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Research and optimization of energy management strategies for range-extended electric vehicles

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Abstract: *Aiming at the problem of energy management of range-extended electric vehicles, this paper first analyzes the structural char-acteristics of range-extended electric vehicles, and then comprehensively considers the operating conditions of range-extended electric vehicles, and proposes a multi-parameter energy management control strategy. The effectiveness of the control strategy is verified by simulation. Finally, the control parameters are optimized by the multi-objective genetic optimization algorithm (NSGA-II). The optimization results show that the fuel consumption per 100 kilometers of the vehicle is reduced by 5.2% under the premise of meeting the driving range requirements. NOx emissions remained largely unchanged, but CO-emissions were reduced by 2.5% and HC emissions decreased by 2%. The economy of the whole vehicle has been improved to a certain extent.*

Keywords: *range extended vehicle, energy management system, optimization*

1. Introduction

Pure electric vehicle has a single power source, but it will not pollute the environment during driving. It is the best choice to solve the shortage of oil resources and environmental pollution. Nevertheless， the existing power battery has relatively low specific energy, which is difficult to meet the requirements of users for continuous driving range. Meanwhile, the long charging time of pure electric vehicles and other problems seriously restrict the development of pure electric vehicles[1]. The range-extended electric vehicle has pure electric and range-extended working modes. In the pure electric mode, the electric energy mainly comes from the power battery. At this time, The range-extended electric vehicle has no pollution and zero emission. In the range-extended mode, the electric energy is obtained through the ex-tender, And the fuel efficiency can be improved by controlling the working point of the extender to reduce pollution emissions and extend driving mileage. The range-extended electric vehicle is the best model for the transition from fuel vehicle to pure electric vehicle.

The main feature of the range-extended electric vehicle is the dual power source—power battery and range extender. Therefore, the energy management control strategy is very important for the range extended electric vehicle. For range-extended electric vehicle, reasonable and effective power management and control strategy is the key to achieve energy saving and emission reduction and ensure the efficient work of power components. At present, the energy man-agement strategies of range-extended electric vehicle mainly include thermostat control strategy, power following con-trol strategy and hybrid control strategy[2]. The main difference between the CS-CD strategy and the power following control strategy is whether the output power of the range extender is constant.The energy consumption maintenance control strategy proposed by Banvait[3] has poor fuel economy in long-distance driving, and relatively highfuel econo-my in short-distance driving; The energy management control strategy based on speed and battery state of charge(Soc) proposed by Zha yunfei[4] improves the fuel economy to some extent, However, due to the constant output power of the range extender, there is a problem of energy waste; Niu Jigao[5] proposed the optimal curve energy management strate-gy, which has improved economical efficiency, but is only suitable for small engines; The Blended control strategy is to control the work of the range extender by detecting the running condition of the vehicle, so that it works in the high-efficiency area[6];Moura[7] proposed a real-time online energy management strategy that takes into account both the fuel economy and power performance of the vehicle.

The CS-CD control strategy improves the fuel economy of range-extended electric vehicles to a certain extent, but the reduction in energy demand at the end of the vehicle driving will lead to energy waste and reduced fuel economy. Therefore, this paper improves the CS-CD control strategy, and

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proposes a multi-parameter energy management control strategy based on different vehicle speed stages. The effectiveness of the control strategy is verified by simulation, and Through multi-objective genetic algorithm optimization, on the basis of ensuring the cruising range of range-extended electric vehicles, the fuel economy and pollutant emissions are further optimized, so that the performance of the vehicle is improved.

2. Vehicle structure

The range-extended electric vehicle are divided into three types: series connection, parallel connection and hybrid connection according to the cooperative working mode between different power sources. This paper takes urban public transport as the research object, and the economy, safety and convenience of its power system are the primary consider-ations[8]. Therefore, the series connection range-extended electric vehicle is selected as the research object, as shown in Figure 1. It can be seen from Figure 1 that there is no mechanical connection between the range extender and the drive axle of the series-type range-extended electric vehicle, so the working state of the engine is not affected by external work-ing conditions,and the engine can work in a range with high fuel economy.

