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Optimal Route Algorithm Considering Traffic Light and Energy Consumption

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ABSTRACT Vehicle speed trajectory and traffic signals significantly impact vehicle's fuel consumption and travel time in the urban road network. In this paper, we proposed an optimal vehicle routing algorithm that takes the waiting time at signalized intersections and eco-driving model into consideration. First, the data of the floating car collected by the GPS are matched with the electronic map, and the average traveling speed of the vehicle in each road segment is calculated in real time. The position and timing information of the signal lights at each intersection are pre-acquired to establish an eco-driving model at signalized intersections with the support of cooperative vehicle infrastructure system technologies. The vehicle accelerates through the signalized intersection to reduce the waiting time in the case, where the headway is allowed, while the vehicle decelerates to the minimum speed to avoid idling. Based on the traffic lights red light, green light conversion probability, and vehicle energy-saving driving model, the signal light cycle duration is divided into four parts: the green light pass section, the red-light acceleration section, the red light idle section, and the red-light deceleration section. Combining the probability distribution and the fuel consumption model, the average fuel consumption at the intersection area can be calculated. Taking the optimal energy consumption as the goal, combined with the A* algorithm, an optimal path algorithm that considers the influence of traffic lights and energy consumption is proposed. Finally, two examples are tested, including a real-world road map in Changsha city to demonstrate the effectiveness of the proposed algorithm. And the results show that the proposed model has good performance on energy consumption reduction.

INDEX TERMS Optimal path algorithm, vehicle infrastructure cooperative systems, signalized intersection, real-time speed, energy-saving algorithm.

I. INTRODUCTION

The optimal path planning is an important part of the intelligent traffic system, helping the driver to choose the shortest distance, the shortest time or other optimal driving route [1]– [3]. Due to the large number of traffic lights, the driver inevitably needs acceleration, deceleration, and idling in the urban road network. The waiting time at the signalized intersection occupies a large proportion of vehicle's travel time. At the same time, idling parking has also caused a lot of energy waste and exhaust emissions. Therefore, it is necessary to consider the waiting time of the vehicle at the intersection and the waste of fuel consumption in the path planning study.

At present, scholars mainly superimpose the average delay time caused by signalized intersections into the shortest path algorithm [4]– [7]. Yang and Miller-Hooks [8] analyzed the additional delay due to signal control in the random time-varying road network under the condition that the traffic time of the road section and the signal timing of the traffic lights are randomly changed and proposed a label correction algorithm which includes the optimal path of waiting for the green time. Lee *et al.* [9] proposed an intersection-to-intersection real-time travel time estimation model and route suggestion model based on vehicular ad-hoc network (VANET) technology, and the intersection delay is estimated by averaging the timestamp difference of the vehicles entering and leaving an intersection. Fan *et al.* [10] proposed a labeling algorithm that takes into account the waiting time at signalized intersections by modeling the waiting time of signalized intersections. Zhou *et al.* [11] further considered the influence of different steering types on the waiting time at signalized intersections and proposed an extended A* algorithm that considers the steering type at signalized intersections.

At present, domestic and foreign scholars have conducted a large number of studies on energy-saving driving at intersections in urban roads [12]– [15]. Zhao *et al.* [16] proposed an eco-driving control system, aiming to minimize fuel consumption via traffic timing prediction based on fuel consumption model and speed tracking. Based on the continuous multi signal traffic scene model, together with the speed curve and the energy management of hybrid electric vehicles, Luo *et al.* [17] proposed an approach that aims to optimize green light optimal speed advisory and energy management for hybrid vehicles based on genetic algorithm. Xu *et al.* [18] achieved the goal of improving traffic efficiency and reducing vehicle fuel consumption by optimizing both signal timing and vehicle traffic speed. Asadi and Vahidi [19] used short-range radar and traffic light information to pre-optimize the speed trajectory for the vehicle, allowing the vehicle to reach the intersection within the green time and reduce the number of brakes while maintaining a safe vehicle distance, thereby, reducing idle stop time and reducing fuel consumption. Butakov and Ioannou [20] proposed a personalized speed optimization algorithm based on the traffic light position and timing information, considering vehicle fuel economy and waiting time, combined with the driver's preferences and habits. Kamal *et al.* [21] predicted the future driving status of the preceding vehicle by obtaining current road traffic information, and then planned safe vehicle spacing and optimal cruising speed for the vehicle to maximize fuel economy. He *et al.* [22] proposed a multi-level optimization control equation to obtain the optimal speed trajectory of the vehicle at the signalized intersection on the basis of considering both the state of the traffic light and the vehicle queuing. Alsabaan *et al.* [21] proposed a comprehensive optimization model to reduce fuel consumption and emissions based on real-time communication between vehicles and traffic-lights, and used heuristic methods to obtain the optimal results. He *et al.* [23] proposed a new vehicle cooperative driving model based on the scene of signalized intersection under the environment of vehicle interconnection, the model planned trajectories for vehicles in the vicinity of traffic signals in advance to reduce stopping frequency and travel time, it also planed the cooperative lane changing strategy in this scenario to improve safety and comfort in the process of lane changing.

In addition, some scholars also consider the influence of signalized intersections in the study of energy consumption optimal path planning. Yan *et al.* [24] proposed an eco-route planning model, which takes into account the impacts of major acceleration events associated with link changes and intersection idling, it also explicitly captures delays at intersections and the emissions associated with them, and describes the waiting time of intersections with a probabilistic distribution. Gu *et al.* [25] developed an eco-routing algorithm, which incorporates a microscopic vehicle emission model into a Markov decision process (MDP), and then transferring the original MDP based formulation to a linear programming formulation. It using three statuses: deceleration, travel at free flow speed, or acceleration to describe the impact of signalized intersections. Mobasheri [26] proposed a bi-objective eco-routing model based on urban road networks, aiming at reducing energy consumption and saving travel time. The impact of signal lights and turning movement were also considered in the model. The influence of traffic lights in the study of optimal energy consumption route planning have been considered in the above literature, but they just considers the idle speed and delay caused by signalized intersections into the eco-routing model, while how to reduce the delay of signalized intersections to further reduce vehicle travel energy consumption is not analyzed.

