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Transportation Research Procedia 70 (2023) 433–441

Transportation Research Procedia

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8th International Electric Vehicle Conference (EVC 2023)

Research on Energy Management Optimization of Range-Extended Electric Logistics Vehicle

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Abstract

To ensure a reasonable energy distribution of multiple energy sources of extended-range electric vehicles in different driving scenarios, this paper proposes an adaptive energy management strategy optimization based on different road slope information and conducts in-depth real-time applications. Aiming at the problem of searching for the best working curve of APU, the method of cubic polynomial is used to obtain the efficiency curve of the range extender under the same speed and torque distribution from the experimental efficiency curves of the engine and generator, and then the golden section method is used to calculate the best working curve of APU and Search for the best working point. Taking the equivalent fuel consumption as the fuel economy index, the improved genetic algorithm is used to optimize the parameters of the energy management strategy under different working conditions and different road gradient information. Under the C - WTVC and CHTC - HT cycle conditions, the fuel economy simulation of logistics vehicles with different road gradient information is carried out. The simulation results show that: under different conditions and different road gradient information, the automatic adaptive energy management strategy can effectively improve the fuel economy performance, control the SOC fluctuation of the power battery well, and improve the battery life.

Keywords: extended-range electric logistics vehicle; parameter matching; improved genetic algorithm; adaptive energy management strategy

1. Introduction

1.1. Review of Energy Management Strategies

The range-extending electric vehicle adds a set of range-extending system on the pure electric basis (Jiang and

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2352-1465
10.1016/j.trpro.2023.11.049

Guo, 2020). This structure enables the vehicle to have two working modes under different working conditions pure electric mode and range-extending mode. The two modes are reasonable. The switching of energy distribution can control the fuel saving rate at 20 %-30%.

Extended -range electric vehicles are becoming the development trend of new vehicles, and energy management has become one of the core issues of electric vehicles (Miller et.al, 2011). The energy management strategy of the extended-range electric vehicle is that the driver obtains the required torque or power of the vehicle by stepping on the accelerator pedal and brake pedal of the hybrid vehicle, so as to ensure the power, ride comfort, and economical performance of the vehicle. The premise is to reasonably allocate the obtained required power to the power battery and the range extender (Rahman et.al, 2014). It can be seen that the key task of the energy management strategy is to coordinate the energy flow distribution between the APU and the power battery (Liu et.al, 2020). In addition, the state of charge of the power battery should be kept within a reasonable range. On this basis, the fuel economy of electric vehicles is the main goal of energy management (Redelbach et.al, 2014).

With the rapid development of intelligent transportation systems and smart cars, V2V (information interaction between vehicles and people) and V2I (information interaction between vehicles and infrastructure) technologies enable a large amount of information interaction between vehicles, roads, and drivers. Therefore, energy management strategies are mainly divided into two categories: classical energy management strategies without the application of intelligent transportation systems and energy management strategies based on intelligent transportation (Salmasi, 2007; Wirasingha and Emadi, 2011; Chen et.al, 2014; Yang et.al, 2020).

The statistics of the classic energy management strategy types, advantages and disadvantages and application scope of extended-range electric vehicles are shown in Table 1. The energy management strategy of general rules has the advantages of easy implementation and high computational efficiency, so it has become the most direct and widely used strategy. These rules are pre-defined to ensure that the vehicle works with maximum efficiency without any prior information about working conditions etc. Optimization-based control strategies seek the best allocation among multiple energy or power sources in order to minimize the control target (usually fuel consumption). Global optimization is a non-causal approach, since it needs to predict the future driving cycle category or vehicle speed in advance to find the lowest fuel consumption, this approach is also computationally demanding, and the standard on-board processors in actual vehicles cannot provide the required computational power (Luo et.al, 2018; Zhao et.al, 2009; Peng et.al, 2017). Therefore, it is difficult to implement on the controller, but it can be used to guide the design rules for energy management strategies. The main theoretical basis of real-time optimization is to use the fuel-electricity conversion factor to convert power consumption into fuel consumption for instantaneous optimal solution (Zhang et.al, 2014).

Table 1. Energy Management Strategy Analysis of Hybrid Electric Vehicles

Type	Advantage	Shortcoming	Application range
General Rules Policy	The method is simple, the calculation speed is fast, and it is easy to realize in engineering	Requires calibration and parameter optimization, non-portable, cannot guarantee optimality	Various hybrid vehicles

1.2. Main content of this research

The difficulties and deficiencies in the current research on extended-range electric vehicles and energy management strategies, this paper takes a certain extended-range electric logistics vehicle as the research object, and conducts research on the model building of the power system of the research object, the optimization of adaptive energy management strategies, and real-time applications. in- depth research. The main research contents are as follows:

1) Based on the experimental data and vehicle dynamics theory, build the power system model of the extended-range electric logistics vehicle including the range extender (APU), drive motor and power battery, and compare the simulated fuel consumption of the logistics vehicle with the experimental fuel consumption, simulated SOC and experimental data. SOC is compared to verify the correctness of the model.