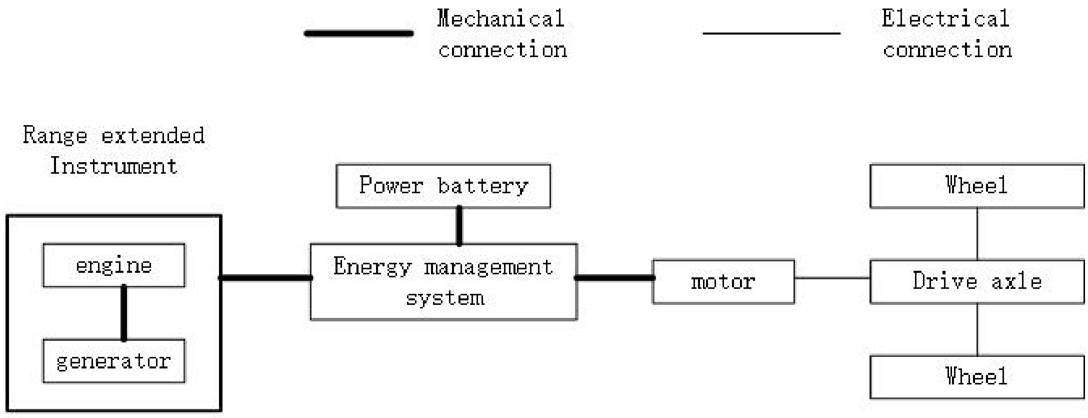

Figure 1: Range extended electric vehicle structure

In this paper, an range-extended electric vehicle is used as the design basis for the energy management control strategy. The vehicle parameters and dynamic performance parameters are shown in Table 1, and the main power sys-tem component parameters are shown in Table 2.Since this paper mainly studies the energy management control strat-egy of the range-extended electric vehicle, in order to shorten the simulation optimization time, the battery capacity of the power battery is limited to 100 Ah, the actual use capacity is 70Ah, and the pure electric driving range is 37km.

Table 1: Parameters of range extended electric bus

Vehicle mass/kg	12300
Loaded vehicle mass/kg	16500
Wheel radius/m	0.478
Wind resistance coefficient CD	0.58
Windward area/m	27.5
Rolling resistance coefficient f	0.016
0-50km/h acceleration time/s	≤20
maximum velocit (km/h)	≥80
Maximum climbing gradient(%)	≥20
Driving range/km	≥70

Table 2: Parameters of dynamic system

Power battery capacity/(A·h)	100
Drive motor peak power/kW	332
Drive motor peak power/kW	6000
Engine peak power/kW	102
Engine peak torque/(N·m)	190
Generator peak power/kW	77
Generator maximum speed/(r/min)	10000
Main reduction ratio	6.2

3. Research on energy management control strategy

The main purpose of the energy management control strategy for range-extended electric vehicle is to ensure that the vehicle can reasonably match the coordination operation ability between the range extender and the power battery while completing the driving task, so as to ensure that the vehicle can make full use of the electric energy absorbed by the battery from the power battery, and at the same time realize the vehicle achieves the best performance in terms of fuel economy, pollutant emissions and overall vehicle dynamics[9].

3.1 Site information

The multi-parameter energy management control strategy, during the whole vehicle driving process, should first meet the power requirements of the vehicle under different working conditions to ensure the handling stability and smoothness of the vehicle. Secondly, the operating point of the range extender is selected according to the vehicle veloci-ty and the battery charge during the driving process. Based on the design principle of pure electric drive as the main and range extender as the supplement, the multi-parameter energy management control strategy is designed as shown in Figure 2:

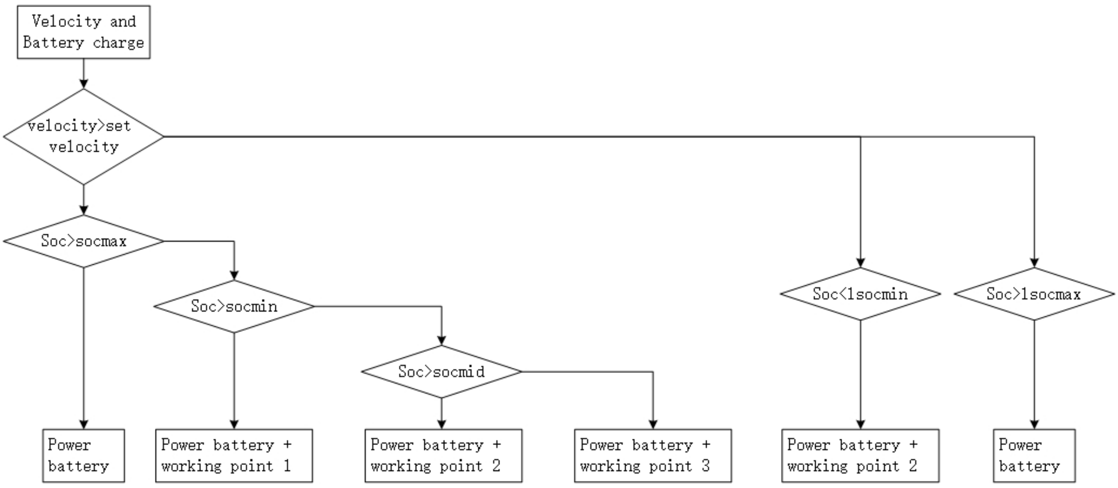

Figure 2: Multi-parameter energy management control strategy

The energy management control strategy is divided into high-speed sections and low-speed sections according to the different vehicle velocity. In the high-speed section, the vehicle travels at a higher speed, which requires higher motor drive power and requires higher instantaneous energy. If the power battery is sufficiently charged at this time, the power will be provided by the power battery, and the power battery can meet the driving requirements at this time. When the charge of the power battery is insufficient, high-power discharge will cause the temperature of the power battery to rise, which will further affect the discharge efficiency. Therefore, in the high-speed section, it is divided into four sections ac-cording to the difference in the charge of the power battery. When Soc>socmax, the power battery provides power. When socmid<Soc<socmax, the range extender works at working point 1. At this time, the range extender

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provides auxiliary power for the power system to prevent the battery life from being affected by excessive discharge power of the power battery; When socmin<Soc<socmid, the range extender works at working point 2, which further increases the power supply ratio of the range extender to the power system and reduces the power supply of the power battery. When the output power is greater than the required power, the power battery can be charged; When Soc<socmin, the range ex-tender works at operating point 3, and the range extender is used as the main power supply device of the power system. When the output power is greater than the required power, the power battery can be charged. In the low-speed area, the work ratio of the range extender should be reduced while the entire vehicle is running, so as to prevent energy waste caused by energy conversion efficiency.Therefore, when Soc<lsocmin, the range extender is turned on and works at operating point 2. The range extender is used as the main power supply device of the power system. When the output power is greater than the required power, the power battery can be charged. The range extender stops working when Soc>lsocmax.

3.2 Range extender operating point selection

Figure 3 is a map of the generator in the range extender, and Figure 4 is a map of the engine in the range extender.

