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Drive on a Greener Way: A Case Study on Navigating Cross-Regional Traffic Networks in South China

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Abstract: Green navigation presents a challenge to sustainable mobility. Carbon emissions are a key indicator for evaluating the sustainability of a route. Some methods of green navigation consider the fastest and shortest route to be the least carbon-emitting option, solely from the driver's perspective. To address this issue, various studies have incorporated road factors into the sustainability evaluation model and designed static route planning algorithms to minimize carbon emissions. However, there has been no comprehensive analysis of carbon emissions from both the road and the driver perspectives, and the influence of a sustainability evaluation using dynamic traffic states has not been considered. In this paper, we propose a carbon emission evaluation model based on the life cycle assessment (LCA) and a dynamic route planning algorithm that focuses on near-real-time traffic states. First, we develop an evaluation model for carbon emissions from both the road and the driver perspectives using a carbon footprint measurement method. Next, we propose a route planning method with both a static calculation and near-real-time adjustment to minimize carbon emissions. Finally, we select three cases from South China with different characteristics to verify the effectiveness of our model and algorithm. This evaluation model calculates the carbon emissions caused by all parties involved, providing a comprehensive assessment of the total carbon emissions generated by traffic. This approach addresses the problem of traditional route planning, which often fails to account for the influences of variable traffic conditions on the greenest route. We verify the effectiveness of the greenest navigation algorithm and near-real-time green navigation and apply these two aspects to cases where the greenest route is compared with other common navigation results from different dimensions. We compare carbon emissions from vehicles and roads from electric vehicles and gasoline-powered vehicles. If an electric vehicle is equipped with a wind power generator, the proportion of the vehicle's carbon emissions will be very small. For other vehicle types, the carbon emissions will be more than 1000 times the road emissions.

Keywords: sustainable mobility; green navigation; route planning; life cycle assessment

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1. Introduction

Navigation and route planning are important problems. Navigation refers to finding the best route given a particular road network, traffic conditions, and origin–destination (OD). Navigation is already common. In April 2021, Amap's average number of daily active drivers exceeded 100 million. However, in general, in a vehicle navigation system, the shortest route is often not the optimal path for the driver [1]. Drivers have different navigation needs, so in addition to the shortest and fastest routes, it is essential to find the best route that aligns with specific goals.

In the process of road transport, green driving is an important strategic goal, and sustainable mobility is the means to achieving this. Sustainability is determined by a complex set of factors that are largely influenced by traffic route choices. Therefore, sustainable route planning is conducive to the promotion of sustainable mobility when the OD has been determined [2]. Environmental factors are an important evaluation index of

sustainable mobility. In the literature [3], the weight of environmental factors is second only to accessibility. Carbon emissions are an important environmental assessment index [4]. China's transport accounts for 10% of the total carbon emissions. Therefore, selecting the most sustainable route option, with the least carbon emissions, should be prioritized.

Few studies have focused on the planning of the most sustainable route. On one hand, shortest and fastest route planning differs from most sustainable route planning. The route planning problem involves the minimization of costs for the driver [5]. From the driver's perspective, existing research mainly focuses on shortest and fastest route planning, the influence of adjusting prices on route planning, and the analysis of driver route choices at key locations, such as toll stations. For example, for a certain OD [6], a vehicle routing algorithm is used to reduce the travel time. Sustainable mobility is evaluated solely from the driver's perspective, considering aspects such as increases in the average speed [1]. Road factors are added to the model as traffic characteristics, such as slope [7]. On the other hand, these methods cannot find the most sustainable route. None of the existing methods can be applied to this problem. First, it is difficult to quantify the carbon emissions generated by sustainable mobility. The types and characteristics of roads can affect carbon emissions from traffic. Increasing the durability of roads helps to reduce carbon emissions [8], and one can evaluate the sustainability of roads by considering the materials used for road maintenance and in the road structure. Many factors affect carbon emissions, and these factors have complex relationships. Both vehicles and roads impact carbon emissions. For example, driving too slowly will increase fuel consumption and, thus, carbon emissions. In the assessment of carbon emissions, vehicle and road factors also interact. For example, excessive traffic will increase the number of carbon-containing materials required for road maintenance, thus increasing carbon emissions. Second, the navigation results should be produced in near-real time. The traffic flow changes frequently. When the traffic flow changes to a certain extent, it will affect the state of traffic, which, in turn, will affect the carbon emissions generated by traffic. Therefore, it is necessary to update the traffic state in near-real time, as well as the optimal route.

To sum up, the research problem concerns the lack of sustainable mobility carbon emission assessment methods and the most sustainable route planning methods that integrate vehicles and roads.

To solve these problems, first, we propose a sustainable mobility evaluation model. The carbon footprint life cycle assessment (LCA) method is used to calculate the carbon emissions from vehicles and roads during periods of traffic. The LCA is a standardized methodology that aims to assess the environmental burden (carbon emissions) of the system in terms of the material and energy resource consumption and emissions [4]. The sustainability of a road evaluation should be defined and fulfilled throughout its different life cycle stages [9]. The LCA method can be used as an evaluation method for sustainable mobility that combines vehicle and road factors. Based on the operating mechanisms of vehicles and roads, the carbon emissions generated by driving, vehicle maintenance, road maintenance, and patrol fleets should be calculated.

Then, we propose a method for designing the most sustainable route plan that is suitable for both static calculations and near-real-time adjustments. Traffic in cities is highly dynamic [10]. Real-time information from car navigation systems has a significant impact on route selection within a traffic network [11]. Dynamic factors include traffic conditions, such as weather and congestion. In this paper, dynamic navigation is achieved through near-real-time adjustments to the results of static route planning. The A* algorithm is a commonly used static route planning method that can calculate the shortest path between ODs on a traffic network. It is efficient for navigation. In this method, the weights of roads are determined using the sustainable evaluation and road capacity results. The shortest path is calculated using the A* algorithm with carbon emission minimization, which serves as the static navigation result. Unlike prediction-based shortest route planning models [12], the real-time adjustment condition is set based on the state of near-real-time traffic. When the condition is triggered, the navigation results are adjusted to guide the vehicle on the

newest route with the least carbon emissions. Finally, we design an algorithm for route adjustment from the perspective of optimal route variation and other route variations. By combining the static path planning results, adjusting methods, and adjusting trigger conditions, the near-real-time route planning results can be obtained.

Finally, the sustainability evaluation model and the most sustainable route planning method are applied to three scenarios with different ODs, and the carbon emission savings are calculated.

In summary, our key contributions include the following:

- We add the characteristics of roads and vehicles to the sustainable mobility evaluation model and utilize the LCA method to calculate carbon emissions during periods of traffic. This allows for the comparison of carbon emissions produced with different routes for navigation purposes.
- We design a dynamic navigation method that accounts for the highly dynamic nature of traffic. The optimal navigation route adjustment condition and method are determined using the results of the A* calculation process, enabling near-real-time route planning for sustainable mobility.
- We conduct case studies based on different traffic network scenarios to demonstrate the effectiveness of the carbon emission model and route planning method and calculate the carbon emission savings that can be achieved through this method.

The structure of this paper is as follows: Section 2 presents the related works. Section 3 presents the sustainable mobility model. Section 4 presents the dynamic route planning method. Section 5 discusses the case study. Section 6 presents the conclusions.

2. Related Works

2.1. Carbon Emission Evaluation

To address the research problems outlined above, there is a significant body of literature on sustainable mobility evaluation and planning. Carbon emissions are a key factor in evaluating sustainable mobility, and various studies have explored this topic [13–15].

Research has been conducted from two perspectives: drivers and roads. Drivers are responsible for initiating traffic processes and can control factors such as the origin–destination (OD), speed, travel frequency, and transportation, among others. Traffic factors have different impacts on sustainability [4], and sustainable mobility evaluation methods for higher education have been designed using standardized and LCA methods. A Sustainable Mobility Indicator was constructed with the LCA, and it can be applied to both institutions and individual members [8]. It is used to analyze the impacts of different travel modes, such as public transportation and private cars, and travel frequency and vacation trips versus business trips, on traffic sustainability. The paper proposes ways to promote sustainable mobility, such as reducing the frequency of travel and taking public transport. The goal of the route planning algorithm in [16] is to minimize the linear combination of the mean and standard deviation of carbon emissions. By changing the weights of the mean and standard deviation, the influence of speed on carbon emissions is discussed for different goals, and 102 days of real-time vehicle speed records in Los Angeles are used as test data. The results show that the method could reduce carbon emissions by a factor of 0.02 to 0.03.

Roads are a crucial component of sustainable mobility. Road construction and frequent maintenance can negatively impact sustainability. Factors such as the slope, pavement material, and the number of road lanes can all affect the sustainability of roads. To address this issue, researchers developed sustainable improvement schemes for local roads in Northeast India using multi-objective planning and k-means methods to design the most sustainable roads [7]. Additionally, implementing sustainable development strategies during periods of road maintenance can improve the environmental quality of asphalt pavement materials using an LCA [17]. Studies have also found that increasing the number or width of the lanes can increase the carbon emissions due to traffic factors [18].