2) Propose and optimize an adaptive thermostat- type energy management strategy and an adaptive power-following energy management strategy based on road slope information for extended-range electric logistics vehicles.

Aiming at the problem of APU working curve search, using the cubic polynomial method to obtain the efficiency curve of the range extender under the same speed and torque distribution from the experimental efficiency curve of the engine and generator, and then using the golden section method to obtain the optimal working curve of the APU and the optimal Work point search. Optimize the parameters of the energy management strategy under different working conditions and different road slope information, and use the equivalent fuel consumption as the fuel economy index, and apply the improved genetic algorithm proposed in this paper from the aspects of encoding method, initialization method, crossover, and mutation process to optimize. The fuel economy simulation of the range-extending electric logistics vehicle under different road gradient information is carried out under two cycle conditions of CHTC - HT and C-WTVC.

2. Research on optimization of adaptive energy management strategy for extended-range electric logistics vehicle

Based on the experimental data and vehicle dynamics theory, the power system model of the extended-range electric logistics vehicle including the range extender (APU), drive motor and power battery is built, and the structure and working mode of the extended-range electric logistics vehicle are analyzed. The description lays the foundation for the design and optimization of energy management strategies. Therefore, this chapter mainly studies the design and optimization of the adaptive energy management strategy of the extended-range electric logistics vehicle.

commonly used energy management strategies that can be applied online on extended -range electric vehicles are thermostat -type energy management strategies and power-following -type energy management strategies. Therefore, this section first designs and optimizes the adaptive thermostat- type energy management strategies.

2.1. Design of Adaptive Thermostat Energy Management Strategy Based on Road Slope Information

The thermostat -type energy management strategy can be applied online in real time, so that the engine can always work at the optimal operating point. Therefore, when the power generated by the engine exceeds the required power of the logistics vehicle, the excess energy can be stored in the power battery. At high speeds, the range extender and power battery need to jointly provide energy to drive the vehicle.

Due to the nonlinearity and randomness of driving conditions, the off-line calibrated thermostat-type energy management strategy parameters cannot make the vehicle performance optimal in actual working conditions, so the typical working conditions of Chinese heavy-duty trucks (CHTC - HT) are selected first Preliminary simulation is carried out with the C-WTVC working condition in the presence of uphill and downhill road sections.

Under the CHTC-HT working condition, the time -varying curves of vehicle speed and altitude with different road gradient information are shown in Fig. 1. Under the C-WTVC working condition, the time -varying curves of vehicle speed and altitude with different road gradient information are shown in Fig. 2.

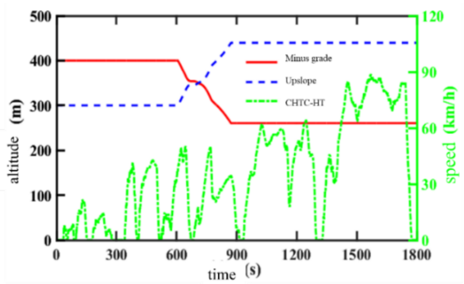

Fig. 1. Under the CHTC-HT working condition, the vehicle speed and altitude change curves with time under different road slope information

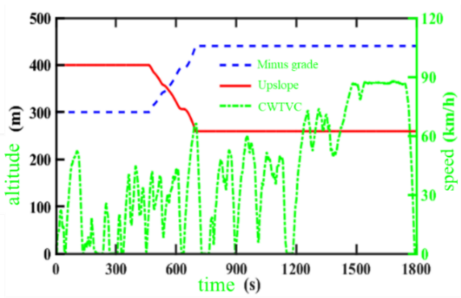

Fig. 2. C -WTVC working conditions, the vehicle speed and altitude change curves with time when different road slope information

There are two energy sources in the extended-range electric logistics vehicle, when evaluating its economy, there will be a contradiction between electricity consumption and fuel consumption. Therefore, the equivalent fuel consumption is selected as the evaluation index of economy in this paper. The calculation method of equivalent fuel consumption is as follows:

$$FC = \int_0^t \dot{m}_f d(t) + \int_0^t \mu \frac{P_{bat}}{Q_{lhv}} d(t) \tag{2.1}$$

The formula, FC is expressed as the fuel consumption (g) in the time period [0,t] ; $\dot{m}_f$ is the fuel consumption rate of the engine (g/s); μ is the oil-electricity conversion factor , according to the literature, the value is 2.8; P_{bat} is the instantaneous power of the driving motor (kW); Q_{lhv} is the low calorific value of the engine (g/J).