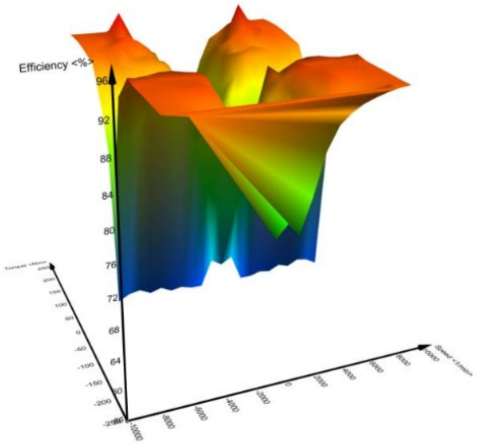

Figure 3: Map of generator

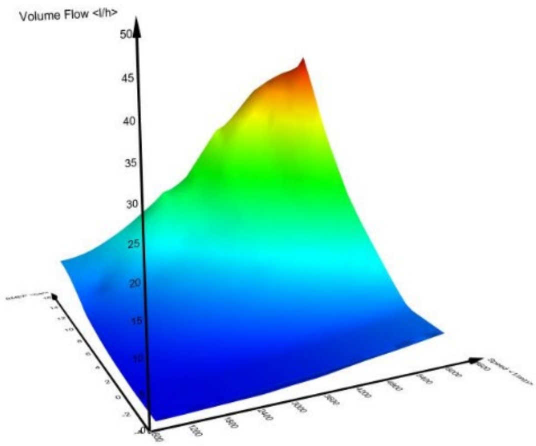

Figure 4: Map of engine

The range extender is the second power source of the whole vehicle, and the selection of the working point has an important influence on the economy of the whole vehicle. There are three range extender operating points in the energy management control strategy designed in this paper. Among them, operating point 1 is mainly used for power supplementation under high-speed operating conditions, and operating point 2 is the main power source of the vehicle under medium and high speed conditions, and it is also the driving power source for driving under low speed conditions. The operating point 3 is the vehicle charging and driving power source under medium and high speed conditions. When only rolling resistance and wind resistance are considered, the required power calculation formula of the whole vehicle is as follows.

$$P_{\varepsilon} = \frac{1}{3600_{\eta T}}(mgfu_a + \frac{C_D A u_a^3}{21.15}) \quad (1)$$

Where P_e is the required power of the vehicle;η_T is the mechanical transmission efficiency; A is the friction coefficient of rolling resistance; u_a is the vehicle velocity.

Bringing in the vehicle parameters, when the vehicle velocity is set to 22km/h, the required power is 14kw, when the vehicle velocity is set to 50km/h, the required power is 38kw, and when the vehicle velocity is set to 80km/h, the required power is 82kw. After consulting the generator data, it can be seen that the power generation at 500r/min is 12kw, the power at 2000r/min is 50kw, and the power at 2500r/min is 60kw. In order to avoid problems such as friction loss and energy conversion efficiency, the first working point is set to 800r/min, the second working point is set to 1500r/min, and the third working point is set to 3000r/min. Taking into account the principle of preferential discharge of the power battery, the key parameters of the initial energy management control strategy are designed as shown in Table 3.

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Table 3: Key parameters of energy management control strategy

set velocity(km/h)	60
work point 1(r/min)	800
work point 2(r/min)	1500
work point 3(r/min)	3000
socmax	60
socmid	50
socmin	40
lsocmax	50
lsocmin	30

4. Simulation analysis

In summary, in order to verify the effectiveness of the energy management control strategy, this paper builds a ve-hicle model based on the AVL-Cruise simulation software, and takes NEDC as the cycle simulation condition. The ini-tial battery charge is set to 90%, and the depth of discharge is 70% to prevent problems such as the reduction of service life caused by over-discharge of power battery.

The energy management control strategy is brought into the vehicle simulation model, and the simulation results of the climing are presented in Figure 5, the 0-50km/h acceleration simulation results are presented in Figure 6, and the driving range simulation results are presented in Figure 7.It can be seen from Figure 5 that the maximum climing of the vehicle is 21%. From Figure 6, it can be seen that the acceleration time from 0 to 50km/h is 19s. From Figure 7, it can be seen that the driving range of the vehicle is 72.196km/h. The simulation results show that The maximum speed of the vehicle is 88km/h, and the fuel consumption per 100 kilometers is 10.47L/100km.