2.2. Route Planning for Sustainable Mobility

Sustainable mobility is a key function in sustainable development. Route planning is one of the most useful methods of promoting sustainable mobility. The existing literature has proposed different methods for sustainable improvement from multiple perspectives that affect sustainability. These include the micro-level details associated with increasing energy consumption during the transportation process and the macro-level issues of environmental and road safety. These scenarios have different characteristics, and based on these, innovative weight setting has been carried out. In [19], GPS data are used record vehicles' trajectories in a specific road network. In addition to the vehicle perspective, the relationship between braking and the traffic environment is also analyzed through a trajectory analysis. The conclusions are that during traffic flow, the road structure increases braking times and carbon emissions, and the carbon emissions increase rapidly during the peak hours of the workday. In [20], the competitiveness of public transportation and vehicles is compared. The maturity of public facilities varies among different regions of South Korea, so competitiveness differs between public transportation and vehicles. In addition to road condition information, other traffic assistance information can impact carbon emissions. The article uses the T-map API to analyze the vehicle traffic status from temporal and spatial perspectives. The conclusion indicates that the competitiveness of public transportation is stronger during peak traffic periods and in well-equipped areas. In [21], a method is constructed to identify traffic congestion and estimate the air quality. This method is used to map the traffic environment with GPS trajectory data and road spatial data. Then, it predicts environmental data using traffic data. Finally, based on the prediction results, the shortest route that avoids congestion is found and presented as an information system. In [22], a route planning algorithm for vehicle–road coordination is constructed to address the problem of the navigation results being too concentrated for a given OD. If vehicles are concentrated on one road based on the navigation results, the road load will increase and the sustainability will be reduced. When the road load is controlled within a reasonable range, a method for optimal route planning is proposed. The result is a 23% reduction in the total travel time compared to that obtained with the Dijkstra algorithm. In [23], sustainable navigation methods are set. Considering driver safety, they analyze the relationship between travel time and rest habits. This is helpful for enhancing traffic sustainability through navigation from a safety perspective. In [24], navigation technology is used to reduce carbon emissions. Firstly, the traffic flow is predicted based on historical information, and then the predicted results are combined with the carbon emission mechanism model to calculate the carbon emission formula. Finally, the carbon emissions for route planning are calculated, contributing to the formation of intelligent transportation and smart cities. In [25], sustainable navigation methods are proposed to address the issue of inefficient stopping and turning during the navigation process. Firstly, a risk assessment is conducted for the stopping or turning of vehicles. Secondly, a spatial model is built and risk objectives are set for different areas. Finally, route planning is conducted by using the risk density as a weight. These methods reduce the energy consumption by more than 12%.

In the traffic industry, there are various methods for setting dynamic targets for route planning. In [26], both dynamic and static traffic flow allocations are analyzed, and it is concluded that road congestion can affect drivers' route selection, which can then feed back into congestion issues. Differential equations were used to describe the traffic flow distribution process. In [27], methods are proposed to solve congestion problems by controlling the traffic flow and using a Logit model to calculate the probability of a particular road being selected. In [6], the focus is on the problem of uncertain traffic states during navigation, and an algorithm is developed to predict the results of route selection based on traffic state predictions. The algorithm is then used for dynamic adjustments. The effectiveness of the model is demonstrated through a numerical analysis involving five actual traffic scenarios. In [12], a real-time dynamic route planning model that considers the vehicle speed or traffic flow prediction is constructed. This is achieved through three steps: vehicle speed or traffic flow prediction, rolling optimization, and feedback. In [28]

and [29], the characteristics of the industry are considered, and route planning models are designed for different applications. In [28], the focus is on real-time route planning and adjustment for refrigerated trucks based on preoptimization, while [29] proposes a route planning optimization method for evacuation and rescue scenarios considering the unpredictability and dynamic nature of traffic states during these situations.

3. Sustainable Mobility Model

The sustainability assessment model is used to calculate the carbon emissions generated during the traffic process. The carbon footprint is calculated by combining the two dimensions of participants and time. Firstly, we describe the process of sustainable mobility, in which the participating members can be divided into vehicles, road operators, and roads. We define the attributes, methods, and relationships for each member. Then, we define and calculate the carbon footprint of each road using an LCA that can be used for navigation. Finally, we propose a method for calculating the carbon emissions of the route based on the data obtained from the LCA.

3.1. Model Definition

A sustainable mobility description is a kind of system description that includes the system's members and the relationships between different members. When we input the parameters, the specific sustainable mobility scenario can be described. The members and their relationships are shown in Figure 1.

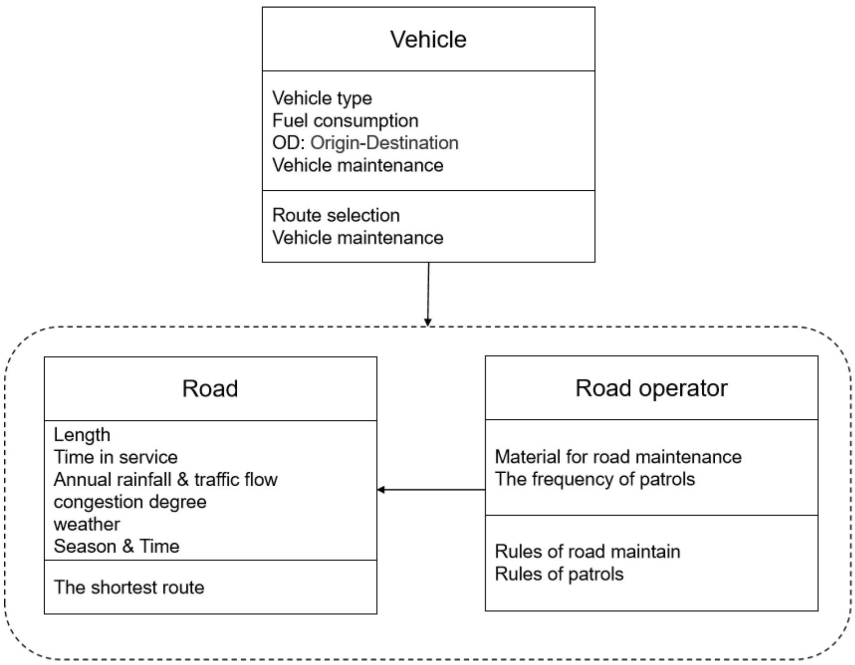


Figure 1. Members of the sustainable mobility model and the relationships between members.

The term vehicle refers to the vehicle driven by the driver during periods of traffic. Drivers can choose routes according to their OD. Different traffic routes will lead to different volumes of carbon emissions based on the vehicle type, fuel consumption, and other road parameters. Roads, routes, and the traffic network represent different levels of roads. The shortest route and fastest route are common algorithms. The operating company refers to the company responsible for repairing and maintaining highways. The road operator can choose different maintenance methods based on factors such as the annual traffic flow, annual rainfall, and time in service. Carbon emissions are used as the estimation indicator of sustainable mobility in this paper and are determined by the parameters mentioned above. According to the structural characteristics of the road network, the components of

the road network can be divided into roads and routes. The sustainable mobility model is also divided into road and route models.

3.2. Road Model Estimation

The main sources of carbon emissions from traffic are vehicles and roads. According to the LCA, carbon emissions are not only generated by fuel consumption but also by the maintenance of vehicles and roads. In this method, the carbon emission calculation of sustainable mobility does not include the carbon emissions generated during the construction of cars and roads, because these carbon emissions are not generated by traffic. Therefore, the carbon emissions can be divided into the following five parts.

- Carbon emissions from vehicle fuel consumption.

Gasoline is a carbon-containing material that emits carbon dioxide when used. The factors influencing CO_2 emissions can be divided into vehicle aspects, roads, and traffic states. Different types of cars have different levels of fuel consumption per kilometer, so their carbon emissions are different. An increase in the length of the road will increase the total fuel consumption. Traffic flow is also a key factor that affects the fuel consumption. If the traffic flow is too high, it will slow down the traffic speed and increase the fuel consumption, which will increase the carbon emissions. Rain is a negative factor associated with carbon consumption, because the vehicle needs more power to maintain its balance. Thus, the carbon emissions caused by vehicle fuel consumption can be expressed as Equation (1).

$$E_1 = f_1(fuel_consumption,\ road_length,\ congestion,\ weather) \quad (1)$$

- Carbon emissions from vehicle maintenance

The CO_2 generated by vehicle maintenance refers to the periodic maintenance carried out after the vehicle has travelled a certain distance. The Chinese government requires maintenance for vehicles traveling 5000 km. The vehicle maintenance process consumes carbon-containing substances such as oil as well as CO_2. The consumption of carbon-containing substances is mainly directly related to the car type and fuel consumption: the higher the fuel consumption, the higher the maintenance consumption. Thus, the carbon emissions caused by vehicle maintenance, $E_{2,}$ can be expressed as Equation (2).

$$E_2 = f_2(car_type,\ fuel_consumption,\ road_length) \quad (2)$$

- Carbon emissions from road maintenance

Road maintenance involves the repair of damaged roads caused by vehicle traffic. During this process, materials such as asphalt and cement are used, along with large energy-consuming machinery that emits CO_2. The carbon emissions generated from road maintenance are directly related to the materials used and the type of road. Different types of road surface and damage require different repair techniques and materials. Roads, bridges, and tunnels have different maintenance needs and consume different materials. The carbon emissions produced from road maintenance can be adjusted based on several factors, including the time taken for the servicing of roads, the annual rainfall, and the annual traffic flow. Heavy rainfall will increase the frequency and complexity of maintenance. High traffic flow can increase the damage level and lead to higher carbon emissions during periods of maintenance. The carbon emissions associated with road maintenance can be expressed using Equation (3):

$$E_3 = f_3(material,\ time\ in\ service,\ annual_rainfall, annual_traffic_flow) \quad (3)$$

- Carbon emissions from road maintenance patrols

Patrol refers to the inspection of road damage. The method is driving on the road by professional staff for inspection. There is a positive correlation between patrol frequency

and traffic flow. The carbon emissions generated in the process of road patrol are fuel consumption. Carbon emissions of road maintenance patrols can be expressed as Equation (4).

$$E_4 = f_4(patrol_frequency,\ road_length,\ annual_traffic_flow) \tag{4}$$

- Carbon emissions from additional road maintenance and road inspections

In addition to periodic road maintenance, other factors can cause additional maintenance needs for roads. These include accidents, road damage caused by natural disasters or human activities, and changes in weather conditions that can lead to increased wear and tear on the road surface. Congestion, poor weather, and reduced visibility can also contribute to additional maintenance events. It is important to regularly monitor and assess the condition of the roads to identify potential issues before they become major problems. Carbon emissions from additional road maintenance and road inspections can be expressed as Equation (5).

$$E_5 = f_5(material,\ weather,\ congestion,\ season,\ time) \tag{5}$$

In summary, the total carbon emissions from each road can be expressed as Equation (6). Parameter i is the serial number of carbon emissions.

$$E_{road} = \sum_{i}^{N} E_i \tag{6}$$

The carbon emissions of the road are affected by the factors shown in Table 1.