The contributions of this work may be stated as follows. Firstly, we proposed an eco-routing algorithm with optimal energy consumption, which considers the influence of signalized intersection based on the traditional route planning algorithm. Secondly, in most existing route planning algorithm, the speed of the road section is preset and does not change with time. In this paper, the running speed of the vehicle is changed, which is divided into four states: acceleration, deceleration, idle speed and uniform speed, and through the use of vehicle-road coordination technology to obtain and update the average speed of the road. Finally, in the planning of the optimal path of energy consumption, the principle of minimum travel time of the vehicle is taken into consideration, and the vehicle is considered to be environmentally driven to pass the signalized intersection to further reduce the energy consumption of the vehicle.

This paper is organized as follows. In Section 2, we proposes the optimal path algorithm considering the impact of traffic lights and energy consumption. In Section 3, we carries out experimental simulation analysis of the algorithm proposed in this paper. In Section 4, we draw the conclusion of this paper and propose the next stage of research plan.

II. OPTIMAL PATH ALGORITHM CONSIDERING SIGNAL LIGHT AND ENERGY CONSUMPTION IMPACT

A. ROAD NETWORK MODEL CONSTRUCTION

Based on the dynamic time-division network [27], the urban road network model is constructed. The road network is characterized by G=(N, D,V,F), where N={1, . . . , n} represents a set of nodes (i.e., intersections), D indicates the length of the arc between the connected nodes, V represents the real-time speed associated with each arc, and F represents the energy consumption of the vehicle from the start to the end of the trip. In the urban road network, the travel time of the vehicle mainly consists of the travel time of the road section and the waiting time at the signalized intersection.

B. THE AVERAGE SPEED OF THE VEHICLE

Nowadays, more and more vehicles are equipped with satellite navigation and wireless communication equipment. Through the satellite navigation module and communication module installed on the vehicle, vehicle position, speed, and time information are periodically sent to the information center. Analyzing and processing such information can lead to better understanding of traffic flow information of each road segment in the real time. Assuming that the number of floating vehicles on a road at time t is n and the instantaneous speed of each vehicle is V_i ($i = 1, 2 \ldots, n$), the average speed of vehicles on that road segment at time t is:

$$V = \sum_{i=1}^{n} V_i/n \tag{1}$$

Matching the satellite navigation data with the electronic map [28] can get the real-time speed of the vehicle on each road section.

C. DRIVING ENERGY SAVING DRIVING MODELS AT SIGNALIZED INTERSECTIONS

Through the vehicle-to-Infrastructure cooperation/ communication system, the vehicle can obtain the current phase of the traffic light ahead as well as its remaining time (assuming a signal controller having fixed time logic), the real-time distance information of the vehicle from the intersection ahead. Therefore, the driver can adjust the corresponding speed in advance for different signal lights to ensure that the vehicle passes the signal quickly, and at the same time minimize the probability of vehicle's idle stop.

Under the speed-guiding strategy, driving through signalized intersections can be divided into the following four conditions based on the current state of traffic lights:

(1) Passing the stop line of the intersection at a constant speed

When the state of the traffic light to be reached by the vehicle is in green phase and the remaining time of the green light is sufficient, the corresponding driver can pass through the intersection by maintaining its current speed.

(2) Passing the stop line of the intersection by accelerating

When the traffic light state of the intersection to be reached by the vehicle is in the green phase but is about to turn red . For such case, the vehicle can pass the stop line of the signalized intersection before the end of the green phase by accelerating to the maximum speed limit.

It is assumed that the communication distance of the signalized intersection is S, the maximum speed limit of the road segment is V_{max}, and the minimum speed of the road segment is V_{min}. The vehicle enters the communication distance S of the road section at time A, and travels at the average speed of V_i, reaching to stop line at time t_2. If the vehicle enters the S range and accelerates to the maximum speed of V_{max} with the acceleration a_1, it will pass through the stop line just before the end of the green time (at time t_1).

$$S = V_i \cdot t_2 \tag{2}$$

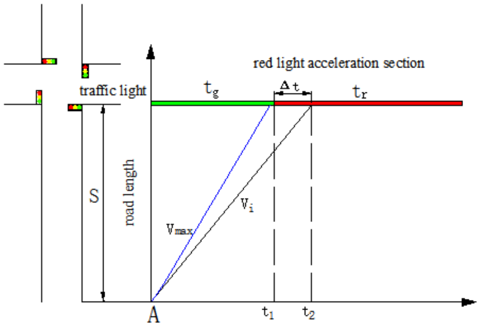

FIGURE 1. Vehicle acceleration through the signal intersection.

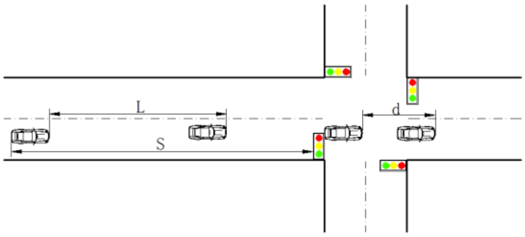

FIGURE 2. Diagram of the time headway.

$$\begin{aligned} S &= (V_{\max}^2 - V_i^2)/2a_1 + V_{\max} \\ &\quad \cdot [t_1 - (V_{\max} - V_i)/a_1] \qquad (3) \\ \Delta t &= t_2 - t_1 \qquad (4) \end{aligned}$$

It is worth noting that when the vehicle accelerates through the intersection, it is necessary to consider whether there is a car in front of the vehicle and the distance between the two cars (this article does not consider overtaking conditions).

$$\begin{aligned} S - L + d &= t_1 \cdot V_i \qquad (5) \\ d &= \frac{V_{\max}^2 - V_i^2}{2a_2} - \frac{V_i(V_{\max} - V_i)}{a_2} + D \qquad (6) \end{aligned}$$

Where d is the minimum safe distance between the vehicle and the vehicle in front when passing through the stop line at the intersection. After the vehicle passes through the intersection stop line, it decelerates to the average speed of the road section, where a_2 is the deceleration of the vehicle and D is the minimum vehicle distance following the car.