The simulation analysis of equivalent fuel consumption, termination SOC and APU opening time under two working conditions and three different road information is carried out, and the simulation results are shown in Table 2. According to Table 2, we can see that:

（1）The termination SOC and equivalent fuel consumption are different under the same working condition and different road information;

（2）of uphill is higher than that of the other two road conditions, but the termination SOC is lower.

The specific reasons for the different termination SOC and equivalent fuel consumption under the same working condition and different road information are as follows:

（1）The APU starts and stops more often on uphill slopes, resulting in higher instantaneous fuel consumption;

（2）Fixed control parameters limit the optimal distribution of energy.

Through the above analysis, it can be seen that logistics vehicles will show different fuel economy under different road slope information. Therefore, this paper proposes an adaptive thermostat- type energy management strategy that uses the global positioning system (GPS) and geographic information system (GIS) to obtain road slope information in the future and whose control parameters change with the change of road slope information.

Table 2. Simulation analysis of three different road information under CHTC - HT and C-WTVC working conditions

Parameter	Condition	Flat slope	Uphill	Downhill
Equivalent fuel consumption	CHTC-HT	12.08	16.13	9.37
	C-WTVC	12.84	16.34	10.36
Terminate SOC	CHTC-HT	0.42	0.41	0.44
	C-WTVC	0.40	0.39	0.38
APU start time	CHTC-HT	364	632	229
	C-WTVC	544	800	324

When the extended-range electric logistics vehicle is started, its driving destination needs to be set. The driving route of the logistics vehicle can be identified through the on-board navigation system. The upper and lower limits of the SOC of the power battery of the logistics vehicle can be determined according to the road gradient information in the driving route. fixed value. By comparing the SOC threshold of the on-board power battery with its real- time value , the driving mode of the logistics vehicle is determined : when the SOC of the on-board power battery is smaller than the minimum threshold , the logistics vehicle will automatically switch to the range-extending mode, and the power of the range extender is range-extending Optimum working power Popt of the inverter system ; when the SOC is higher than the highest threshold, the logistics vehicle switches to the pure electric mode, and the output power of the power battery at this time is the power $P_{R\ required}$ by the driving motor for the power battery ; when the SOC is between the maximum When between the high and minimum thresholds , the driving mode of the logistics vehicle remains consistent with the previous moment. When the driving route of the logistics vehicle changes, the road slope information and the threshold value of the SOC of the on-board power battery will also change accordingly, and the driving mode of the extended-range electric logistics vehicle is determined again through the SOC of the on -board power battery.

2.2. Optimization variables

The main control parameters in the adaptive thermostat-type energy management strategy selected in this paper are optimization variables, as shown below.

$$X = [x_1, x_2, x_3, x_4, x_5, x_6]^T = [SOC_{up\_L}, SOC_{up\_H},\ SOC_{f\_L},\ SOC_{f\_H},\ SOC_{d\_L}, SOC_{d\_H}]^T \tag{2.2}$$

In the formula, SOC_{up_L}, SOC_{up_H}, SOC_{f_L}, SOC_{f_H}, SOC_{d_L} and SOC_{d_H} are the minimum and maximum SOC thresholds of the uphill mode, flat slope mode and downhill mode , respectively .

2.3. Objective function

The optimization goal of this strategy design is: in the power consumption stage, on the premise of ensuring the vehicle's dynamic performance, improve the fuel economy of the vehicle as much as possible and increase the driving range. Therefore, this paper converts electricity consumption into fuel consumption through a conversion factor, and the sum of it and engine fuel consumption is called equivalent fuel consumption. The equivalent fuel consumption is used as the evaluation index of fuel economy and as the objective function. The equivalent fuel consumption is calculated as follows:

$$f(x) = \int_0^t \dot{m}_f d(t) + \int_0^t \mu \frac{P_{bat}}{Q_{lhv}} d(t) \tag{2.3}$$

The formula, $f(x)$ it is expressed as fuel consumption (g) in the time period [0 , t] ; $\dot{m}_f$ is the fuel consumption rate of the engine in g/s; μ is the oil-to-electricity conversion factor ; P_{bat} is the instantaneous power of the drive motor (kW); Q_{lhv} is the low calorific value of the engine (g/J) .