Table 1. The factors influencing carbon emissions, the sources of factors, and the indexes they affect.

No.	Factors	Owner	Indexes
y_1	Traffic network	Road	Constant
y_2	Origin–destination	Driver	Constant
x_1	Vehicle type	Driver	E_2
x_2	Fuel consumption	Driver	E_1, E_2
x_3	Road length	Road	E_1, E_3, E_3, E_4
x_4	Annual rainfall/snowfall	Road	E_3
x_5	Annual traffic flow	Road	E_3, E_4
x_6	Time in service	Road	E_3
x_7	Material for road maintenance	Road	E_3, E_5
x_8	Frequency of road patrols	Road	E_4
x_9	Weather	Traffic state	E_2, E_5
x_{10}	Congestion	Traffic state	E_2, E_5
x_{11}	Season	Traffic state	E_5
x_{12}	Time	Traffic state	E_5

NMF (Non-Negative Matrix Factorization) is a linear feature extraction algorithm that splits a high-dimensional matrix into two matrixes: one containing the extracted feature matrix and the other containing the dimension transformation matrix. The advantage of NMF is that it transfers non-negative matrixes into two non-negative matrixes to reduce the number of dimensions. In this paper, the carbon emissions are always non-negative, and the Dijkstra algorithm in the next section requires the weights of the traffic network to also be non-negative. Therefore, NMF is a more suitable method for this problem.

The input is $(x_1, x_2, \ldots, x_{12})$, and the output is (X_1, X_2). Thus, the influencing factors can be expressed as $Z = (X_1,\ X_2)$. The carbon emission function of road F is the sum of the five above types of carbon emissions, so the carbon emissions of the road are represented by $E = F(Z, y_1, y_2)$.

3.3. Route Model Estimation

The carbon emissions of a route refer to the carbon emissions consumed by a driver driving a vehicle through a route. The carbon emissions of route E_{route} are the sum of the carbon emissions of each road.

$$E_{route} = \sum_{1}^{L} E_{road} \tag{7}$$

This equation shows that the route consists of L roads. The carbon emissions of the route are equal to the sum of the carbon emission of these L roads.

4. Dynamic Route Planning Method

To calculate the most sustainable route for dynamic navigation, we use a static route planning algorithm and a near-real-time adjustment method. Firstly, we designed a method to calculate the weight of each road based on the road and vehicle characteristics and traffic state. Next, we calculated the optimal route from the origin to the destination, which is the minimum sum of the weights. This is the static route planning result. Finally, we designed a dynamic adjustment method that includes a trigger condition and an optimal route adjustment method. The trigger condition is caused by various factors such as the traffic congestion or weather. When the trigger condition is met, the optimal route is adjusted to ensure that the most sustainable route is updated over time. By integrating the static route planning algorithm with the dynamic adjustment method, we can provide near-real-time navigation for both users and roads while considering the changing traffic state.

4.1. Method Overview

When the user determines the OD, the optimal route will be calculated by the dynamic route planning method. The processes used in the method are shown in Figure 2:

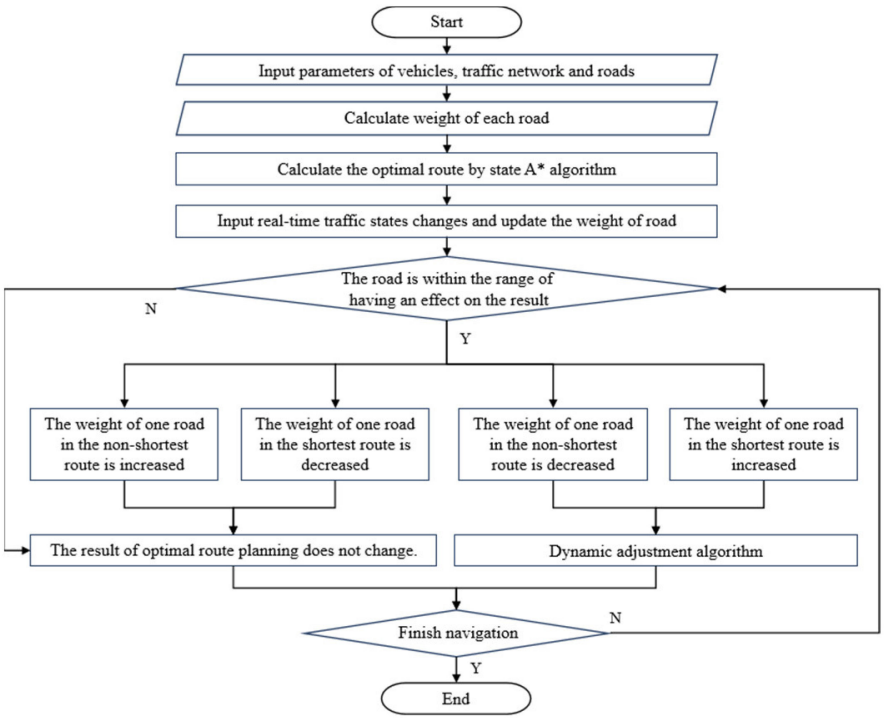


Figure 2. The processes used in the algorithm. The main parts are the calculation of weights, route planning by the static A* algorithm, and the dynamic adjustment algorithm. These are described in detail in the following part. "Y" means "Yes", and "N" means "No".

4.2. Weights for Traffic Network

The weight is the cost of using each road in the traffic network. In this study, the weight is defined as the sustainability and it includes two components: carbon emissions generated by the vehicles driving on each road, and a coefficient of the traffic flow allocation calculated by the carbon emissions produced from regular maintenance. The weights help to determine which roads are more sustainable.

Carbon emissions are a crucial factor for assessing sustainable mobility, and the calculation method is thoroughly explained in Section 3. The traffic flow allocation coefficient takes into account not only the absolute carbon emissions of each road but also considers whether the navigation results are reasonable for the entire traffic network. This is different from navigation from the perspective of drivers, who aim to reach their destinations as quickly as possible. From the road point of view, the goal is to make the most of the existing resources and optimize the network for maximum efficiency.

There are n subsequent roads at intersection m. The carbon emission ratio of subsequent intersection i can be calculated as shown in Equation (8).

$$\alpha_{m,i} = \frac{E_{3,i} + E_{4,i}}{\sum_{i=1}^{n} E_{3,i} + E_{4,i}} \tag{8}$$

Equation (8) represents the capacity of the carbon emissions from the road perspective. Because of the maintenance routine, the greater $\alpha_{m,i}$ is, the greater the percentage of traffic flow that needs to be allocated. $\alpha_{m,i}$ is in the fields of 0 and 1. Carbon emissions from vehicles can be calculated as shown in Equation (9).

$$E_{m,i} = E_{1,i} + E_{2,i} + E_{5,i} \tag{9}$$

$E_{m,i}$ is the carbon emissions associated with choosing road i at intersection m caused by vehicles. Equation (10) is the traffic flow allocation ratio of each road for green navigation from the road perspective. Carbon emissions represent a cost that hinders traffic flow. Thus, when a vehicle is at intersection m, the lower the carbon emissions, the greater the probability of choosing road i.

$$\beta_{m,i} = \frac{1 - \alpha_{m,i}}{\sum_{i=1}^{n} 1 - \alpha_{m,i}} \tag{10}$$

Thus, the weight of each road is shown in Equation (11).

$$W = \beta * \ (E_1 + E_2 + E_5) \tag{11}$$

4.3. Static A* Algorithm

The A* algorithm is a heuristic search algorithm that can find the shortest route between the origin and the destination. The applicable scenario is one of a search for the optimal route with a known traffic network and nodes. Compared with the Dijkstra algorithm, it does not need to search all nodes and is more efficient.

The processes of static route planning consist of determining the road network and weights $g(n)$, calculating the prediction cost function $h(n)$, and calculating the shortest route by $f(n) = g(n) + h(n)$.

Step 1: Determining the road network and weights, $g(n)$

The road network is abstracted from the map. Because we focus on cross-regional traffic networks, the network consists of highways. The weights of each road are calculated in Section 4.2.

Step 2: Calculating the prediction cost function, $h(n)$

The Dijkstra algorithm is used to calculate the shortest route from the destination to any node in the network to reduce the calculation process and improve the results. We use the shortest route calculated by the Dijkstra algorithm from the destination to the other nodes as a prediction cost function. In the calculation, the real-time road condition is not

considered. The Dijkstra algorithm is more expensive, but it does not need to be recalculated during dynamic adjustment, only once at the beginning of the navigation process.

Step 3: Calculating the shortest route

The A* algorithm is used to calculate the optimal route for the OD in the road network. In this problem, the cost function $g(n)$ represents the weights of each road, which are calculated in Step 1; the prediction cost function $h(n)$ is calculated in Step 2. When a road is selected at a node, the function $f(n) = g(n) + h(n)$ is used to calculate the expected optimal route from the current node to the destination. The next road is then chosen based on this calculation. This process continues until the destination is reached.

4.4. Dynamic Adjustment Trigger

In the scenario of sustainable mobility, traffic flow and weather are considered to be near-real-time parameters. The congestion degree of a road is used to measure traffic flow. Data on the congestion degree and weather can be obtained from navigation software. The level of rain is also used as a parameter to quantify the weather conditions. The information storage and calculation of the rain and congestion degree are straightforward and can be easily obtained. On the other hand, the congestion degree serves as an accurate reflection of the impact of traffic flow on the traffic conditions.