The expression of the time headway t is:

$$t = L/V_i \tag{7}$$

In this paper, the Weibull distribution model with three parameters is used to describe the distribution of time headway. According to Weibull distribution, the probability distribution of time headway is:

$$P(h \geq t) = \exp[-(\frac{t-\gamma}{\beta-\gamma})^{\alpha}], \quad \gamma \leq t \leq \infty, \quad \alpha > 0, \ \beta > 0, \ \gamma \geq 0, \ \beta > \gamma \tag{8}$$

In the formula, h denotes the time headway of two adjacent vehicles, and t denotes the critical time interval headway.

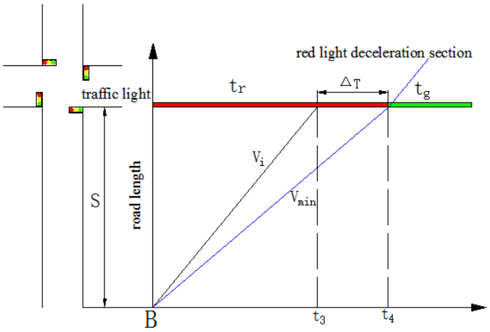

FIGURE 3. **Diagram of the passing signalized intersection after the vehicle decelerates.**

Where α, β, γ are called the distribution parameters, α is the starting point parameter, β is the shape parameter, and γ is the scale parameter.

(3) Passing the stop line of the intersection by decelerating

When the vehicle is approaching to the intersection stop line at its current speed, while the traffic light is in red phase and the remaining red time is short. For such case, the vehicle can go through the intersection stop line after the red light phase ends through decelerating the speed to the minimum speed limit.

Assuming when the vehicle is traveling at an average speed of V_i, it enters the range of the communication distance S of the road segment at time B, and it will reaches the stop line at time t_3. Hence, when the vehicle enters the range of S and subsequently decelerates to the minimum speed of V_{min} at deceleration a_2, the vehicle can pass through the stop line right after the red light phase ends (at time t_4), here is the formulation:

$$S = V_i \cdot t_3 \tag{9}$$

$$\begin{aligned} S = &(V_i^2 - V_{\min}^2)/2a_3 + V_{\min} \\ &\cdot [t_4 - (V_i - V_{\min})/a_3] \end{aligned} \tag{10}$$

$$\Delta T = t_4 - t_3 \tag{11}$$

(4) Passing the stop line of the intersection after the end of the red light

When the vehicle runs at the current speed toward the stop line with traffic lights being in red and the remaining time being long, the vehicle still needs to stop even to the minimum speed limit. At this time, the vehicle should slow down slowly to stop and waiting for the coming green light phase.

D. CONSTRUCTION OF SIGNAL TRAFFIC LIGHT MODEL

On the basis of the independent 4-phase signal control intersection, the phase of traffic lights in each traffic direction is divided into red light (yellow light time is included into red light phase calculation) and green light state.

According to the speed guidance strategy at the signal intersection, the phase of the traffic signal cycle can be further divided into four stages: green light section, red light acceleration section, red light idling speed section, and red light deceleration section. The proportion of the four stages in the traffic signal cycle can be calculated from the contents of the previous section, as shown in Figure 4.

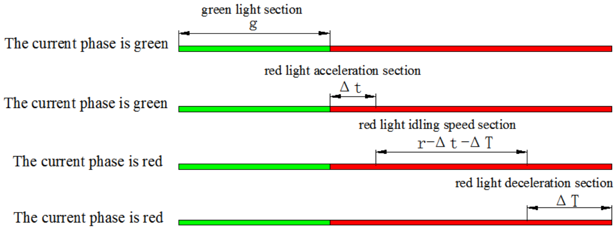

FIGURE 4. **Diagram of phase segmentation.**

$$\begin{cases} P_g = \dfrac{g}{r+g} \\ P_{r_1} = \dfrac{\Delta t \cdot P_h}{r+g} \\ P_{r_2} = \dfrac{r - \Delta t \cdot P_h - \Delta T}{r+g} \\ P_{r_3} = \dfrac{\Delta T}{r+g} \end{cases} \tag{12}$$

Where P_g is the probability of the green light passage section, P_{r1} is the probability of the red light acceleration section, P_{r2} is the probability of the idle speed section of the red light, P_{r3} is the probability of the deceleration section of the red light, and P_h is the probability of headway, which can meet the acceleration of the vehicle.

E. VEHICLE FUEL CONSUMPTION MODEL

The driver can reduce the fuel consumption of the entire journey by passing the signalized intersection at a reasonable speed. The fuel consumption of a vehicle is affected by many factors such as driving behavior, wind speed, and engine technology, etc. Therefore, it is difficult to use a simple mathematical model to accurately describe the vehicle's fuel consumption. This study adopts an instantaneous fuel consumption rate model proposed in [18]. The instantaneous fuel consumption model uses the acceleration and the vehicle speed v as input parameters to obtain an estimation model of the fuel consumption rate. The model can accurately calculate the instantaneous fuel consumption of vehicles under acceleration, idling, deceleration and isokinetic conditions. The fuel consumption formula uses the driving inputs of acceleration a (m/s2) and velocity v (m/s) to provide an estimate on the fuel consumption rate F (ml/s).

$$F(a, v) = \max\{(\alpha + \beta_1 \cdot v \cdot R_T + [\beta_2 \cdot M \cdot a^2 \cdot v]_{a>0}), \alpha\} \tag{13}$$

$$F = \begin{cases} \alpha, \quad if\ a < \dfrac{-b_1 - b_2 V^2 - gMG}{M} \\ \alpha + \beta_1 \cdot V \cdot R_T, \quad if\ \dfrac{-b_1 - b_2 V^2 - gMG}{M} \\ \qquad \leq a < 0 \\ \alpha + \beta_1 \cdot V \cdot R_T + \beta_2 \cdot M \cdot a^2 \cdot V, \quad if\ 0 \leq a \end{cases} \tag{14}$$

TABLE 1. Parameter definitions and its values used in the example.

