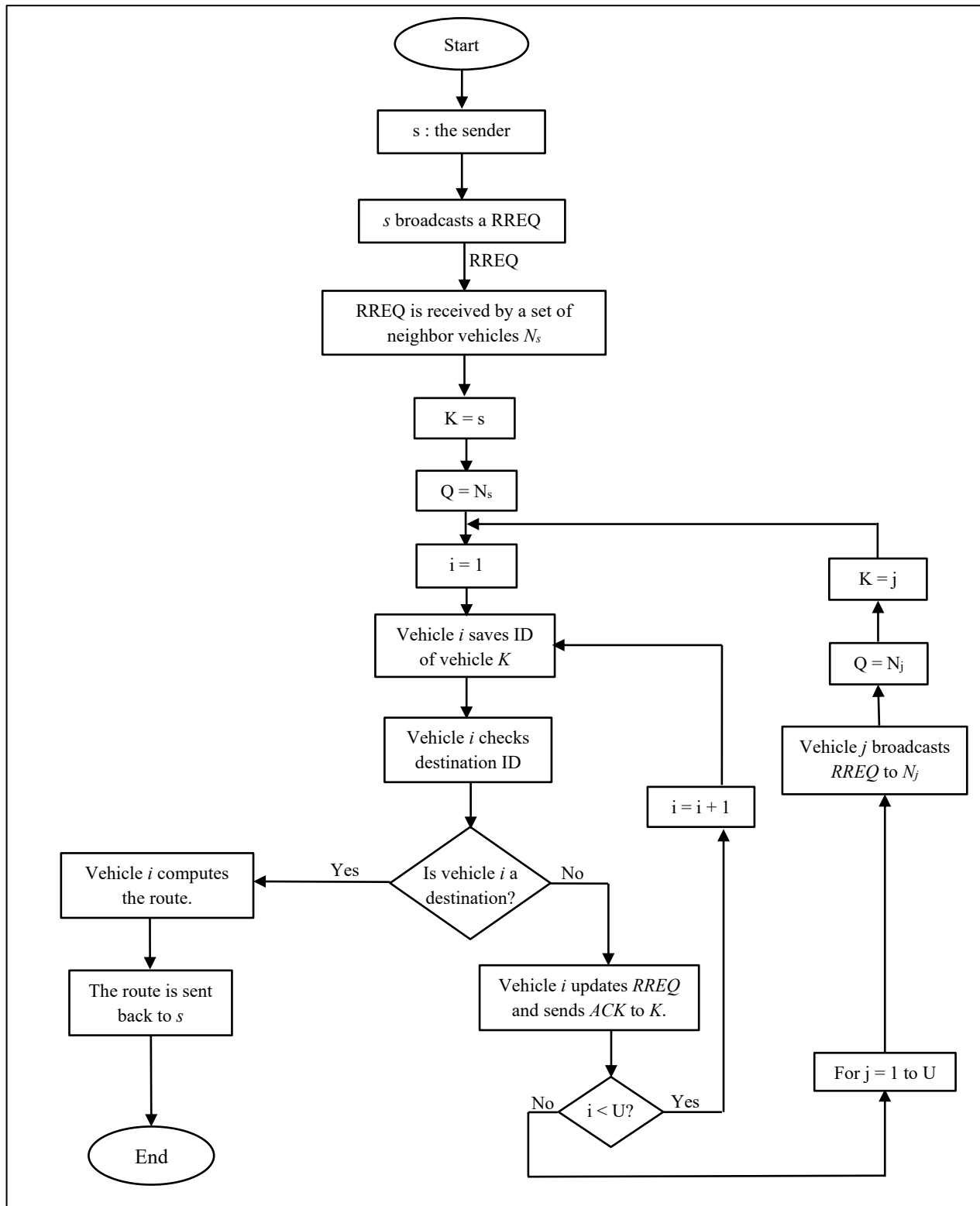


Fig. 4 - Route Discovery Procedure

5. Simulation and Results

The simulators NS-3 and SUMO have been merged to build E-VANET and investigate its behavior and performance when REME, AH-SFLA [30], and SANCV [31] are applied. This investigation was conducted in a system with