Real-time traffic has no impact on the traffic state within a certain range, and only when the traffic is greater than or less than the threshold will it have an impact on the traffic state. Furthermore, if the rainfall level is low, it will not influence the traffic state. If the rainfall changes from light rain to heavy rain, the carbon emissions will increase. Therefore, the near-real-time adjustment triggers are changes in the congestion degree and weather. The triggering factors and details are described in Table 2.

Table 2. Triggering factors and details.

Triggering Factors	Details
The weight of one road on the shortest route is increased	Congestion is increased on non-shortest routes More rainfall on the shortest routes
The weight of one road that is not on the shortest route is reduced	Congestion reduction on non-shortest routes Less rainfall on the non-shortest routes

4.5. Dynamic Adjustment Algorithm

Considering the near-real-time traffic status of the road, when the traffic status changes, the optimal route should be calculated. The impact of the change in the traffic status on the shortest path can be divided into the following four scenarios:

(1) The weight of one road in the shortest route is increased
(2) The weight of one road in the shortest route is reduced
(3) The weight of one road that is not on the shortest route is increased
(4) The weight of one road that is not on the shortest route is reduced

Scenarios (2) and (3) do not affect the selection of the optimal route. For scenario (2), the optimal route will be better. For scenario (3), the other routes will be worse.

For scenarios (1) and (4), the route adjustment method involves the identification of the start and end points of the road that fit scenarios (1) and (4). The A* algorithm is used to determine the optimal route component and the nodes being compared at the current location, and this step is recalculated based on the new information. If the optimal road changes as a result of this process, the calculation will continue until an updated optimal route is determined. If the same road remains chosen, the original optimal route will remain unchanged. In addition, only roads that start or end on the shortest route are used for the analysis.

As Figure 3 shows, the vehicle is before the red point. When congestion happens on the best route, the process of the red point in the A* algorithm should be recalculated. If

the red road is still the optimal choice (the red arrows), the result will not be changed. If it is changed, A* will continue to calculate with the new choice (the blue arrows).

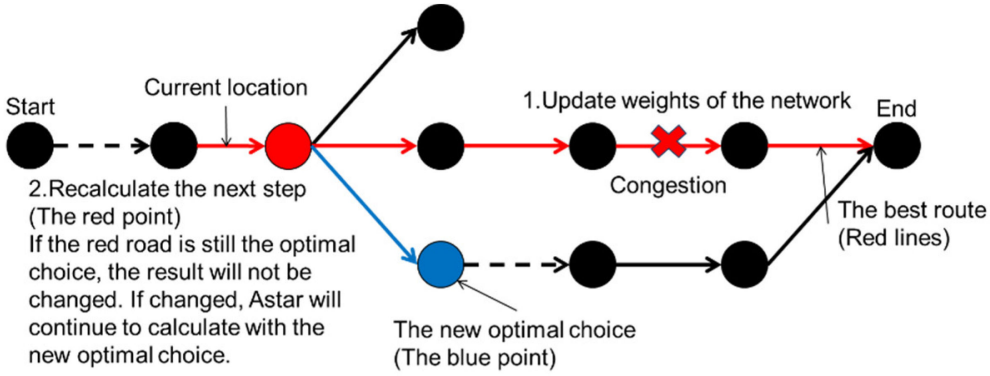


Figure 3. The dynamic adjustment algorithm.

5. Case Study

In this section, we provide an overview of the case study, including the three scenarios, purposes, parameter settings, and results. We also demonstrate the effectiveness of the algorithms and calculate the carbon emission savings associated with the most sustainable route.

5.1. Traffic Network in South China

South China refers to a part of Guangdong Province in China. The region is characterized by a developed economy and a developed transportation industry. The South China Road Network is a network of roads that connects most cities and counties in South China. The road network has the following characteristics:

- The road network in South China is characterized by high accessibility, as it has a dense network of roads that connect major cities and towns.
- The weather in this region is changeable, with abundant rainfall and rapid climate change, as well as frequent typhoons during the summer months.
- The traffic flow in South China is also significant, with short distances between cities and a high demand for transportation services.
- The maturity of the road network is another key feature, with highway construction starting early and maintenance standards being clearly defined.

5.2. Route Planning Cases

1. Roads with different service times

Foshan and Shenzhen are two of the core cities of South China, and they had a combined GDP of CNY 45,086.07 trillion in 2022. Intercity road transportation plays a crucial role in their economic development. The map is shown in Figure 4.

The construction of highways in Guangdong Province began early. The highway was built as far back as 1986. The roads have become worn down, requiring more maintenance materials. Although new highways have been built in recent years, the original ones remain irreplaceable. The length of road use affects the carbon footprint associated with road maintenance, which has an impact on the sustainability of roads.



Figure 4. The map illustrates the road network structure from Foshan to Shenzhen. The road network is dense, with many roads connected to each other on both sides of the Pearl River, including three routes that connect the two sides of the river. The black arrow shows the start point and the end point.

2. Routes with various types of roads

Zhaoqing and Dongguan are also important cities in South China. There is a large amount of passenger flow between the two cities. According to 12306.cn, which is the China Railway website, on a single day, 10 trains operate between the two cities https://kyfw.12306.cn/otn/leftTicket/init?linktypeid=dc&fs=%E8%82%87%E5%BA%86,ZVQ&ts=%E4%B8%9C%E8%8E%9E,RTQ&date=2023-10-02&flag=N,N,Y (accessed on 18 September 2023). The map is shown in Figure 5.



Figure 5. The map illustrates the road network structure from Zhaoqing to Dongguan. The black arrow shows the start point and the end point.

The connection between Zhaoqing and Dongguan crosses the east and west sides of South China. The road types are normal roads and bridges. As the route crosses the dense traffic network of Zhaoqing and Dongguan, there are large numbers of roads and bridges on the route. Since bridge maintenance requires the use of additional carbon-containing materials, the route choice will affect carbon emissions due to the number of roads and bridges.

3. Routes with variable weather

The road network from Guangzhou to Zhongshan is a crucial north–south route that connects the Guangdong, Hong Kong, and Macao highways. The map is shown in Figure 6.



Figure 6. The map illustrates the road network structure from Guangzhou to Zhongshan, which shows several north–south routes. The black arrow shows the start point and the end point.

It also serves as a link between coastal areas and inland cities, with significant climate differences along the way. As roads produce different carbon emissions based on the climate, it is essential to consider this weather when analyzing the most sustainable route.

5.3. Goals of Route Planning

1. To demonstrate the effectiveness of the sustainability evaluation model, including the calculation results for carbon emissions, road weights, and the most sustainable route.
2. To analyze the calculation results for carbon emissions from vehicles and road maintenance.
3. To analyze the change in carbon emissions compared with those produced by the shortest route and the reasons for this according to the results of the most sustainable route.

5.4. Applicability of the LCA Method

The LCA method is applied to calculate the carbon footprint in road traffic. Firstly, the LCA provides a systematic approach that integrates all parties involved in road traffic to calculate the total carbon emissions. Secondly, the LCA takes a comprehensive perspective, considering various dimensions of time and carbon-emitting events to ensure accurate calculation results. Furthermore, carbon emissions can be measured, and there are a lot of data available for transportation, making it feasible to use the LCA for calculating carbon emissions using mechanistic models. Finally, the LCA produces reliable and quantifiable results, which can be used for further analysis.

The three cases mentioned in the article all involve road traffic situations where the LCA can be used to calculate the carbon footprint. The LCA can comprehensively consider the carbon emissions generated by various parties, including road maintenance and driving, etc. The data available for the three scenarios are complete, allowing for objective and quantifiable calculations of carbon emissions.

5.5. Data Description

The dataset consists of rainfall, the service time for traffic flow in the last year, and the road length. There are 139 points and 454 roads. Every road has recordings such as the road length, rainfall per year, service time per year, and traffic flow per year. There are eight cities in the traffic network: Zhaoqing, Foshan, Jiangmen, Zhongshan, Guangzhou,

Dongguan, Huizhou, and Shenzhen. Most roads have a service time of over 10 years and a great traffic flow per year. Detailed information is shown in Figure 7.