Parameter	Value
α	0.444（ml/s）
β_1	0.09（ml/kJ）
β_2	0.04 $ml/(kJ\cdot m/s^2)$
g	9.8（m/s^2）
M	1200（kg）
b_1	0.333（KN）
b_2	0.00108（KN）
G	0°

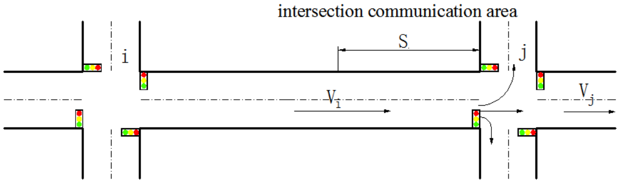

FIGURE 5. Diagram of road segmentation.

Where α is the constant idling fuel rate (ml/s), M is the vehicle mass (kg), β_1 is an efficiency parameter which relates fuel consumption to the energy provided by the engine (ml/kj), β_2 relates fuel consumption with positive acceleration (ml/(kj*m/s^2)).

$$R_T = b_1 + b_2 \cdot V^2 + M \cdot a + gMG \tag{15}$$

Where b_1 is the drag force due to rolling resistance (KN), b_2 represents the drag force due to aerodynamic resistance (kg/m). G is the road gradient and g is the gravitational acceleration (9.81 m/s^2). For convenience of calculation, this paper assumes that the road gradient is zero.

F. FUEL CONSUMPTION OF VEHICLES PASSING THROUGH SIGNALIZED INTERSECTIONS

Previously, we have analyzed the four driving modes of vehicles passing through signalized intersections, and accordingly proposed a time-phased signal traffic light probability model. The fuel consumption of the vehicle passing through the signalized intersection can be obtained by combining the proportion of the four traffic modes in the whole signal cycle and the fuel consumption under each passing mode. As shown in Fig. 5, the section between intersection i and intersection j can be divided into two parts: an intersection communication area and a non-communication section.

1) GREEN LIGHT PASSAGE SECTION (CONSTANT SPEED)

When the vehicle enters the communication range of the signalized intersection and the phase of the traffic light is in the green light passage section, the vehicle can pass through the intersection directly at the current speed. At this time, the fuel consumption of the vehicle passing through the intersection is:

$$F_g = \int F(V_i, 0)dt \tag{16}$$

Among them, the vehicle travels at the current speed assuming Vi, Vi=Vj, the same as below.

2) RED LIGHT ACCELERATION SECTION (ACCELERATION - CONSTANT VELOCITY - DECELERATION)

When the vehicle enters the communication range of the signalized intersection and the phase of the traffic light is in the red light acceleration phase, the vehicle accelerates from speed V_i to $V_{\max}$ with acceleration a_1, and then travels at speed $V_{\max}$ to the intersection stop line, and finally with deceleration a_2 by the speed $V_{\max}$ decelerates to V_j, the fuel consumption through the intersection in this way is:

$$F_{r_1} = \int F(V(a_1,t), a_1)dt + \int F(V_{\max}, 0)dt + \int F(V(a_2,t), a_2)dt \tag{17}$$

Where the driving time of the vehicle in the acceleration phase is $(V_{\max} - V_i)/a_1$, the driving time at maximum speed limit is $t_1 - (V_{\max} - V_i)/a_1$, the driving time in deceleration phase is $\left(V_{\max} - V_j\right)/a_2$.

3) RED LIGHT IDLE SECTION (CONSTANT SPEED - DECELERATION - IDLE - ACCELERATION)

When the vehicle enters the communication range of the signalized intersection and the phase of the traffic light is at the red idle stage, the vehicle travels at the speed V_i to the vicinity of the intersection, and then decelerates to 0 with the deceleration a_2 from the speed V_i. When the green light starts to brighten, it accelerates to V_j with acceleration a_1, the fuel consumption through the intersection in this way is:

$$F_{r_2} = \int F(V,0)dt + \int F(V(a_2,t), a_2)dt + \int F_\alpha dt + \int F(V(a_1,t), a_1)dt \tag{18}$$

Where the driving time of the vehicle at the current speed is $(S - V_i^2/2a_2)/V_i$, the driving time in deceleration phase is V_i/a_2, the driving time in idle speed phase is r/2, the driving time in acceleration phase is V_j/a_1.

4) RED LIGHT DECELERATION SECTION (DECELERATION - CONSTANT SPEED - ACCELERATION)

When the vehicle enters the signalized intersection communication range and the traffic light phase is in the red light deceleration section, the vehicle decelerates from the speed V_i to $V_{\min}$ with the deceleration a_2, then travels to the intersection stop line at speed $V_{\min}$, and finally accelerating to V_j with acceleration a_1, the fuel consumption through the intersection in this way is:

$$F_{r_3} = \int F(V(a_2,t), a_2)dt + \int F(V_{\min}, 0)dt + \int F(V(a_1,t), a_1)dt \tag{19}$$

Where the driving time of the vehicle in deceleration phase is $(V_i - V_{\min})/a_2$, the driving time at minimum speed limit is $t_4 - (V_i - V_{\min})/a_2$, the driving time in acceleration phase is $\left(V_j - V_{\min}\right)/a_1$.