Windows 10 as the operating system, utilizing various comprehensive simulation scenarios with different numbers of EVs, velocities, and residual energy levels. In this section, we compare these routing protocols based on various performance measures, including average route stability, energy consumption, network overhead, and the number of dead electric vehicles. The dead electric vehicle is a term that refers to an electric vehicle with a residual energy level equal to 0. The general simulation parameters are as displayed in Table 3. To show the efficacy and superiority of REME, the following scenarios have been simulated:

Table 3 - General Simulation Parameters

Parameter	Value
Computer Type	HP
RAM	16.0 GB
CPU	13th Gen Core(TM) i7-1355U
Windows version	10
Simulators	NS-3 and SUMO
Simulation type	Urban
Routing protocols	REME, AH-SFLA, and SANCV
Number of EVs	Ranges from 1500 to 4000
Average velocity of EVs	5, 10, 15, 20, 25, and 30 m/s
Number of transmission sessions	50
Data volume	Ranges from 250MB to 500MB
Packet size	512 bytes
Communication protocol	IEEE 802.11p
Simulation area	4000 m * 4000 m
Runs	15 times
Simulation time	10 minutes

5.1. Scenario 1: Network Density

In this scenario, 1500, 2000, 2500, 3000, 3500, and 4000 vehicles move at velocities of less than or equal to 15 m/s. The residual energy level varies from one vehicle to another, ranging from 10% to 60%.

Fig. 5 (i-iv) illustrates the performance of REME, AH-SFLA, and SANCV as the network density increases. Fig. 5(i) explains that the average route stability is high with a large number of vehicles. The reason for this is the large number of available stable links that can be selected as part of the route to the destination. On the other hand, in networks with low density, the number of available links is small. As a result, when a link fails, the probability of finding an alternative link is low. The high route stability of SANCV allows for the use of RSU in forwarding data in some cases. However, the stability of routes computed using REME is better than that of AH-SFLA and SANCV, as it focuses on the velocity and direction of connected vehicles. It gives vehicles that move in the same direction and have a minimum average velocity the highest priority to work as intermediate nodes in the selected routes.

Fig. 5(ii) displays the amount of energy consumption due to route discovery and maintenance, data exchange, and control packet forwarding. In AH-SFLA and SANCV, vehicles must frequently send information to the SDN server. Thus, maximizing the number of vehicles leads to generating a significant number of control packets, which consume a large amount of vehicle energy. Moreover, they did not focus on the energy required to discover and correct the routes. Thus, their energy consumption is high. On the other side, REME sends control packets only when there is a need to discover or correct a route. The small number of vehicles means that the distances between vehicles may be long, and the number of links is limited. In addition, the probability of disrupting the existing links is high, and as a result, the number of route correction operations will increase. Thus, the energy consumption of the network with low density is high. On the contrary, with the high network scale, the number of available alternative links that can be used to maintain the broken links is large. From this, we conclude that increasing the number of vehicles in the network has a positive impact on the network's lifetime and routes. Moreover, REME builds and corrects the routes by taking into account the energy factors. Thus, it is clear that its energy consumption is less than that of AH-SFLA and SANCV and decreases with increasing network density.