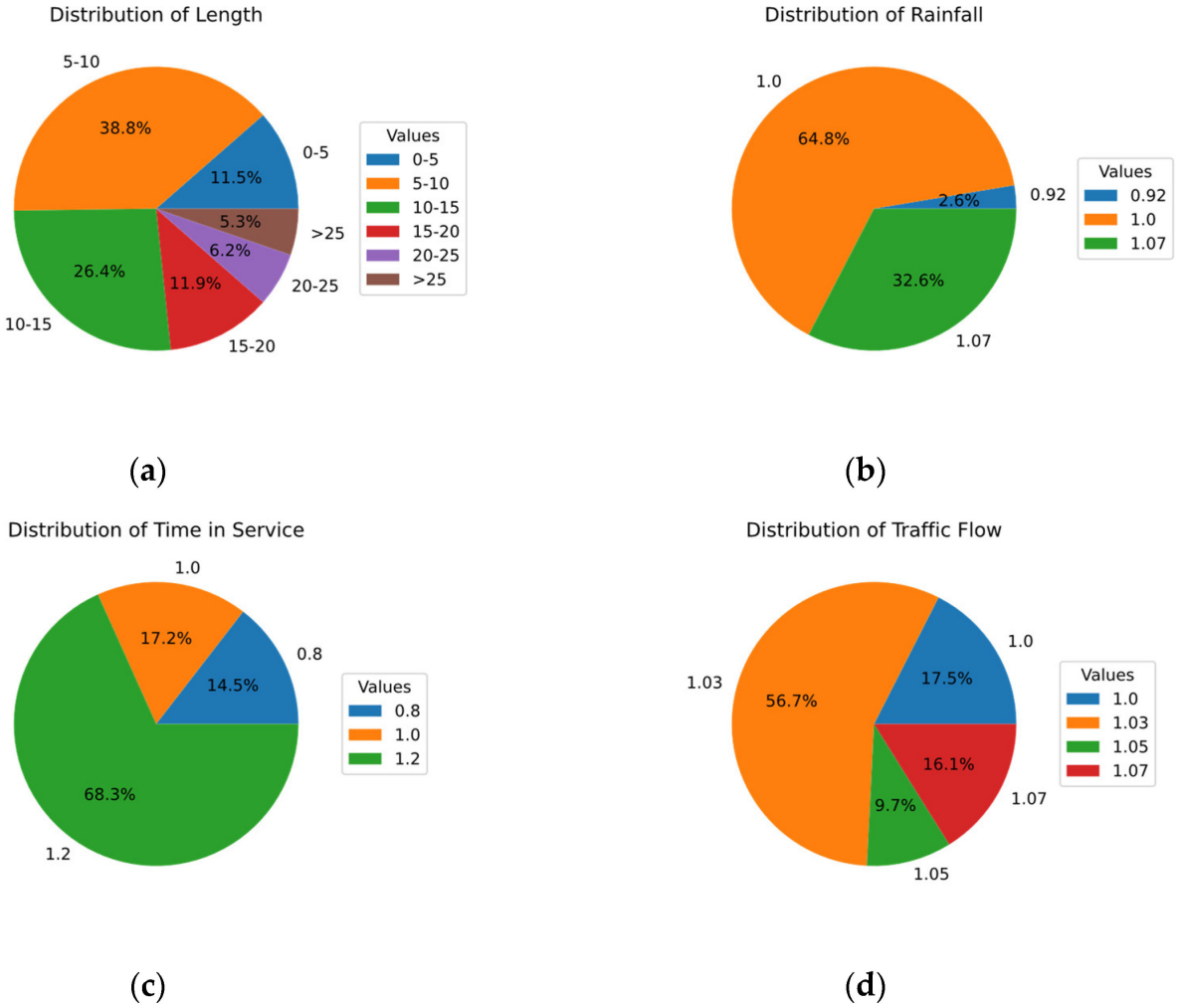


Figure 7. Data description for the South China highway. (**a**–**d**) are descriptions of the dataset, representing the distributions of road length, road rainfall, road service time, and road traffic flow, respectively. The values are calculated according to Table 9 and Table 11, and the proportions are the statistical values of the dataset.

5.6. Parameters

1. Vehicles

The following vehicles were selected as the experimental conditions for measuring the carbon emissions generated by fuel consumption in Table 3. However, it should be noted that the fuel consumption of each car can be affected by external environmental factors such as weather and congestion, which can vary depending on the location and time of day.

Table 3. Vehicle information.

No.	Fuel Consumption
1	6.8 L/100 km
2	16 kwh/100 km (wind power generation)
3	16 kwh/100 km (thermal power generation)

2. Road maintenance

The road maintenance and road patrol information was taken from the standard file of highway maintenance in China. The file describes the materials used and frequency of road maintenance.

Carbon-containing materials used in road maintenance are divided into two categories: carbon-containing materials such as cement and high-powered electrical equipment. The carbon emissions that can be generated by these two categories are shown in Table 4.

Table 4. Four vehicles information.

No.	Maintenance of Carbon-Containing Materials	Carbon Emissions
1	Asphalt	295 kg/t
2	Cement	634 kg/t
3	Transport	6.048 kg/(km×unit) [1]
4	Air compressor	42.768 kg/time
5	Road roller	52.8 kg/time
6	Cutting machine	63.36 kg/time
7	Concrete mixer	158.4 kg/time

[1] 6.048 kg/(km×unit) means carbon emissions of 6.048 kg per 1 km of transport each time.

The quantity of maintenance materials differs for different kinds of roads. Normal road maintenance items are shown in Table 5. Bridge maintenance items are shown in Table 6.

Table 5. The number of materials consumed during normal road maintenance.

No.	Maintenance Item	Asphalt (Tons/Day)	Cement (Tons/Day)	Transport (Times/Unit)	Air Compressor (Times/Day)	Road Roller (Times/Day)	Cutting Machine (Times/Day)	Concrete Mixer (Times/Day)
1	Asphalt pavement cracks reparation	0.042	0.05	0.25	0.25			
2	Asphalt potholes reparation	0.08		0.38		0.03		
3	Cement concrete pavement maintenance		0.44	0.11			0.02	0.06
4	Curb reparation		0.013	0.1				
5	Slope reparation		1.23	1.65				
6	Road shoulder and center zoning Cleaning			0.13				
7	Drainage Maintenance		0.78	1.52				

Table 6. The number of materials consumed during bridge maintenance.

No.	Maintenance Item	Asphalt (Tons/Day)	Cement (Tons/Day)	Transport (Times/Unit)	Air Compressor (Times/Day)	Road Roller (Times/Day)	Cutting Machine (Times/Day)	Concrete Mixer (Times/Day)
8	Bridge deck pavement concrete reparation		0.524	0.5				
9	Concrete surface reparation				4.28			
10	Bridge cone slope reparation		1.021	3.16				
11	Corrosion protection of bridge members		0.07					

Based on Tables 4–6, the carbon emissions for every maintenance item are shown in Table 7.

Table 7. Carbon emissions for each maintenance item per kilometer.

No.	Maintenance Item	Carbon Emission
1	Asphalt pavement cracks reparation	$54.78 + 1.51 * \text{length}$
2	Asphalt potholes reparation	$25.18 + 2.3 * \text{length}$
3	Cement concrete pavement maintenance	$289.73 + 0.67 * \text{length}$
4	Curb reparation	$8.242 + 0.6 * \text{length}$
5	Slope reparation	$779.82 + 10 * \text{length}$
6	Road shoulder and center zoning cleaning	$0.79 * \text{length}$
7	Drainage maintenance	$494.52 + 9.2 * \text{length}$
8	Bridge deck pavement concrete reparation	$332.22 + 3.02 * \text{length}$
9	Concrete surface reparation	183.05
10	Bridge cone slope reparation	$647.31 + 19.11 * \text{length}$
11	Corrosion protection of bridge members	44.38

The maintenance frequency is calculated by setting values and factors that affect the frequency such as the weather and traffic flow. The set values are shown in Table 8.

Table 8. The maintenance frequency.

No.	Maintenance Item	Influencing Factor	Maintenance Frequency
1	Asphalt pavement cracks reparation	Time in service and traffic flow	0.04%
2	Asphalt potholes reparation	Time in service and traffic flow	0.04%
3	Cement concrete pavement maintenance	Time in service, traffic flow, and rainfall	0.10%
4	Curb reparation	Time in service and traffic flow	1.50%
5	Slope reparation	Traffic flow	Once a year
6	Road shoulder and center zoning cleaning	Traffic flow	Once a year
7	Drainage maintenance	Time in service and traffic flow	0.30%
8	Bridge deck pavement concrete reparation	Time in service and traffic flow	Once a year
9	Concrete surface reparation	Time in service and traffic flow	Once a year
10	Bridge cone slope reparation	Time in service and traffic flow	Once a year
11	Corrosion protection of bridge members	Time in service and traffic flow	Once a year

Three influencing factors can be used to adjust the maintenance frequency. Table 9 shows the impacts of time in service, traffic flow, and rainfall on the maintenance frequency. Table 9 applies to normal roads and bridges.

Table 9. Adjustment coefficients for the frequency of maintenance.

Influence Factors		Adjustment Coefficient			
Time in service	Level	3–6 years		7–10 years	>10 years
	Coefficient	0.8		1	1.2
Rainfall	Level	<700 mm		700–900 mm	>900 mm
	Coefficient	0.92		1	1.07
Traffic flow	Level	<1000	1000–5000	5000–10,000	>10,000
	Coefficient	1	1.03	1.05	1.07

3. Patrol maintenance

Road patrol is the method of regular inspection by professional personnel. There are two categories of parameters for patrol maintenance. One is the frequency of road patrol (Table 10), and the other one is the factors influencing the frequency (Table 11).

Table 10. Patrol frequency and transportation consumption.

No.	Maintenance Item	Maintenance Frequency	Transport
1	Patrol	Once a day	0.0285
2	Transportation, placement, and removal of traffic diversion facilities—Bridge	Once a day	0.38
3	Transportation, placement, and removal of traffic diversion facilities—Tunnel	Once a day	0.39

Table 11. Factors influencing the maintenance frequency.

Influence Factors		Adjustment Coefficient			
Traffic flow	Level	<1000	1000–5000	5000–10,000	>10,000
	Coefficient	1	1.03	1.05	1.07

Applying the parameters, the carbon emission can be calculated by Formula (12):

$$\begin{aligned} \textit{Carbon emission} = {} & 3.26e^{-11}{z_1}^9 + 4.36e^{-9}{z_1}^8z_2 + 6.87e^{-7}{z_1}^8 + 2.78e^{-9}{z_1}^7{z_2}^2 + 8.05e^{-5}{z_1}^7z_2 + \\ & 0.00026{z_1}^7 + 1.93e^{-13}{z_1}^6{z_2}^3 + 5.13e^{-5}{z_1}^6{z_2}^2 + 0.00039{z_1}^6z_2 + 0.00078{z_1}^6 + 4.49e^{-18}{z_1}^5{z_2}^4 + \\ & 3.57e^{-9}{z_1}^5{z_2}^3 + 0.00015{z_1}^5{z_2}^2 + 0.0005{z_1}^5z_2 + 8.75e^{-5}{z_1}^5 + 3.48e^{-23}{z_1}^4{z_2}^5 + 8.29e^{-14}{z_1}^4{z_2}^4 + \\ & 1.03e^{-8}{z_1}^4{z_2}^3 + 3.46e^{-8}{z_1}^4{z_2}^2 + 0.012{z_1}^4z_2 + 6.07e^{-6}{z_1}^4 + 6.42e^{-19}{z_1}^3{z_2}^5 + 2.4e^{-13}{z_1}^3{z_2}^4 + \\ & 8.03e^{-13}{z_1}^3{z_2}^3 + 0.0075{z_1}^3{z_2}^2 + 0.0016{z_1}^3z_2 - 1.87e^{-16}{z_1}^3 + 1.86e^{-18}{z_1}^2{z_2}^5 + 6.22e^{-18}{z_1}^2{z_2}^4 + \\ & 3.46e^{-7}{z_1}^2{z_2}^3 + 0.11{z_1}^2{z_2}^2 + 0.057{z_1}^2 + 4.02e^{-12}z_1{z_2}^4 + 2.5e^{-6}z_1{z_2}^3 + 7.57z_1z_2 + 0.00018{z_2}^2 \end{aligned} \quad (12)$$

4. Traffic network

A traffic network is a group of roads and the connections between the roads. According to the characteristics of the cross-regional road network in South China, the road network was extracted, as shown in Figure 8.