In summary, it is possible to calculate the fuel consumption of the vehicle passing the signalized intersection in four different ways according to the phase of the traffic light. Combined with the probability of these four ways, the average fuel consumption of vehicles passing signalized intersection can be calculated, the calculation formula is as follows:

$$f = P_g \cdot F_g + P_{r_1} \cdot F_{r_1} + P_{r_2} \cdot F_{r_2} + P_{r_3} \cdot F_{r_3} \tag{20}$$

G. THE REAL-TIME SHORTEST PATH ALGORITHM CONSIDERING FUEL CONSUMPTION

In the urban road network, due to the presence of signalized intersections, the operating conditions of the vehicle include acceleration, deceleration, idling, and constant speed. The idling conditions account for a relatively large proportion of the entire driving process, which has a great impact on the energy loss of vehicles and the emission of pollutants. Therefore, in the urban road network considering the influence of traffic signal lights, the vehicle needs to pass through the signal intersection in a nonstop way and avoid idle stop to reduce the waiting time and the loss of energy consumption at the intersection. This study proposes a model of energy-saving driving of vehicles at signalized intersections, and combines the probability model of traffic lights to obtain a fuel consumption calculation method for vehicles passing through signalized intersections. There are four ways for vehicles to pass through signalized intersections based on the energy-saving driving model and the current traffic light phase.

A* algorithm is a heuristic search algorithm, which uses the evaluation function to limit the search range. It has the advantages of high search efficiency and easy implementation. The traditional A* algorithm does not consider the waiting time and energy consumption at the signalized intersection. In this paper, the A* algorithm is extended based on the fuel consumption model of the signalized intersection, and the optimal route algorithm considering the influence of traffic lights and energy consumption is proposed.

Its evaluation function is expressed as the following formula:

$$\begin{cases} f(j) = g(j) + h(j) \\ g(j) = g(i) + (d_{ij} - S) \cdot F(V_i, 0)/V_i + F_j \\ h(j) = D(j) \cdot F(V_j, 0)/V_{\max} \end{cases} \tag{21}$$

Where $f(j)$ is the evaluation value of arc node j, $g(j)$ is the actual cost of the initial arc node to node j, $g(j)$ i, d_{ij} is the actual cost of the initial arc node to node i, d_{ij} is the distance between intersection i and intersection j, S is the communication distance of the intersection, F_j is the fuel consumption of the vehicle passing through intersection j, $(d_{ij} - S) \cdot F(V_{ij}, 0)$ is the fuel consumption of the distance between non-communication sections between intersections i and j, $h(j)$ is the estimated cost of arc node j to the target arc node, $D(j)$ is the Euclidean distance between the arc node j to the target arc node. $V_{\max}$ is the maximum speed limit value of the road network.

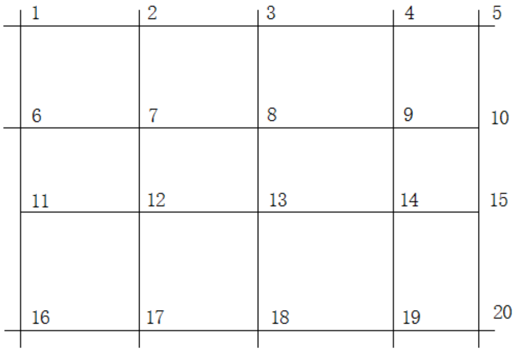

FIGURE 6. Example road network.

To ensure that the optimal path is found, h(j) must be less than or equal to the actual cost of the arc node j to the target arc node. Since the Euclidean distance between two points in the road network is the shortest, it is compared with the maximum speed limit value of the whole road network and multiplied by the corresponding fuel consumption rate, and the obtained fuel consumption must be smaller than the actual fuel consumption.

III. NUMERICAL EXAMPLE

A. A SMALL EXAMPLE

A simple road network is designed to illustrate the implementation process of the optimal path planning algorithm considering the influence of signal lights and energy consumption. As shown in Figure 6, the road network contains 25 intersections and 40 road sections. The example is set as follows:

(1) Each road section in the road network is bidirectional. The length is shown in Table 2. The maximum speed limit of the road network is 60km/h, the minimum speed limit is 15km/h, and the average speed of the smooth road section is 40km/h.

(2) Uniformly define the phase sequence of all signalized intersections in the network: the intersection has 4 phases, phase 1 is north-south through, phase 2 is left-turn for south-north entrance, phase 3 is east-west through, phase 4 left-turn for east-west entrance. The phase of each signalized intersection is independent, known, and fixed. The signal timing parameters are shown in Table 3.

(3) The vehicle can communicate with each traffic light in real time through wireless communication. The communication distance S is 200m. The vehicle enters this distance range to obtain the real-time phase and timing information of the traffic light ahead.

(4) The acceleration of the vehicle is set to 1.5 m/s^2, and the deceleration of the vehicle is set to 2.5 m/s^2.

(5) The arrival traffic flow at the intersection satisfies the Weibull distribution with the distribution parameter $\alpha = 2.2$,

TABLE 2. The length of road in the example.

road	length	road	length	road	length	road	length
$d_{1,2}$	700m	$d_{1,6}$	600m	$D_{13,14}$	800m	$D_{11,16}$	700m
$D_{2,3}$	700m	$D_{2,7}$	600m	$D_{14,15}$	500m	$D_{12,17}$	700m
$D_{3,4}$	800m	$D_{3,8}$	600m	$D_{16,17}$	700m	$D_{13,18}$	700m
$D_{4,5}$	500m	$D_{4,9}$	600m	$D_{17,18}$	700m	$D_{14,19}$	700m
$D_{6,7}$	700m	$D_{5,10}$	600m	$D_{18,19}$	800m	$D_{15,20}$	700m
$D_{7,8}$	700m	$D_{6,11}$	500m	$D_{11,12}$	700m	$D_{9,14}$	500m
$D_{8,9}$	800m	$D_{7,12}$	500m	$D_{12,13}$	700m	$D_{10,15}$	500m
$D_{9,10}$	500m	$D_{8,13}$	500m	$D_{19,20}$	500m		

TABLE 3. Signal timing information at each intersection.