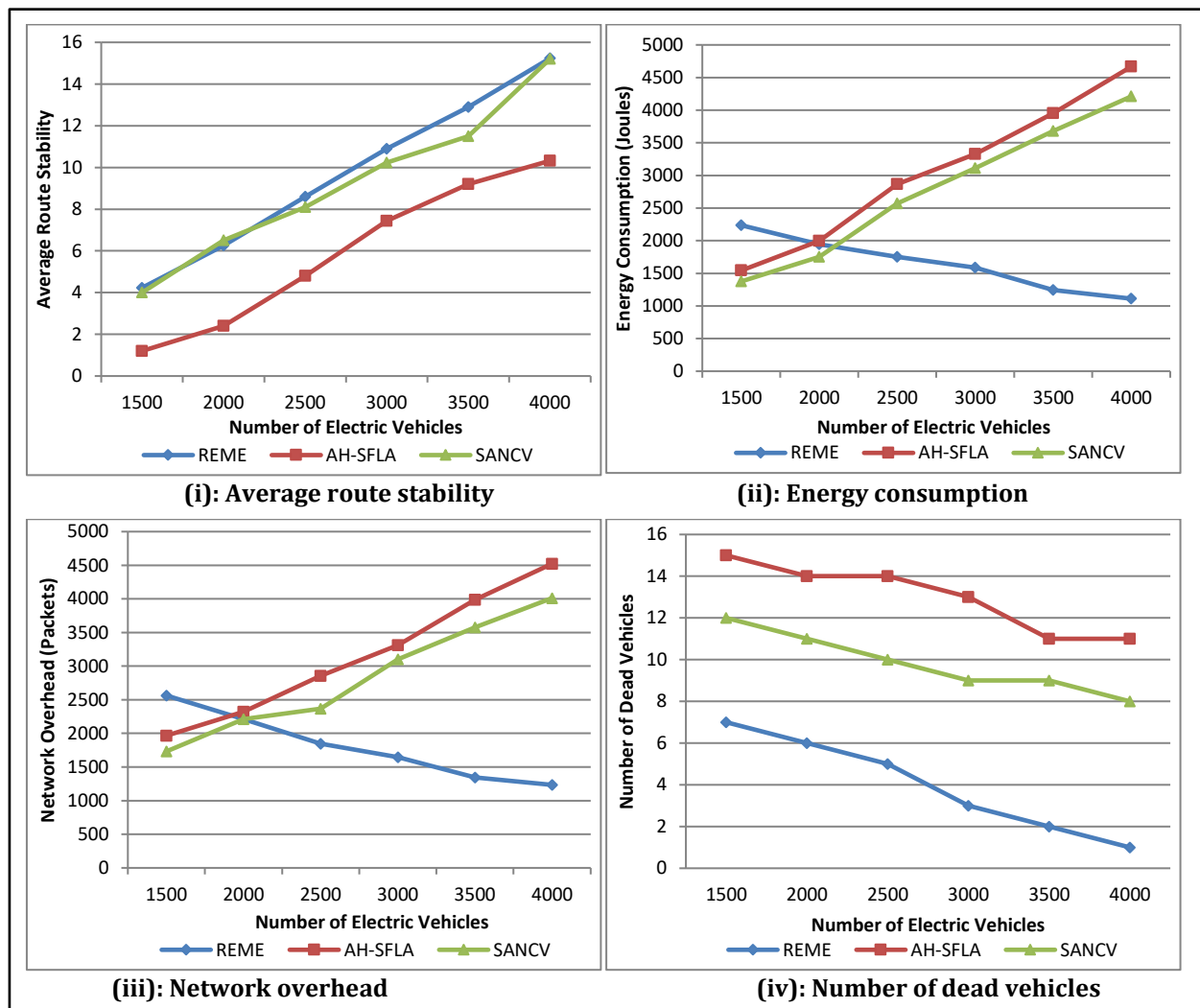


Fig. 5(i-iv) - Performance Results of REME, AH-SFLA, and SANCV with Various Numbers of EVs.

Fig. 5(iii) illustrates that maximizing the network density increases the network overhead when applying AH-SFLA and SANCV due to the significant number of exchanged control messages, which are transferred toward the SDN servers frequently, whether there is a need to compute or maintain a route or not. The number of these packets increases with increasing network density. As a result, the overhead of applying AH-SFLA and SANCV is high and increases as the network density maximizes. However, the network overhead when applying REME is low because vehicles exchange control packets only when needed to discover or reconstruct a route. Moreover, the network overhead of REME is reduced by maximizing the number of vehicles, which can be achieved by increasing the number of available links that can be selected as alternatives to the broken links.