2.4. Constraints

The constraints are as follows:

$$
\begin{cases}
T_{fc\_\min} < T_{fc} < T_{fc\_\max} \\
\omega_{fc\_\min} < \omega_{fc} < \omega_{fc\_\max} \\
0 < T_{mc} < T_{mc\_\max} \\
0 < \omega_{mc} < \omega_{mc\_\max} \\
SOC_{final} \geq SOC_{\min} \\
P_{bat} \leq P_{\max}
\end{cases}
\tag{2.4}
$$

In the formula, T_{fc_min} is the minimum torque of the engine (Nm); T_{fc} , T_{mc} are the torque of the engine and the driving motor (Nm); T_{mc_max} , T_{fc_max} are the maximum torque of the driving motor and the engine, respectively Torque (Nm); $\omega_{fc\_\min}$ is the minimum engine speed (rad/s); ω_{fc}, ω_{mc} is the engine and drive motor speed (rad/s); $\omega_{fc\_\max}$, $\omega_{mc\_\max}$ is the engine maximum speed and the drive motor maximum speed (rad/s); SOC_{final} and SOC_{min} are the termination SOC and minimum SOC respectively; P_{bat} and P_{max} are the actual power (kW) and maximum power (kW) of the power battery respectively .

2.5. Analysis of optimization results

Of the thermostat-type energy management strategy into the energy management strategy together with the corresponding working conditions, identify the road slope information through GPS and GIS, and then change the SOC threshold and turn on or off the range extender in advance to form an adaptive constant temperature Device - based energy management strategies. In this paper, the improved genetic algorithm is used to optimize the parameters of the adaptive thermostat energy management strategy under different working conditions and different road slope information, so that the vehicle can make full use of the power battery to drive and improve the fuel economy during the operation of the vehicle. In order to verify the rationality of the optimized adaptive thermostat-type energy management strategy, simulation analysis is required in the MATLAB/Simulink environment. During the simulation, the initial value of the SOC is set to 0.7, and the fourth-order-fifth-order Runge-Kutta algorithm is used to solve the problem.

Under the CHTC-HT and C-WTVC working conditions and different road slope information, the economic performance simulation of the extended- range electric logistics vehicle using the optimized adaptive thermostat-type energy management strategy is carried out. The simulation results are shown in Fig. 3. The broken lines in the figure respectively represent the equivalent fuel consumption reduction rate after the optimization of the adaptive thermostat energy management strategy under the CHTC-HT working condition and the C-WTVC working condition compared with that before the optimization of the energy management strategy.

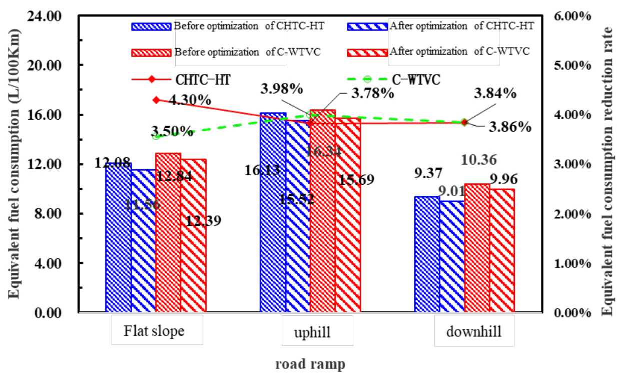

Fig. 3. The equivalent Fuel consumption before and after optimization under different working conditions and different road slope information

The Fig. 3:

（1）The equivalent fuel consumption of the uphill section is the highest, followed by the flat slope, and the lowest is the downhill section.

（2）Under the CHTC-HT working condition, the equivalent fuel consumption of the flat slope section is reduced by 4.30 %, the equivalent fuel consumption of the uphill section is reduced by 3.78 %, and the equivalent fuel consumption of the downhill section is reduced by 3.84% through the improved genetic algorithm.

（3）Under the C-WTVC working condition, the equivalent fuel consumption of the flat slope section is reduced by 3.50%, the equivalent fuel consumption of the uphill section is reduced by 3.98 %, and the equivalent fuel consumption of the downhill section is reduced by 3.86 %.

（4）Under the CHTC-HT condition , the equivalent fuel consumption reduction rate after the optimization of the adaptive thermostat energy management strategy is the largest when the energy management strategy is optimized, and the smallest when the uphill; under the C-WTVC operating condition , the equivalent fuel consumption reduction rate after the optimization of the adaptive thermostat-type energy management strategy compared with that before the optimization of the energy management strategy is the largest when going uphill, and the smallest when it is flat.