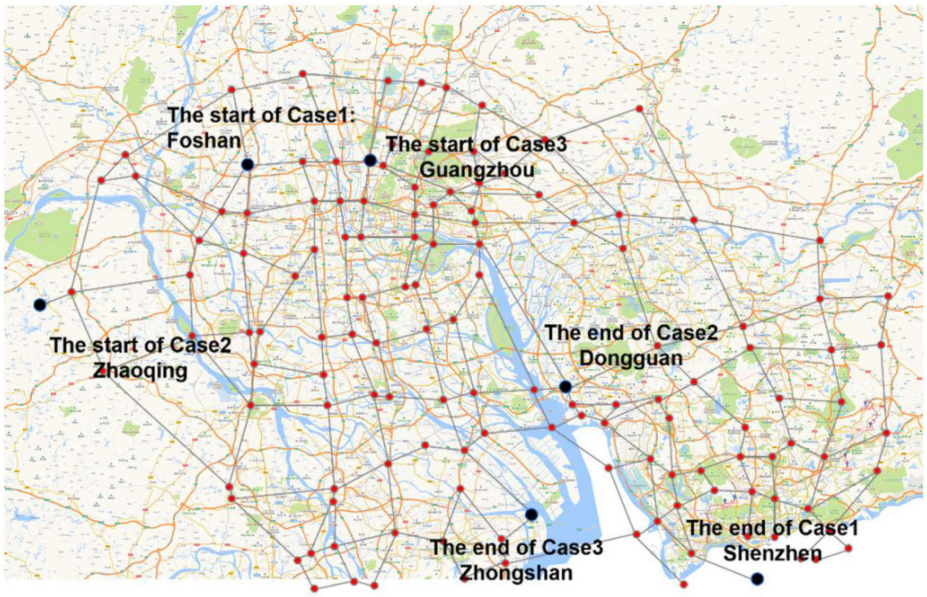


Figure 8. The red dots in the figure are the road connections, which, in the case of cross-regional roads, are often bridges. The lines connecting the black dots in the figure refer to roads. The starting points and end points of the three cases are marked in the figure.

5.7. Results

This section shows the results of the three route planning cases from both the planning algorithm and adjustment algorithm.

1. The result of the three route planning cases

(1) Roads with different service times

Figure 9 shows the results of case 1. In the traffic network, the thick line is the result of green navigation. The routes do not contain old roads, and a road that has little annual traffic flow is chosen to cross the river.

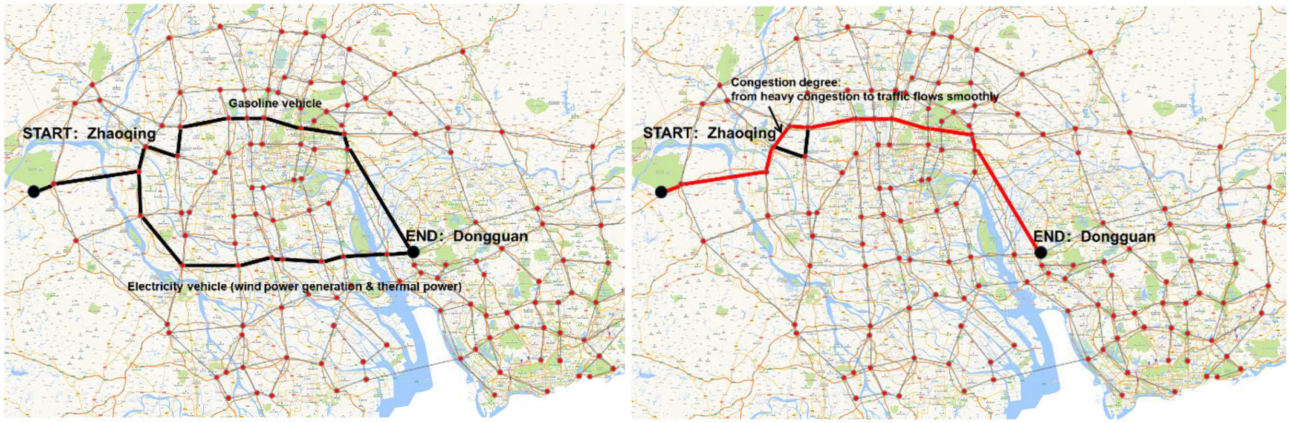


(**a**) (**b**)

Figure 9. (**a**) The result of green navigation from Foshan to Shenzhen. When the congestion degree marked in (**b**) increases, the greenest route for gasoline vehicles changes to the red route in (**b**).

(2) Routes with various types of roads

Figure 10 shows the results for case 2. In the traffic network, the thick line is the result of green navigation. For the greenest route, few bridges are used to reduce the carbon emissions from road and bridge maintenance. The length of the route reduction also keeps carbon emissions at a low level.

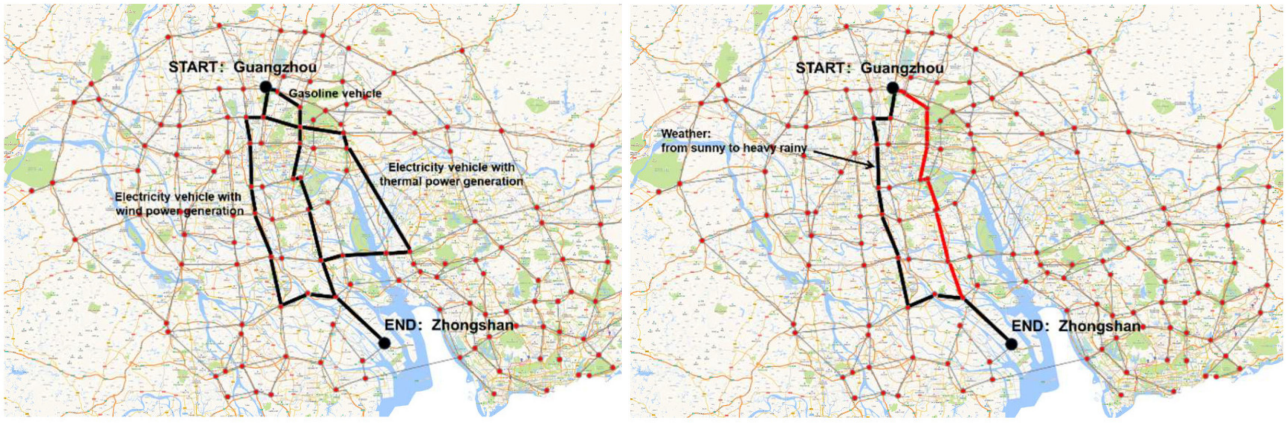


(**a**) (**b**)

Figure 10. (**a**) The result of green navigation. When the congestion degree marked in (**b**) increases, the greenest route for gasoline vehicles changes to the red route in (**b**). "(4) The weight of one road that is not on the shortest route is reduced" is the trigger used in case 2.

(3) Routes with variable weather

Figure 11 shows the results for case 3. In the traffic network, the thick line is the result of green navigation.

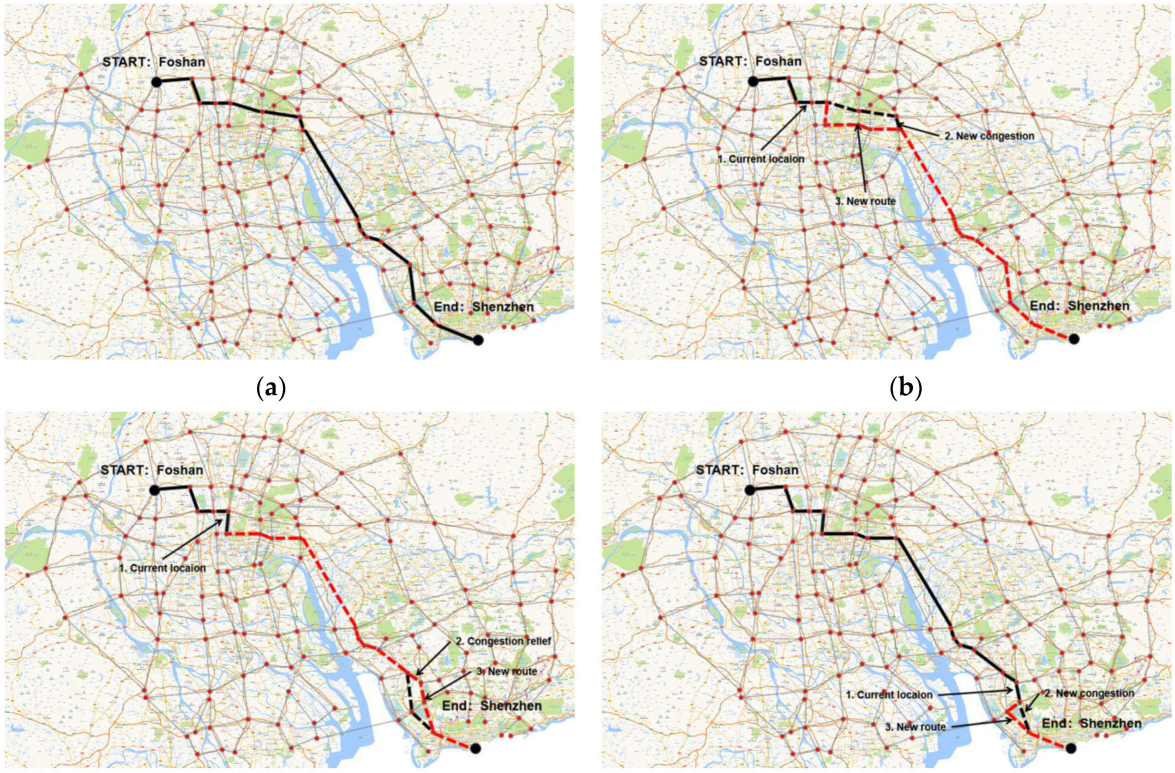


(**a**) (**b**)

Figure 11. (**a**) The result of green navigation. When the weather on the road changes from sunny to heavy rain, as marked in (**b**), the greenest route changes to the red route in (**b**). The type of adjustment trigger is "(1) the weight of one road on the shortest route is increased" in both Figures 8 and 10.