Fig. 5(iv) illustrates that the number of dead vehicles decreases with an increase in the number of vehicles. Computing the route to a destination in a network with low density consumes an additional amount of energy due to the repeated attempts to find the route. The source and intermediate vehicles that don't receive an ACK message will continue broadcasting the RREQ until a vehicle receives it. Moreover, the small number of vehicles increases the number of broken links, and as a result, the number of dead vehicles increases due to the energy consumption during the frequent operations of route maintenance. On the contrary, increasing the network density reduces the distances among vehicles and increases the available routes, which makes the route discovery process easier and results in lower energy wastage. Therefore, the number of dead vehicles in the high-density networks is low. However, AH-SFLA and SANCV suffer from a large number of dead situations of EVs owing to the frequent forwarding operations of information to the SDN servers. On the other hand, using REME helps reduce the number of dead vehicles because it computes the route with the minimum energy. Moreover, it prevents EVs with minimal

remaining power levels from participating in the data routing operation by taking their residual energy levels into consideration.

5.2. Scenario 2: Vehicle Velocity

In this subsection, the effect of vehicle velocity on the efficiency and efficacy of REME, AH-SFLA, and SANCV in constructing the route is investigated. To achieve this, we assume a simulation environment with 3000 electric vehicles moving at various maximum velocities, which are 5, 10, 15, 20, 25, and 30 m/s. These vehicles move in different directions and have different levels of residual energy, ranging from 10% to 60%.

Fig. 6 (i-iv) presents the simulation results of applying E-VANET with varying vehicle velocities and computing routes using REME, AH-SFLA, and SANCV. It is normal that high velocity increases the dynamicity of network topology and the probability of disconnection of the links among the vehicles. Fig. 6(i) clearly explains that velocity is the largest factor affecting route stability. With low velocity, the links break rarely, while they break quickly when the vehicle velocity increases. However, REME addresses this challenge efficiently and focuses on the parameters that have the largest effect, which are velocity and direction. As shown in this figure, REME is superior to AH-SFLA and SANCV in terms of average route stability.