Node	Cycle time/*s*	Change interval /*s*	Phase 1 green time/s	Phase 2 green time/s	Phase 3 green time/s	Phase 4 green time/s
11	118	3	40	20	30	16
6	120	3	42	20	30	16
1	114	3	38	22	28	14
2	100	3	36	18	22	12
3	148	3	46	22	46	22
4	140	3	44	22	42	20

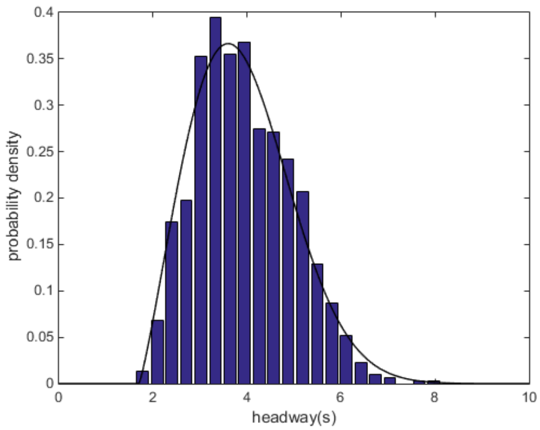

FIGURE 7. Weibull probability density curve.

TABLE 4. Statistics of traffic fuel consumption at intersection section.

Intersection node	11	6	1	2	3	4
Fuel consumption(ml)	36.1	35.8	36.2	34.8	37.7	37.4

$\beta = 2.5$, $\gamma = 1.7$. The probability density curve is shown in Figure7.

The path calculated by the algorithm presented in this paper is: 16-11-6-1-2-3-4-5. The path includes six intersections, one of which is right and six are straight. The total length of the road is 4.5km.

First, according to the phase timing information of each traffic signal, the probability of each segment of the traffic light cycle duration can be calculated by formula 13. According to the known information such as road traffic speed, road network speed limit, vehicle acceleration, deceleration, etc., the fuel consumption of the vehicle passing through the intersection under four conditions can be calculated by Equations 16-19. The four conditions related to the phase of the traffic light include the green pass section, the red light accelerating section, the red light idle section, and the red light deceleration section. Combined with the previously calculated probability, the fuel consumption of the vehicle passing through a signalized intersection can be obtained by formula 20. The fuel consumption of each intersection in the path obtained by the example is shown in Table 4. The fuel consumption that the vehicle spends through the entire path can be obtained by the vehicle's fuel consumption at the intersection section plus the fuel consumption of the road section, the final result of this example is 488.3ml.

B. A REAL-WORLD EXAMPLE BASED ON ELECTRONIC MAP

The map information of a certain area in Changsha City was selected from OpenStreetMap [29]. The test vehicle model is Hover H6. We install a data acquisition device in the on-board diagnostic system of the experimental vehicle, through which we can collect the working condition data of the vehicle, including longitude and latitude, real-time speed, instantaneous fuel consumption and so on. Before the experiment, the traffic lights in the planned route need to be investigated to obtain the position and phase timing information of the traffic lights, which is provided by the Changsha traffic police detachment. The average speed of the road section is calculated according to the floating car data. The floating car data comes from the‘‘the platform of the Project of China automotive test cycles(CATC)''. Through the CATC platform, we can obtain information such as the latitude, longitude and instantaneous speed of the running vehicle . By matching the latitude and longitude information of the vehicle with the map, the average traveling speed of the road can be calculated. According to the timing information of the traffic light and the average running speed of the road section, the fuel consumption of the communication section of each intersection can be calculated. Then, we can obtain the optimal route through the extended A* algorithm proposed in this paper. After calculating the route by selecting the departure point and destination on the map, the actual vehicle experiment is performed according to the planned route.

At the same time, it is necessary to select the time when the traffic conditions are relatively smooth in order to conduct experiments. In the experiment, the main driver is responsible for driving the vehicle, and the assistant driver is responsible for the broadcast of the phase of the traffic light and the guidance of the driving mode. The experimental comparison route is the shortest path calculated using the traditional A* algorithm (without considering the influence of traffic lights and energy consumption), as shown in Figure 9, path 4. The path calculated by the optimal path algorithm considering the influence of traffic signals and energy consumption proposed in this study is path 3 shown in Figure 8. By comparison,

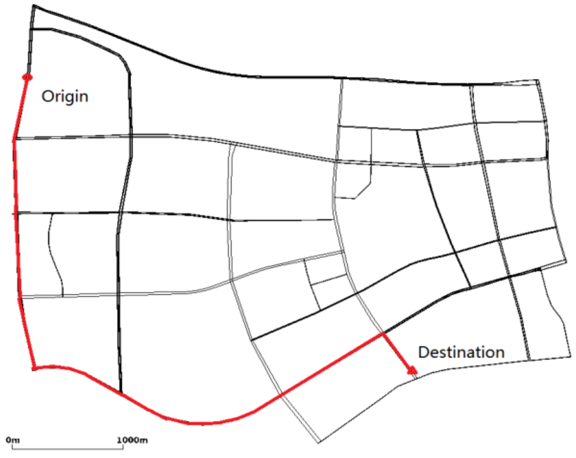

FIGURE 8. Path 3.