To sum up: Under any working condition and different road slope information, the optimized adaptive thermostat energy management strategy can improve the fuel economy of logistics vehicles.

Under the CHTC - HT working conditions and different road gradient information, the range - extending electric logistics vehicle before and after the optimization of the adaptive thermostat-type energy management strategy was simulated, and its SOC simulation curve is shown in Fig. 4. It can be seen from Fig. 4 that:

(1) Under the CHTC - HT working condition, after optimization, the S OC fluctuation curves under the three kinds of road gradient information are all reduced, which can improve the battery life;

(2) Under the CHTC - HT working condition, the SOC fluctuates greatly when going uphill, indicating that when the logistics vehicle is driving on a road with more uphill, the battery life will be reduced.

Under the C-WTVC working condition and different road slope information, the range - extending electric logistics vehicle before and after the optimization of the adaptive thermostat energy management strategy is simulated, and the SOC simulation curve is shown in Fig. 5.

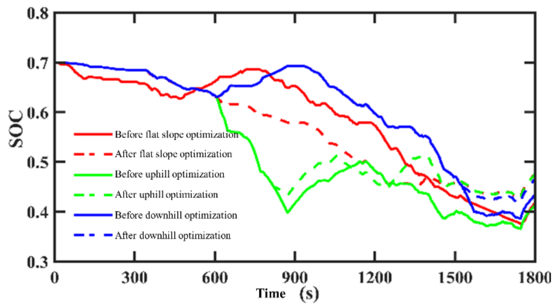

Fig. 4. SOC before and after optimization under different road slope information under CHTC-HT working condition

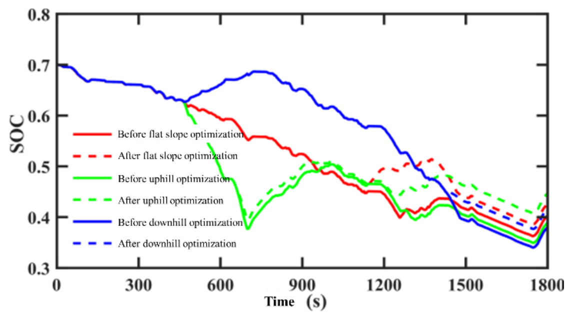

Fig. 5. SOC before and after optimization under different road slope information of C-WTVC working condition

It can be seen from Fig. 5 that:

（1）Under the C-WTVC working condition, after optimization, the S OC fluctuation curves under the three kinds of road gradient information are all reduced, which can improve the life of the power battery;

（2）Under the C-WTVC working condition, the SOC fluctuates greatly when going uphill, indicating that when the logistics vehicle is driving on a road with more uphill , the battery life will be reduced.

optimized simulation results are shown in Table 3.

Table 3. Simulation results after optimization

Parameter	Condition	Flat slope	Uphill	Downhill
Terminate SOC	CHTC-HT	0.48	0.48	0.47
	C-WTVC	0.43	0.45	0.42
APU start time	CHTC-HT	454	723	274
	C-WTVC	579	882	376

Comparing the optimized simulation results (Table 2.2) with the simulation results of two working conditions and three different road slope information (Table 2.1), it can be known that under different working conditions and different road slope information, the optimized power battery terminates The SOC has been improved, and the APU turn-on time has been increased.

3. Conclusion

Based on the experimental data and the theory of vehicle dynamics, this paper builds a mathematical model of the power system of the extended-range electric logistics vehicle including the range extender (APU), the drive motor and the power battery. Build the Simulink model according to the modeling formula of each module, and connect the input and output of each module to get the Simulink model of the whole vehicle. 2) The structure and working mode of the extended-range electric logistics vehicle are described and analyzed, which lays the foundation for the formulation of energy management strategies. According to the performance indicators and parameters of the vehicle, the parameters matching and selection of the drive motor, power battery and range extender are carried out.

An adaptive thermostat-type energy management strategy and a power-following energy management strategy based on road slope information are proposed ; the genetic algorithm proposed in this paper is improved from the aspects of encoding method, initialization method, crossover and mutation process, and the equivalent fuel consumption is used as The fuel economy index optimizes the parameters of the energy management strategy under different working conditions and different road gradient information . The fuel economy simulation of the adaptive energy management strategy with different road gradient information is carried out under two cycle conditions of C-WTVC and CHTC - HT. The simulation results show that: under different conditions and different road gradient information, by improving the adaptive energy management strategy optimized by the algorithm can effectively improve the fuel economy performance, and can better control the SOC fluctuation of the battery pack and improve the battery life.

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