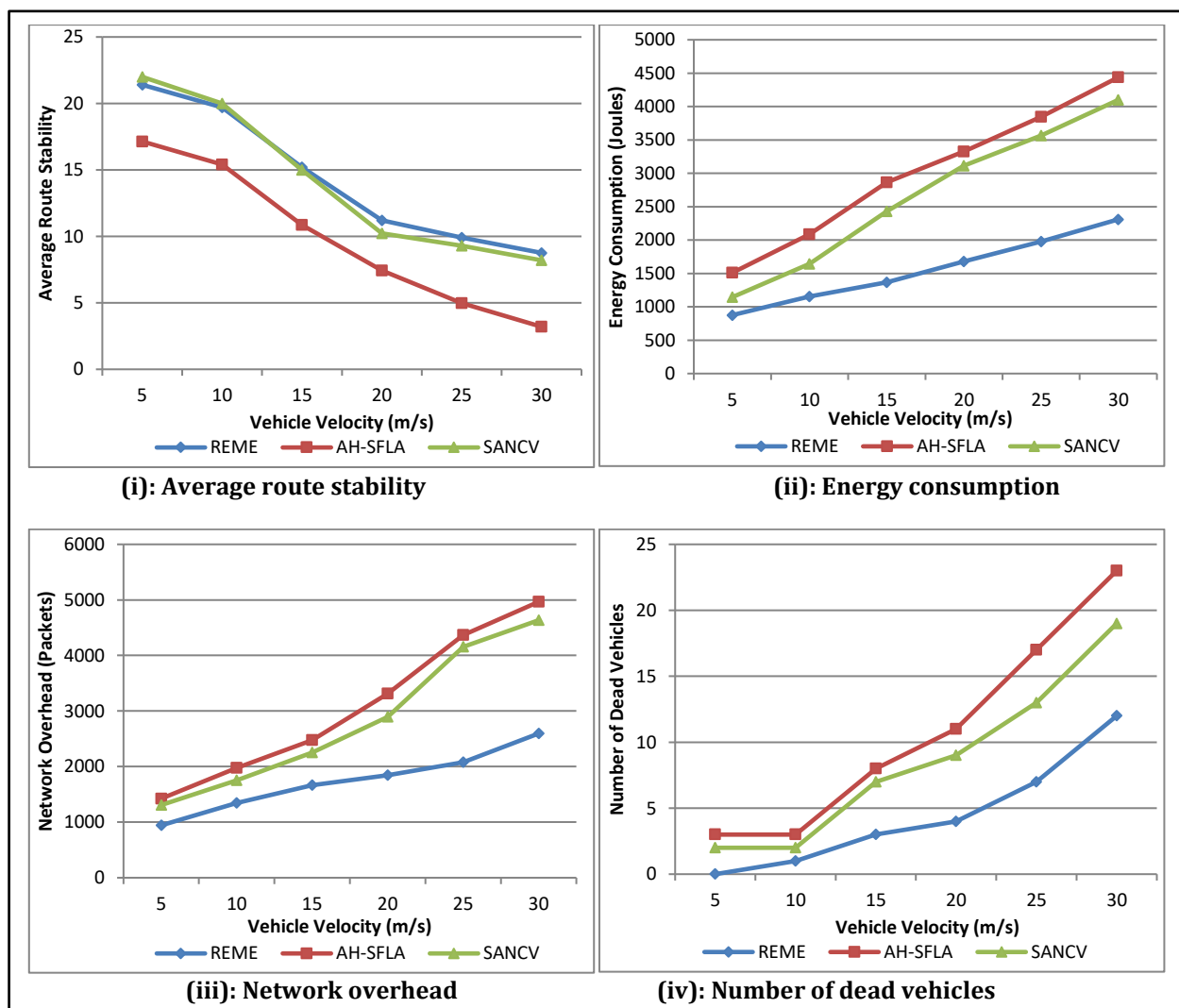


Fig. 6(i-iv) - Performance Results of REME, AH-SFLA, and SANCV with Various Vehicle Velocities.

Fig. 6(ii) shows that the energy consumption is high when the velocity is high because the links are disjoint frequently. As a result, the maintenance operations that require a large amount of energy increase. AH-SFLA and SANCV don't focus on energy consumption and velocity in computing operations of the routes. Moreover, they

depend on the fresh information about the vehicles and links saved in the SDN controller. Thus, the electric vehicles send a large number of control packets to the SDN server to save fresh information about the network. Increasing the velocity means increasing the number of sent packets, and therefore, the consumed energy will be high. In contrast, REME helps reduce energy consumption by selecting the route that requires the minimum energy to forward data to the destination. Moreover, it helps reduce the cases of link reconstruction by taking the vehicle's velocity and direction into account.

Fig. 6(iii) displays the network overhead with increasing the velocity of vehicles when REME, AH-SFLA, and SANCV are applied. In AH-SFLA and SANCV, whenever there is a change in the network topology, an alert must be sent to the controller. With high velocity, the topology of the network changes frequently. Therefore, the number of transmitted alerts to the controller increases, and thus the network overhead maximizes. In REME, the route is discovered and corrected reactively. Thus, the overhead of REME is lower than that of AH-SFLA and SANCV.

Fig. 6(iv) illustrates the number of dead vehicles at various mobility velocities. The frequent occurrence of broken links resulting from high movement velocity increases the energy consumption required to correct these links. Thus, the number of dead EVs maximizes. In AH-SFLA and SANCV, the energy consumption is high because information is transferred to the SDN servers. In contrast, REME consumes an amount of energy during the route discovery and maintenance procedures, without any redundant exchange of information. Moreover, REME prevents vehicles with residual energy levels below the threshold from participating in data forwarding, thereby increasing their lifetime. Therefore, the number of dead vehicles of REME is low.

5.3. Scenario 3: Residual Energy

This subsection explains how REME, AH-SFLA, and SANCV handle the residual energy level of electric vehicles when computing routes. To do this, we simulate a scenario with 3,000 electric vehicles, varying in residual energy levels, and subject them to a speed of 15 m/s. In this scenario, we use various levels of residual energy, which are 10-30%, 10-40%, 10-50%, 10-60%, 10-70%, and 10-80%.