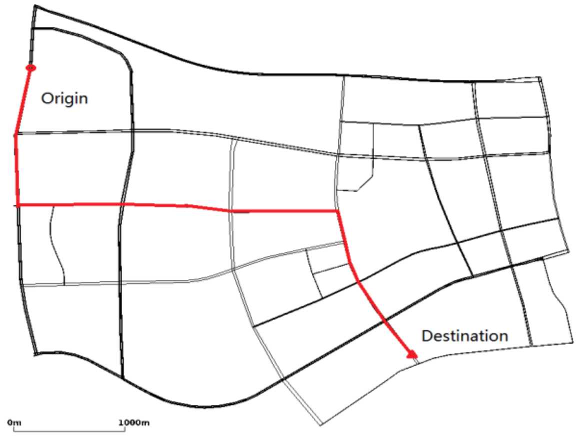

FIGURE 9. Path 4.

it can be seen that the two paths are significantly different. The length of the entire section of path 4 is shorter, but the number of intersections passing through is greater; the length of the entire section of path 3 is longer, but the road level is higher, and the number of intersections is small.

The results of the road test experiment data are now statistically analyzed, as shown in Table 5. Among them, the calculated value of fuel consumption is calculated using the calculation method of this study, and the rest of the data are measured values of the vehicle. The actual travel distance of Path 3 is 6.3 km. This path contains 7 signalized intersections, of which 5 are straight, 1 is left, and 1 is right. The total travel time of this path is 11.4 minutes and the fuel consumption is 632ml. The actual travel distance of Path 4 is 5.7 km. This path includes 10 signalized intersections, of which 8 are straight, 1 is left, and 1 is right. The total travel time of this path is 14.5 minutes and the fuel consumption is 705 ml.

Compared to Route 4, the actual trip distance of Route 3 has increased by 9.5%, but the travel time has reduced by 21.4% and the fuel consumption has reduced by 10.3%. This is because of the large number of signalized intersections along path 4, which leads to a large increase in waiting time for the vehicle at intersections. At the same time, frequent acceleration and deceleration operations at signalized intersections also increase fuel consumption. In Route 3, the number of intersections is small, which not only saves the waiting time at the intersection, but also increases the average traffic speed of the vehicle during the entire driving process.

TABLE 5. The comparison between two routes.

	Route 3	Route 4
Travel distance	6.3*km*	5.7*km*（-9.5%）
Number of signalized intersections	7	10
Travel time	11.4*min*（-21.4%）	14.5*min*
Fuel consumption (calculated)	625ml（-7.1%）	673ml
Fuel consumption (measured value)	632ml（-10.3%）	705ml

IV. CONCLUSIONS

This study proposes an optimal path planning algorithm that considers the effects of traffic lights and fuel consumption. By constructing a traffic light model based on Markov chain, considering that the traffic light in advance will be changed from green light to red light, and when the headway distance is greater than the critical threshold, the vehicle accelerates through the intersection. When the front traffic light is about to change from the green light to the red light, the vehicle decelerates to avoid idling. On this basis, combined with the A* algorithm, an extended A* algorithm based on optimal vehicle energy consumption is proposed. The example verification shows that as compared to the traditional A* algorithm, the proposed algorithm has a better route, shorter time, and less fuel consumption. The algorithm proposed in this study takes into account the influence of signalized intersection on the basis of traditional algorithm. When the vehicle passes through the signalized intersection, it needs to perform acceleration and deceleration operations according to the phase of the traffic light, which will increase fuel consumption. The algorithm can effectively avoid the route with too densely-spaced signalized intersection. By calculating the energy consumption of road sections and the energy consumption at signalized intersections, the effect of route length and density of signalized intersections can be effectively weighed. In addition, the use of energy-saving driving through the signalized intersection can achieve the purpose of saving energy. The algorithm is applicable to a dense network of traffic lights in urban roads, and the denser the traffic lights on the road, the more obvious the superiority of the algorithm. At the same time, the algorithm also has some limitations. There are obvious differences in the arrival traffic flow at the signalized intersections in different time periods. During traffic peak hours, the traffic flow is dense, the distance between the front and the vehicle is small, and the probability that the vehicle accelerates through the intersection is also small.

In the follow-up study, the following four aspects need to be further considered: (1) Consider the coordination of signalized intersections and accordingly control the phase difference at adjacent intersections to further reduce the waiting time at intersections. (2) Consider the distribution of traffic flow in different time periods, further analyze the headway distance under the influence of traffic flow, and improve the accuracy of the algorithm. (3) Taking into account the impact of the maximum speed limit of the road section and vehicle acceleration at the extension of the green light duration at, and the delay of queued vehicle needs to be considered in the case of large traffic flow. (4) Refine the estimated volume-delay function of the signal to improve the accuracy of the prediction results, and further considering the influence of various setting parameters (such as maximum speed limit, minimum speed limit, acceleration, deceleration, etc.) on the results of the algorithm.

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REFERENCES

[1] C. Li, T. Ding, X. Liu, and C. Huang, "An electric vehicle routing optimization model with hybrid plug-in and wireless charging systems," *IEEE Access*, vol. 6, pp. 27569–27578, 2017.

[2] L. Wen, B. Çatay, and R. Eglese, "Finding a minimum cost path between a pair of nodes in a time-varying road network with a congestion charge," *Eur. J. Oper. Res.*, vol. 236, no. 3, pp. 915–923, 2014.

[3] E. Ericsson, H. Larsson, and K. Brundell-Freij, "Optimizing route choice for lowest fuel consumption—Potential effects of a new driver support tool," *Transp. Res. C, Emerg. Technol.*, vol. 14, no. 6, pp. 369–383, 2006.

[4] S.-P. Gao, H.-B. Zhao, L. Zhang, and J.-X. Wang, "Dynamic route guidance model based on signal lamp time assignment," *China J. Highway Transport*, vol. 24, no. 1, pp. 109–114, 2011.