2. Near-real-time adjustment

The greenest route from Foshan to Shenzhen for electric vehicles is used in this case. We can obtain the greenest route from the last section, which is shown in Figure 12a. There are three scenarios for weight adjustment. The results are shown in Figure 12b–d.



(**a**) (**b**)

(**c**) (**d**)

Figure 12. (**a**) The greenest route. (**b**) Scenario 1: When the vehicle is on its way, a road that is on the greenest route starts to become congested. (**c**) Scenario 2: When the vehicle is on its way, a road that is not on the greenest road stops being congested. (**d**) Scenario 3: When the vehicle is on its way, a road that is on the greenest route starts to become congested. These show the near-real-time adjustments to the greenest route when the traffic state is modified.

5.8. Discussion

In this section, first, we analyze different routes based on different goals such as obtaining the shortest and fastest route and compare them using six aspects. Second, we compare the carbon emissions from vehicles and road maintenance. Finally, we analyze the influences of different variables on the total carbon emissions during driving.

1. Comparison of different routes

The route with different goals contains the greenest route, the shortest route, the fastest route, the route with the least carbon emissions, and some other routes that are recommended by map apps. There are six dimensions used to assess routes: weight, road length, carbon emissions, cost, number of bridges, and time. The minimum weight is the goal of green navigation. The road length, carbon emissions, and time are common goals in the navigation app. The cost is the toll on the road. The greater the number of bridges, the greater the additional material needed for road maintenance. The results are shown in Figures 13–15.

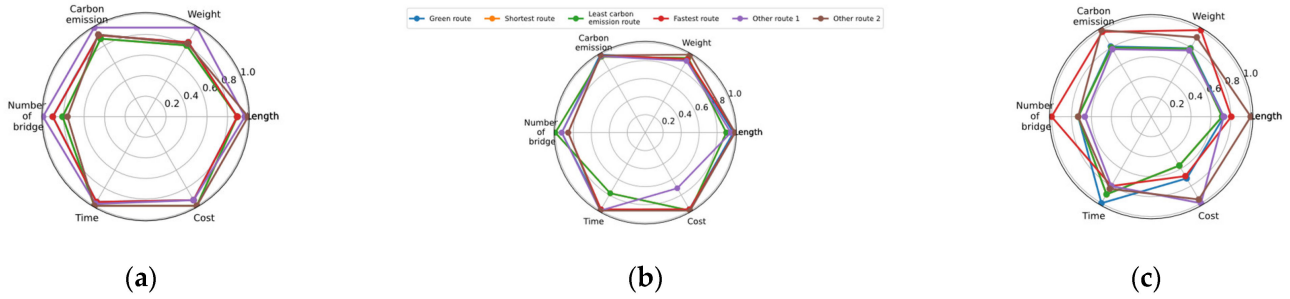


Figure 13. These figures show the result for a gasoline vehicle. (**a**–**c**) The results of cases 1, 2, and 3.

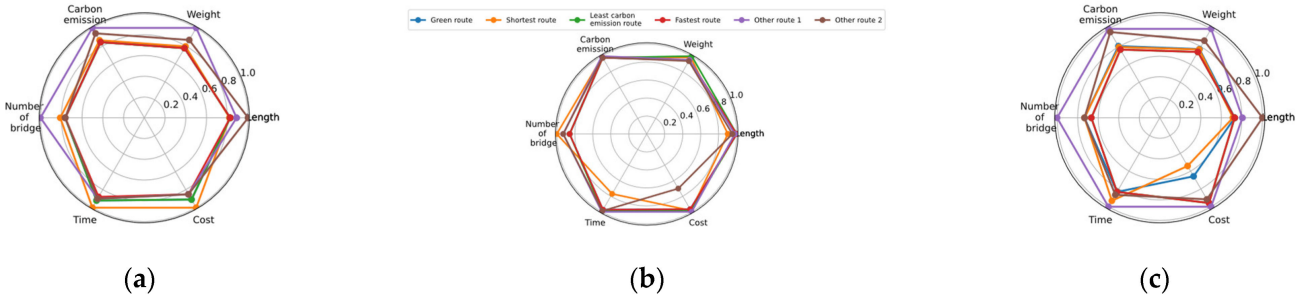


Figure 14. These figures show the result for an electricity vehicle with wind power generation. (**a**–**c**) The results of cases 1, 2, and 3.

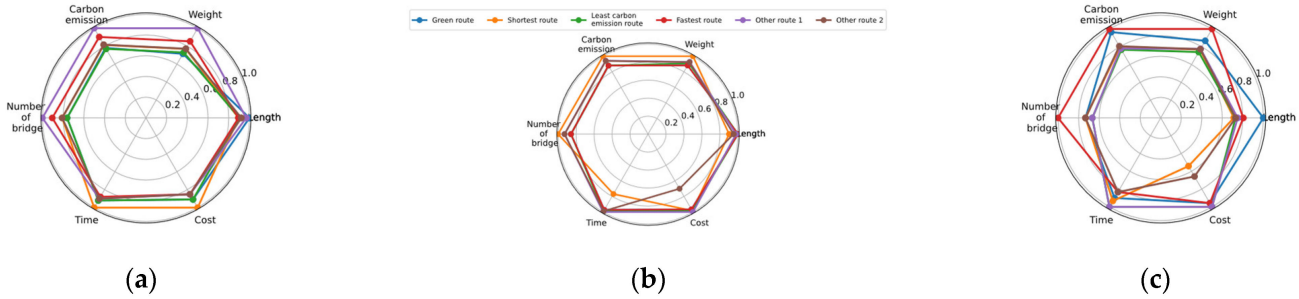


Figure 15. These figures show the result for an electric vehicle with thermal power generation. (**a**–**c**) The results for cases 1, 2, and 3.

The shortest routes are usually the ones with the least carbon emissions. The reason for this is that if the fuel consumption is determined and there are no real-time factors, the carbon emissions will be influenced by the road length. However, the green degree of the road is not the best, because it is not only influenced by vehicles but also by road maintenance.

The green line is the route with the least carbon emissions, which is the result with the minimum carbon emissions, $f1 + f2 + f5$. Both the greenest route and the route with the least carbon emissions have lower carbon emissions than other routes, although the road length is greater. Green navigation combines vehicles and road maintenance to help with the release of the pressure on roads that have problems with aging, heavy rainfall, and heavy traffic, so the greenest route is better.

The blue line is the greenest route. This route is always between the shortest route and the fastest route, because fast and short are saving-energy indicators. There are usually some scenarios with congestion or rain that adjust the fastest or shortest route. Compared with the least-carbon-emissions route, because we do not want to increase the bearing strength of the road, an allocation method for the road's capacity for carbon emissions is proposed. Thus, the greenest route is not the route with the least carbon emissions.

Other routes are taken from navigation maps. These may be the routes that the user is the most used to. These routes are always arterial traffic routes with a greater probability of congestion. Thus, from the perspective of green routes, these may not be the best choice.

2. Comparison of vehicles and road maintenance

Carbon emissions are caused by vehicles and road maintenance. In this paper, $f1$ and $f2$ are taken from a vehicle driving directly. $f5$ is also caused by driving because the maintenance in $f5$ is additional and does not rely on routine maintenance. $f3$ and $f4$ represent road maintenance. Figure 11 describes the carbon emissions from vehicles and road maintenance using 3D pictures.

Based on the results of NMF dimensional reduction, the most influential factor in $z2$ is the road length, which is 100 times more influential than the material used for road maintenance, which is the second most influential factor. Figures 16 and 17 show the carbon emissions from the fuel consumption per vehicle. $f1 + f2 + f5$ represents the carbon emissions from the fuel consumption per vehicle. $f3 + f4$ represents the carbon emissions from road maintenance per year.

On the whole, according to Figures 16 and 17f, the ratio of vehicle carbon emissions to road carbon emissions has a maximum value; that is, when the vehicle is determined, the influential capacity associated with vehicle carbon emissions has a maximum value compared with that from the road. For gasoline vehicles and non-clean-energy vehicles, when $z2$ (road length) is less than the threshold, the longer the road, the greater the proportion of vehicle carbon emissions. This result indicates that vehicles have a greater impact on carbon emissions than roads. When $z2$ (road length) is greater than the threshold, the longer the road, the smaller the vehicle impact, but it is still much larger than the road impact. For clean-energy trams, the longer the road, the smaller the proportion of vehicle carbon emissions. When calculating the carbon emissions from each vehicle, no distinction is made between electric vehicles and gasoline vehicles, which is the reason why, in Figure 16f, Y is not 0.