Fig. 7 displays the number of dead EVs when REME, AH-SFLA, and SANCV are used. As shown, the number of dead vehicles decreases with an increase in the ratio of residual energy in the vehicles. AH-SFLA and SANCV do not focus on the residual energy and energy cost through computing the routes. Thus, the number of dead vehicles of these routing protocols is large. On the other hand, REME produces better performance compared to AH-SFLA and SANCV because it works reactively to compute routes only when needed. This means that the number of exchanged control packets is low, resulting in low energy consumption. In addition, it chooses the path that requires the minimum power to deliver the information to the target. Moreover, it reduces the participation probability of vehicles with residual energy levels below their thresholds as intermediate nodes to forward the data. Therefore, it is the best one in terms of the number of dead vehicles.

From the above three scenarios, we ensured that AH-SFLA and SANCV cannot be applied in E-VANET, and REME is the most suitable option for this network.

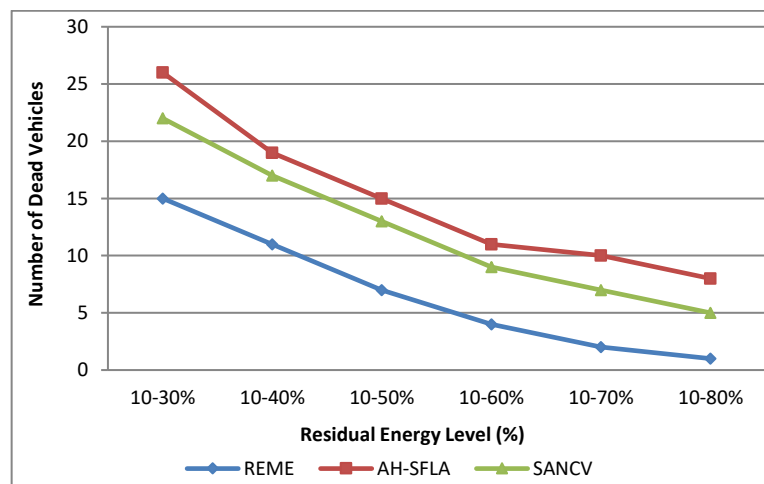


Fig. 7 - Number of Dead Vehicles with Various Residual Energy Levels.

6. Conclusions and Future Works

In E-VANET, the main issue is the energy limitation of the electric vehicle's battery. Thus, forwarding data to destinations without incurring additional energy loss is the primary goal of any routing protocol in E-VANET. A suitable solution for data forwarding is the use of an energy-based routing protocol. However, due to the frequent movement of vehicles at unknown velocities and directions, the dynamicity of network topology maximizes. Thus, the standard routing protocol fails in E-VANET. In this paper, we focused on these issues and produced an efficient energy-mobility-based routing protocol for E-VANET. In terms of energy, the proposal takes into consideration the required energy to forward the data to the destination and considers the route with the minimum energy as the most optimal one. Moreover, to prolong the lifetime of the network and selected routes, the proposed routing scheme prioritizes the links that connect vehicles with residual energy exceeding their energy thresholds. In this paper, the threshold computation is performed based on the battery capacity and differs from that in previous papers. In the vehicle mobility aspect, the highest priority is given to the link that connects vehicles moving at a minimum average velocity in the same direction. This procedure can increase the lifetime of the link, resulting in higher average route stability and reduced broken link situations, as well as lower energy consumption. From the simulation experiments with different cases of electric vehicles, velocities, and residual energy levels, we found that REME outperforms AH-SFLA and SANCV in terms of average route stability, energy consumption, network overhead, and the number of dead EVs. In the future, we will focus on utilizing deep learning techniques to configure the optimal route with minimal energy. Moreover, the security side will be a major part of our plans.