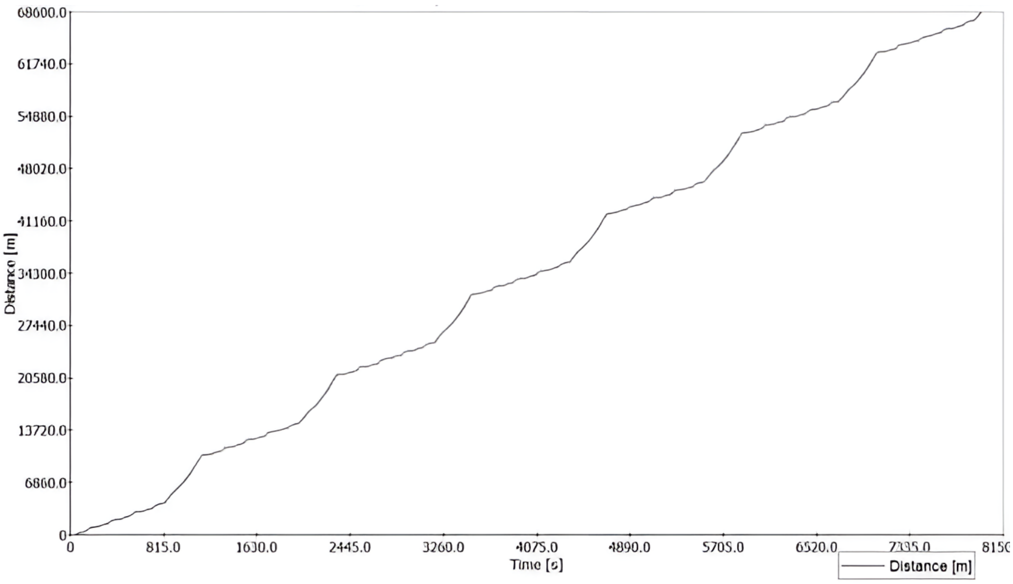

Figure 5: Simulation results of climing

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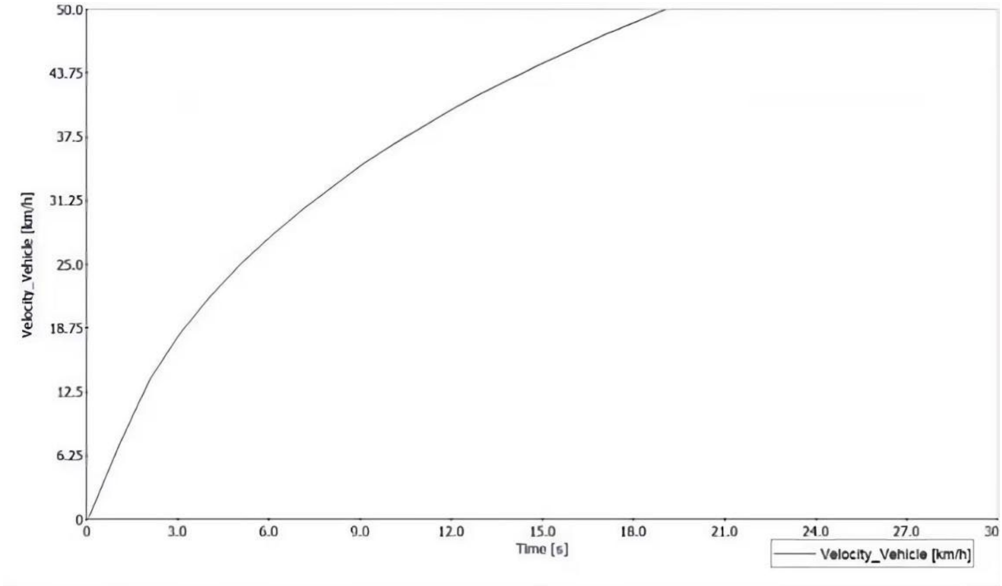