[5] A. Frangioni, L. Galli, and M. G. Scutellà, "Delay-constrained shortest paths: Approximation algorithms and second-order cone models," *J. Optim. Theory Appl.*, vol. 164, no. 3, pp. 1051–1077, 2015.

[6] L. Hu, J. Yang, and J. Huang, "The real-time shortest path algorithm with a consideration of traffic-light," *J. Intell. Fuzzy Syst.*, vol. 31, no. 16, pp. 2403–2410, 2016.

[7] M. Khanjary, K. Faez, M. R. Meybodi, and M. Sabaei, "Shortest paths in synchronized traffic-light networks," in *Proc. IEEE CCECE*, May 2011, pp. 882–886.

[8] B. Yang and E. Miller-hooks, "Adaptive routing considering delays due to signal operations," *Transp. Res. B, Methodol.*, vol. 38, no. 1, pp. 385–413, Jun. 2014.

[9] W.-H. Lee, K.-P. Hwang, and W.-B. Wu, "An intersection-to-intersection travel time estimation and route suggestion approach using vehicular ad-hoc network," *Ad Hoc Netw.*, vol. 43, pp. 71–81, Jun. 2016.

[10] F. Yang, X. Yang, and M. Yun, "Shortest path algorithm with a consideration of waiting time at signalized intersections," *J. Tongji Univ. (Natural Sci.)*, vol. 41, no. 5, pp. 680–686, 2013.

[11] X. Zhou, Z. Yang, W. Zhang, Q. Bing, and Q. Shang, "Optimal route planning algorithm considering movement type at signal intersections," *J. South China Univ. Technol. (Natural Sci. Ed.)*, vol. 44, no. 4, pp. 101–108, 2016.

[12] M. Alsabaan, K. Naik, and T. Khalifa, "Optimization of fuel cost and emissions using V2V communications," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 3, pp. 1449–1461, Sep. 2013.

[13] G. De Nunzio, C. C. de Wit, P. Moulin, and D. Di Domenico, "Eco-driving in urban traffic networks using traffic signal information," in *Proc. IEEE. 52nd IEEE Conf. Decis. Control*, Florence, Italy, Dec. 2013, pp. 892–898.

[14] B. Liu, Q. Sun, and A. El Kamel, "Improving the intersection's Throughput using V2X communication and cooperative adaptive cruise control," *IFAC-PapersOnLine*, vol. 49, no. 5, pp. 359–364, 2016.

[15] S. Mandava, K. Boriboonsomsin, and M. Barth, "Arterial velocity planning based on traffic signal information under light traffic conditions," in *Proc. IEEE 12th Int. Conf. Intell. Transp. Syst.*, St. Louis, MO, USA, Oct. 2009, pp. 160–165.

[16] B. Zhao, G. Guo, L. Wang, and Q. Wang, "Vehicle speed planning and control for fuel consumption optimization with traffic light state," *Acta Automatica Sinica*, vol. 43, no. 3, pp. 1–10, 2017.

[17] Y.-G. Luo, S.-M. Hu, and S.-W. Zhang, "Multi-segment green light optimal speed advisory for hybrid vehicles," *China J. Highway Transport*, vol. 30, no. 10, pp. 119–126, 2017.

[18] B. Xu, X. J. Ban, Y. Bian, J. Wang, and K. Li, "V2I based cooperation between traffic signal and approaching automated vehicles," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Jun. 2017, pp. 1658–1664.

[19] B. Asadi and A. Vahidi, "Predictive cruise control: Utilizing upcoming traffic signal information for improving fuel economy and reducing trip time," *IEEE Trans. Control Syst. Technol.*, vol. 19, no. 3, pp. 707–714, May 2011.

[20] V. A. Butakov and P. Ioannou, "Personalized driver assistance for signalized intersections using V2I communication," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 7, pp. 1910–1919, Jul. 2016.

[21] M. A. S. Kamal, M. Mukai, J. Murata, and T. Kawabe, "Model predictive control of vehicles on urban roads for improved fuel economy," *IEEE Trans. Control Syst. Technol.*, vol. 21, no. 3, pp. 831–841, May 2013.

[22] X. He, H. X. Liu, and X. Liu, "Optimal vehicle speed trajectory on a signalized arterial with consideration of queue," *Transp. Res. C, Emerg. Technol.*, vol. 61, pp. 106–120, Dec. 2015.

[23] Y. He, D. Sun, M. Zhao, and S. Cheng, "Cooperative driving and lane changing modeling for connected vehicles in the vicinity of traffic signals: A cyber-physical perspective," *IEEE Access*, vol. 6, pp. 13891–13897, 2018.

[24] B. Yan, D. Yang, J. Ding, K. Li, and X. Lian, "An adaptive algorithm for route guidance system based on dynamic time-division traffic network model," *Automot. Eng.*, vol. 25, no. 6, pp. 606–609, 2003.

[25] G. Zhengqi, H. Lin, H. Jing, Y. Yi, and H. Fang, "Vehicle navigation map matching based on modified D-S evidence rule," *Automot. Eng.*, vol. 30, no. 2, pp. 141–145, 2008.

[26] A. Mobasheri, "A rule-based spatial reasoning approach for OpenStreetMap data quality enrichment; Case study of routing and navigation," *Sensors*, vol. 17, no. 11, p. 2498, 2017.

[27] Y. Nie and Q. Li, "An eco-routing model considering microscopic vehicle operating conditions," *Transp. Res. B, Methodol.*, vol. 55, pp. 154–170, Sep. 2013.

[28] J. Sun and H. X. Liu, "Stochastic eco-routing in a signalized traffic network," *Transp. Res. Procedia*, vol. 7, pp. 110–128, Oct. 2015.

[29] G. De Nunzio, L. Thibault, and A. Sciarretta, "Bi-objective eco-routing in large urban road networks," in *Proc. IEEE 20th Int. Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2017, pp. 1–7.

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