References

- [1] K. Mahmud, G. E. Town, S. Morsalin, & M. J. Hossain (2018, February). Integration of electric vehicles and management in the internet of energy. *Renewable and Sustainable Energy Reviews*, 82(3), (pp. 4179–4203).
- [2] J. I. Naser & A. J. Kadhim (2024, September). A Pareto optimization-based multipath routing protocol for E-VANET. *International Journal of Intelligent Engineering & System*, 17(6), (pp. 506–518).
- [3] A. J. Kadhim & J. I. Naser (2021, March). Toward electrical vehicular ad hoc networks: E-VANET. *Journal of Electrical Engineering & Technology*, 16, (pp. 1667–1683).
- [4] C. Lv, Y. Liu, X. Hu, H. Guo, D. Cao, & F. Wang (2018, August). Simultaneous observation of hybrid states for cyber-physical systems: a case study of electric vehicle powertrain. *IEEE Transactions on Cybernetics*, 48(8), (pp. 2357–2367).
- [5] Y. Feng, Y. Huang, B. Li, H. Peng, J. Wang, & W. Zhou (2023, January). Connectivity enhancement of E-VANET based on QL-mRSU self-learning energy-saving algorithm. *IEEE Access*, 11, (pp. 3810–3825).
- [6] P. Liu, X. Wang, A. Hawbani, B. Hua, L. Zhao, & Z. Liu (2022, December). BETA: beacon-based traffic-aware routing in vehicular ad hoc networks. *IEEE Transaction on Intelligent Transportation Systems*, 23(12), (pp. 24206–24219).
- [7] A. J. Kadhim & S. A. H. Seno (2018, March). Energy-efficient multicast routing protocol based on SDN and fog computing for vehicular networks. *Ad Hoc Networks*, 84, (pp. 68–81).
- [8] A. J. K. Alshaibany (2025, January). An energy resource management for cluster based IoHV supported by fog computing. *Karbala International Journal of Modern Science*, 11, (pp. 35–55).
- [9] M. A. Karabulut, A. F. M. S. Shah, & H. Ilhhan (2020, May). OEC-MAC: A novel OFDMA based efficient cooperative MAC protocol for VANETS. *IEEE Access*, 8, (pp. 2169–3536).
- [10] S. K. Bhoi, P. K. Sahu, M. Singh, P. M. Khilar, R. R. Sahoo, & R. R. Swain (2019, June). Local traffic aware unicast routing scheme for connected car system. *IEEE Transaction on Intelligent Transportation Systems*, 21(6), (pp. 2360–2375).
- [11] J. Wu, M. Fang, H. Li, & X. Li (2020, January). RSU-assisted traffic-aware routing based on reinforcement learning for urban Vanets. *IEEE Access*, 8, (pp. 5733–5748).
- [12] R. Sadakale, N. V. K. Ramesh, & R. Patil (2020, July). TAD-HOC routing protocol for efficient VANET and infrastructure-oriented communication network. *Journal of Engineering*, 2020, (pp. 1–12).
- [13] J. Nadarajan & J. Kaliyaperuma (2021, February). QoS aware and secured routing algorithm using machine intelligence in next generation VANET. *International Journal of System Assurance Engineering and Management*, 2021, (pp. 1–14).
- [14] R. Ramamoorthy & M. Thangavelu (2021, April). An enhanced hybrid ant colony optimization routing protocol for vehicular ad-hoc networks. *Journal of Ambient Intelligence and Humanized Computing*, 13, (pp. 3837–3868).
- [15] A. J. K. Al-Shaibany (2021, March). Stability-delay efficient cluster-based routing protocol for VANET. *Karbala International Journal of Modern Science*, 7(3), (pp. 187–205).
- [16] O. Alzamzami & I. Mahgoub (2021, March). Geographic routing enhancement for urban VANETs using link dynamic behavior: a cross layer approach. *Vehicular Communications*, 31, (pp. 1–14).
- [17] M. A. Shah, F. Z. Khan, G. Abbas, Z. H. Abbas, J. Ali, S. S. Aljameel, I. U. Khan, & N. Aslam (2022, September). Optimal path routing protocol for warning messages dissemination for highway VANET. *Sensors*, 22(18), (pp. 1–12).
- [18] R. K. Mahesh, S. S. Jawaligi, & V. Patil (2022, November). SFTD: A smart forwarding technique based reliable data dissemination scheme for VANETs. *Measurement: Sensors*, 24, (pp. 66–79).
- [19] M. Sindhvani, S. Sachdeva, A. Gupta, S. Tanwar, F. Alqahtani, A. Tolba, & M. S. Raboaca (2023, January). A novel context-aware reliable routing protocol and SVM implementation in vehicular area network. *Mathematics*, 11, (pp. 1–15).
- [20] A. Naem, M. Rizwan, S. Alsubai, A. Almadhor, M. Akhtaruzzaman, S. Islam, & H. Rahman (2023, January). Enhanced clustering based routing protocol in vehicular ad-hoc networks. *IET Electrical Systems in Transportation*, 11(7), (pp. 116–129).
- [21] B. Mehdi, S. Moussaoui, & G. Mohamed (2023, May). A geographic routing based on local traffic density and multi-hop intersections in VANETs for intelligent traffic system in smart cities (GRBLTD-MI). *Wireless Networks*, 31, (pp. 23–37).
- [22] L. Rui, Z. Yan, Z. Tan, Z. Gao, Y. Yang, X. Chen, & H. Liu (2023, September). An intersection-based QoS routing for vehicular ad hoc networks with reinforcement learning. *IEEE Transaction on Intelligent Transportation Systems*, 24(9), (pp. 9068–9083).