For the case presented in this paper, the maximum ratio in Figure 15f is 1.7. If the annual traffic flow on a road is 10,000, the carbon emissions produced from fuel are 1700 times greater than the carbon emissions produced from road maintenance.

$$\frac{f1+f2+f5}{f3+f4} = \frac{f1+f2+f5}{annual\ traffic\ flow\ *carbon\ emission\ from\ road\ maintenance\ per\ vehicle} \tag{13}$$

$$\frac{carbon\ emission\ from\ fuel\ consumption\ per\ vehicle}{carbon\ emission\ from\ road\ maintenance\ per\ vehicle} < 0.17\ *\ annual\ traffic\ flow \tag{14}$$

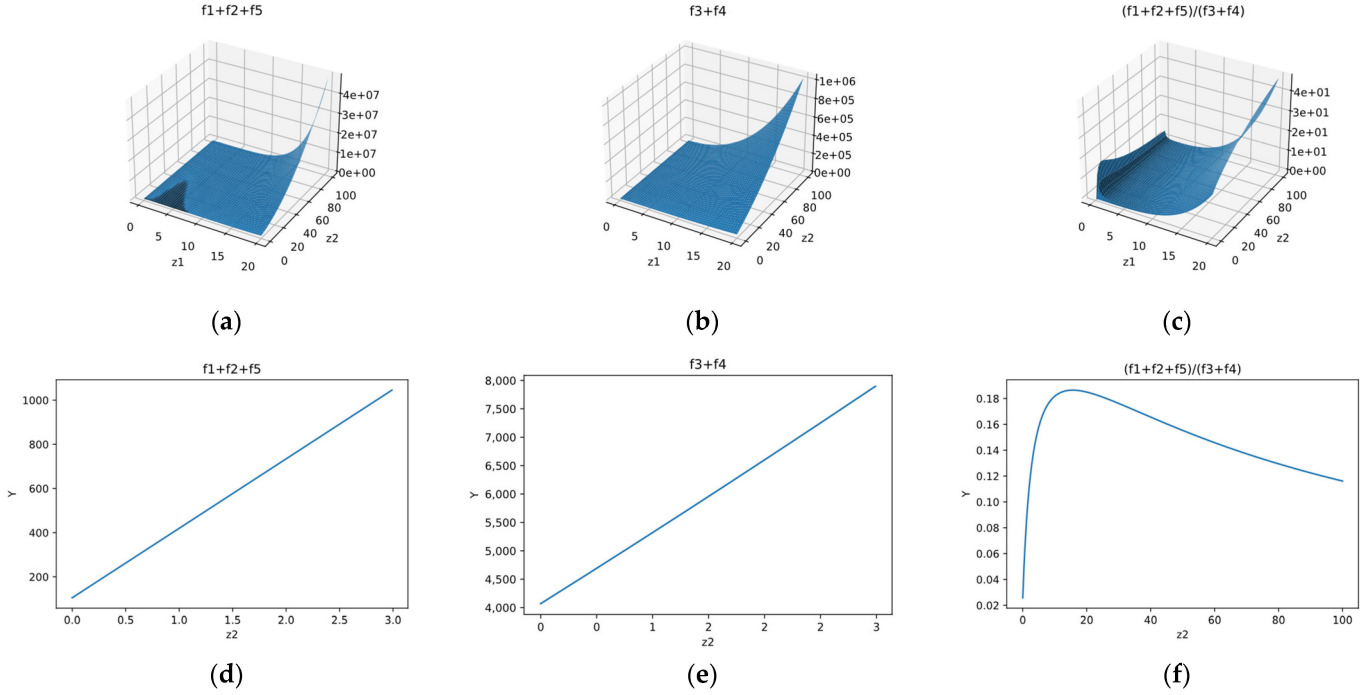


Figure 16. (**a**–**c**) The results for vehicle 1, which is a gasoline vehicle. (**a**,**d**) The carbon emissions from vehicles. (**b**,**e**) The carbon emissions from road maintenance. (**c**,**f**) The ratios of carbon emissions from vehicles to those from road maintenance. Because *z1* is in the range of 11.81 to 11.82 in these cases, (**d**–**f**) are the same as (**a**–**c**) when *z1* is equal to 11.81.

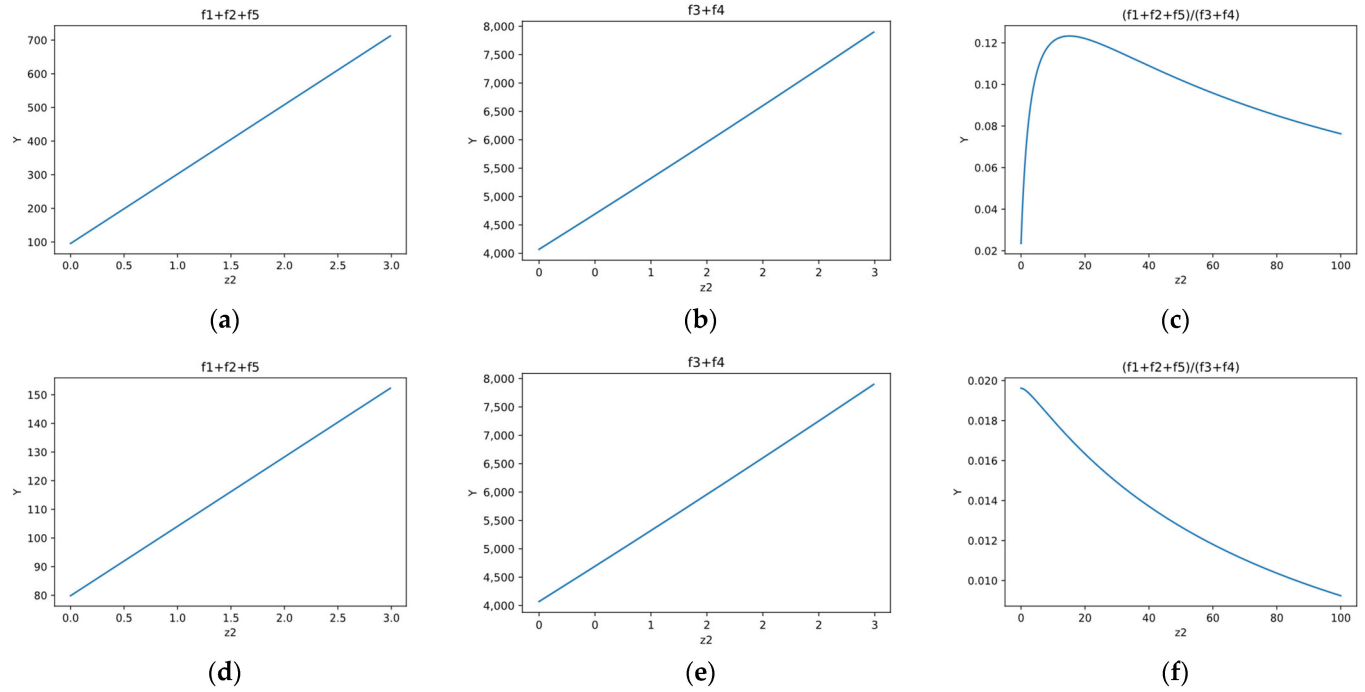


Figure 17. (**a**–**c**) The results for vehicle 2, which is an electric vehicle powered by thermal power generation. (**d**–**f**) The results for vehicle 3, which is an electric vehicle powered by clean power generation.

In the case of the South China traffic network, *z2* is in the range of 0 to 1.9, so the greater *z2* is, the greater the proportion of vehicle carbon emissions. Thus, one of the most

efficient methods to reduce carbon emissions is the reduction of fuel consumption from vehicles. From the perspective of roads, because the second derivative of Figures 15 and 16f is less than 0 when $z2$ is in the range of 0 to 9, if the length of the road is determined, the shorter the roads, the lower the carbon emissions produced.

6. Conclusions

In this paper, we calculated the optimal route in the navigation process from a green perspective, addressing the problems of the lack of a sustainable mobility evaluation model and dynamic route planning algorithm for determining the greenest route. We analyzed three cases from South China with different service times, various types of roads, and variable weather conditions. Based on these cases, we demonstrated the effectiveness of the model and algorithm and compared the carbon emissions produced from vehicles and road maintenance. The conclusions are as follows:

1. A sustainable mobility evaluation model that applies the LCA to measure carbon emissions is proposed. This model can calculate carbon emissions during periods of traffic from both vehicles and roads by considering vehicle fuel consumption, vehicle maintenance, periodic road maintenance, periodic road inspections, and additional road maintenance.
2. An algorithm for greenest route planning that combines static planning with dynamic adjustments is proposed. The A* algorithm calculates the static optimal route, where the road weight is the product of carbon emissions from vehicles and the proportion of carbon emissions from each road at an intersection. Considering the dynamic attributes of traffic conditions such as time, weather, and congestion levels, the near-real-time traffic state dynamic adjustment triggers and adjustment methods are proposed.
3. Three real-world traffic cases are proposed for South China. The results of the case study verify the effectiveness of the model and algorithm and compare the relationship with the shortest route. The carbon emissions caused by vehicles are much greater than the carbon emissions from road emissions. For these cases, decreasing the carbon emissions from vehicles is a more useful method than optimizing the road maintenance. When the road length is determined, shorter roads help to decrease the carbon emissions.

The results of this paper are generalizable. The carbon emission evaluation model can be used in many different regions, unless there are other characteristics with great influences on the carbon emissions, such as steep roads. The navigation algorithm can be used in other traffic networks. The results of the comparison of vehicle carbon emissions and road carbon emissions are also generalizable unless some characteristics associated with road construction are present. For example, if the traffic network is in the desert, the carbon emissions associated with road maintenance will be increased and there may be an additional carbon emission associated with logistics.

Upcoming work will address the issue of traffic flow as a whole. This will not only consider traffic factors but will also concentrate on the characteristics of regions, such as economic and social implications. It will also consider other carbon-containing materials used during road maintenance to construct more accurate and detailed methods for estimating the carbon emissions. In addition, equity and fairness in green route planning can be considered to add to the evaluation model and algorithm to make the results more objective and effective for other scenarios.

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