Figure 6: Simulation results of 0-50km/h acceleration

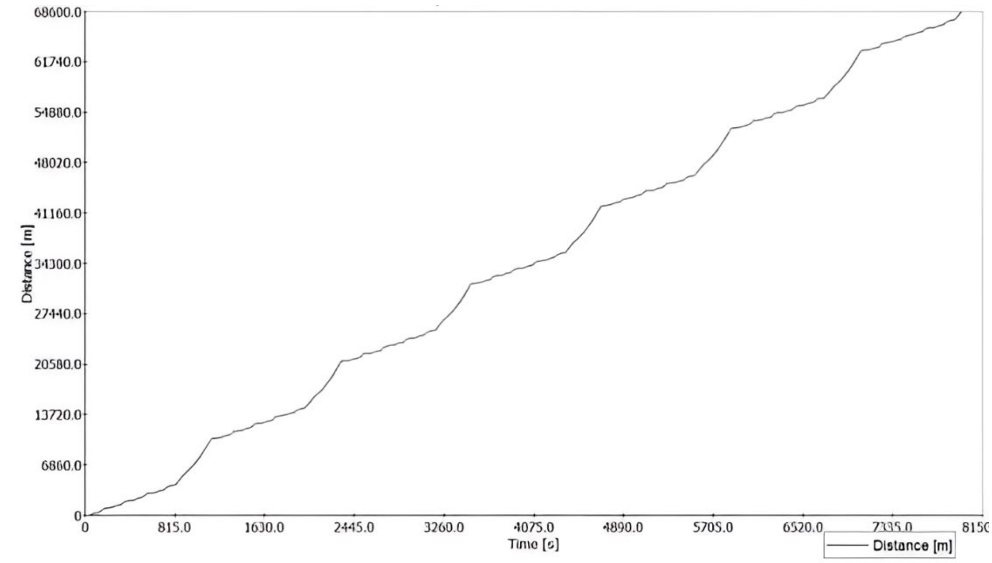

Figure 7: Simulation results of driving range

The simulation results show that the control strategy meets the design requirements of vehicle dynamics and economy.

5. Optimization Analysis

The energy management control strategy designed in this paper basically meets the power and economic requirements of the vehicle. In order to further improve the economy of the vehicle and achieve the goal of energy saving and environmental protection, this paper uses the NSGA-II optimization algorithm to optimize the key parameters in the energy management control strategy.The NSGA-II optimization algorithm has good robustness and can search and solve problems in a global scope. It is one of the most widely used algorithms in the field of multi-objective optimization.

5.1 Optimize settings

The multi-objective optimization is mainly carried out for the fuel consumption and pollutant emission of range-extended electric vehicles. The pollutant emission mainly includes CO, NOX, and HC. The pollutant emission objective function is:

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$$f_1(X) = f_{co}(X) + f_{HC}(X) \tag{2}$$

Where X is the driving range.

The simulation optimization of the range-extended electric vehicle is carried out under the NEDC condition, and the fuel consumption objective function under this condition is:

$$Q_f(\mathrm{X}) = \int_{range} \mathrm{Q}_{fr}\, dt \tag{3}$$

Where range indicates the working time of the range extender; Q_{fr} indicates the fuel consumption per unit time of the range extender.

Since the driving range and energy consumption are in conflict with each other, this paper selects the driving range as a constraint. The multi-objective optimization problem is finally transformed into:

$$\begin{cases} F - \min \;\; F(X) = f_1 + Q_f(X) \\ \quad s.t \quad X > 70km \end{cases} \tag{4}$$

The optimization variables are shown in Table 3.

Table 3: Optimization variables

variables	upper bound	lower bound	initial value
set velocity(km/h)	70	40	60
work point 1(r/min)	1000	0	800
work point 2(r/min)	2000	1000	1500
work point 3(r/min)	3500	2000	3000
socmax	80	60	60
socmid	60	45	50
socmin	45	30	40
lsocmax	60	40	50
lsocmin	40	30	30

5.2 Optimization results and analysis

In this paper, through the co-simulation of Isight and Cruise, the batch method is used to realize the loop iteration. The parameters obtained after optimization are shown in Table 4.