-
- [23] S. Ullah, G. Abbas, M. Waqas, Z. H. Abbas, & A. Khan (2023, December). RSU assisted reliable relay selection for emergency message routing in intermittently connected VANETs. *Wireless Networks*, 29, (pp. 1311–1332).
- [24] R. Ramamoorthy (2024, January). An enhanced location-aided ant colony routing for secure communication in vehicular ad hoc networks. *Human-Centric Intelligent Systems*, 4, (pp. 25–52).
- [25] A. K. Kazi, M. U. Farooq, R. Asif, & S. Hina (2025, October). Adaptive context-aware VANET routing protocol for intelligent transportation systems. *Network*, 5(4), (pp. 146–161).
- [26] R. Muthaiyan, S. Senthilkumar, C. V. Joe, & M. Kavitha (2025, May). Reliability based multi-objective optimized routing protocol for VANETs using pelican optimization algorithm. *Discover Applied Sciences*, 7(22), (pp. 414–427).
- [27] Y. Tang, N. Cheng, W. Wu, M. Wang, Y. Dai, & X. Shen (2019, April). Delay-minimization routing for heterogeneous VANETs with machine learning based mobility prediction. *IEEE Transaction on Intelligent Transportation Systems*, 68(1), (pp. 3967–3979).
- [28] K. L. K. Sudheera, M. Ma, & P. H. J. Chong (2019, April). Connectivity aware tribrid routing framework for a generalized software defined vehicular network. *Computer Networks*, 7, (pp. 167–177).
- [29] K. Eirini & B. Torsten (2020, November). On the impact of SDN for transmission adaptation and FIB in NDN-VANETS. 18th ACM International Symposium on Mobility Management and Wireless Access (MobiWac'20), (pp. 57–66). ACM.
- [30] D. Xinxin, H. Xiaohui, & Z. Jianan (2022, August). A QoS routing algorithm based on software-defined vehicular ad-hoc network. *Computer Engineering*, 48(11), (pp. 184–191).
- [31] H. Zhu, J. Liu, L. Jin, & G. Zhang (2023, May). Intersection-based unicast routing using ant colony optimization in software-defined vehicular networks. *Electronics*, 12(7), (pp. 1–15).
- [32] P. Sehrawat & M. Chawla (2023, June). SDTMRP (software defend traffic management routing protocol) for efficient and reliable communication in vehicular networks. *Wireless Personal Communications*, 131, (pp. 1595–1629).
- [33] Z. H. Ali, N. El-Rashidy, M. A. Elhosseini, & S. M. Ayyad (2024, October). SDN-based reliable emergency message routing schema using digital twins for adjusting beacon transmission in VANET. *Journal of Network and Computer Applications*, 230, (pp. 302–313).
- [34] S. Ahmed, N. V. K. Ramesh, & B. N. K. Reddy (2025, January). An efficient routing mechanism for VANETs in SDN with hybrid meta-heuristic algorithm. *Telecommunication Systems*, 88(13), (pp. 148–164).
- [35] S. J. Rajan, S. Narayanaswamy, T. Balashanmugam, K. Sengottaiyan, & A. Selvaraj (2025, September). Efficient traffic management with adaptive SDN in vehicular networks. *Scientific Reports*, 15, (pp. 233–247).