Table 4: Optimization Results

variable	value
set velocity(km/h)	49.79
work point 1(r/min)	806
work point 2(r/min)	1167
work point 3(r/min)	3123
socmax	60.36
socmid	55.96
socmin	39.05
lsocmax	46.04
lsocmin	35.47

It can be seen from the optimized simulation results that the vehicle dynamics are not affected by the energy man-agement control strategy, but the economy has been improved to a certain extent. Figure 8 shows the simulation results of the optimized follow-up mileage. It can be seen from the figure that the driving mileage of the whole vehicle is 72.058km. The fuel consumption per 100 kilometers of the vehicle is 9.93L/100km.

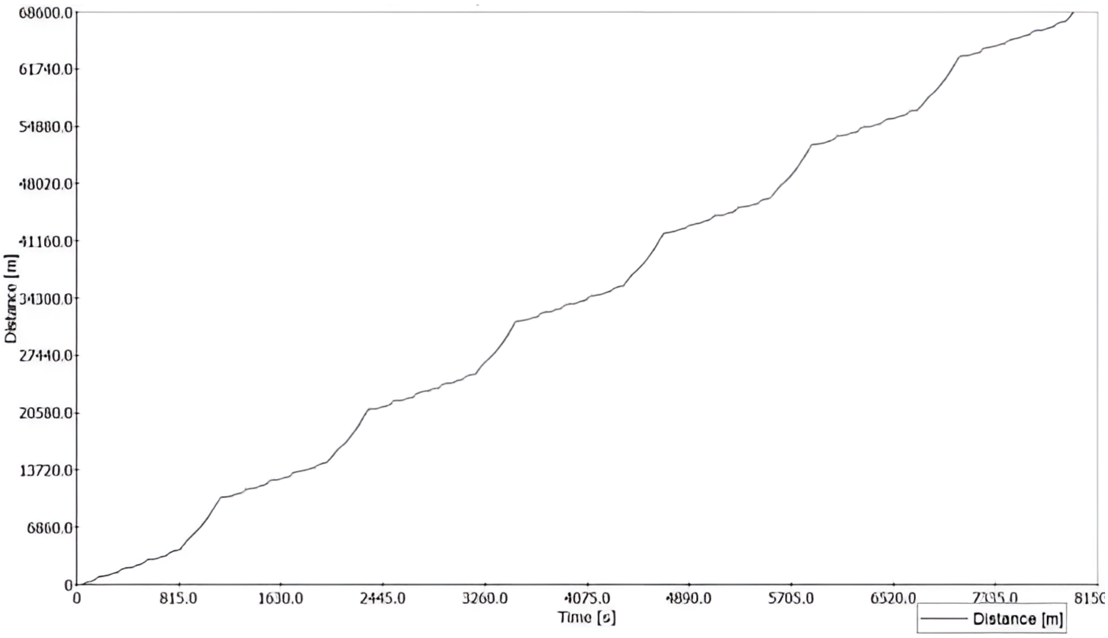

Figure 8: Optimized follow-up mileage

To sum up, the dynamic performance of the range-extended electric vehicle after optimization still meets the design requirements, and the overall vehicle economy has been improved to a certain extent, of which the fuel consumption per 100 kilometers has been reduced by 5.2%. NOX emissions are basically unchanged, but both co and hc emissions have decreased by about 2%. That is to say, the energy management control strategy of range-extended electric vehicle de-signed in this paper can further improve the economy of the whole vehicle and reduce the pollutant emission.

6. Conclusions

Aiming at the energy control problem of range-extended electric vehicles, this paper proposes a multi-parameter energy management control strategy by considering the driving characteristics of range-extended electric vehicles with the goal of meeting the requirement of driving range. The simulation results under NEDC cycle conditions show that the control strategy is effective. In this paper, the key parameters of the control strategy are optimized by the NSGA-II opti-mization algorithm. The optimization results show that the fuel consumption per 100 kilometers and the pollutant emissions are further reduced. This paper is of great significance for the study of range-extended electric vehicles.

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