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RESEARCH ON FUEL CONSUMPTION REDUCTION STRATEGY OF 48V MILD HYBRID ELECTRIC VEHICLE

Zheng Zhichao[1], Nan Jinrui[1,2*], Zou Huihui[1], Liu Bolan[1]

1 School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China

2 Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing Institute of Technology, Beijing 100081, China

ABSTRACT

The introduction of the fourth-stage fuel limit standard and the national VI emission standard has accelerated the development of more energy-efficient and environmentally friendly new energy vehicles by Chinese automakers. Currently, the 48V mild-hybrid system is one of the most effective technical solutions for the easy technology development, low cost, short development cycle, energy saving and emission reduction.

In this paper, the 48V mild-hybrid vehicle is taken as the research object. Through the comparative analysis, the architecture of the 48V mild-hybrid system, the type of the battery and motor are determined. The external characteristics of motor are obtained by bench experiment and the battery model parameters are obtained by offline identification. Aiming at the research focus of the thesis, a single-target optimization strategy based on threshold is proposed, including engine start-stop, power assisting, brake regeneration and SOC balance and the strategy model is built in Simulink. The 48V mild-hybrid vehicle model and the original vehicle model are built in the Cruise software. The co-simulation of the vehicle model and strategy model is achieved by calling the strategy model's DLL file.

The results show that compared with the original vehicle, the ratio of fuel economy improvement of the 48V mild-hybrid vehicle is more than 10%, the acceleration performance is increased by 9.7%, the climbing performance is improved by 23%, and the emission performance improvement effect is remarkable. Also, the proposed control strategy is better in reducing vehicle fuel consumption and maintaining battery SOC balance compared with the control strategy based on logic threshold.

Keywords: 48V mild-hybrid vehicle, control strategy, energy saving and emission reduction, dynamic performance, Cruise

1. INTRODUCTION

"Energy saving and emission reduction" is the theme of today's society. According to incomplete statistics, the annual fuel consumption of automobiles in the world accounts for about 20% of the world's annual oil consumption, and exhaust emission accounts for 30% to 60% of the world's atmospheric pollution[1]. The US Department of Energy predicted that there would be a gap in the supply and demand of petroleum energy around the world in 2020[2]. The best solution for achieving targets of energy saving and emission reduction is to vigorously develop pure electric vehicles. However, pure electric vehicles are still unable to meet the needs of users and the market in terms of driving range, charging time, cost, etc[3]. More and more researchers are turning to hybrid vehicles and hydrogen fuel vehicles. In comparison, hybrid vehicles do not have the mileage anxiety and charging difficulties of pure electric vehicles and there is no high cost of hydrogen fuel vehicles. At the same time, it can effectively reduce the fuel consumption of automobiles and improve exhaust emission[4]. Hybrid vehicles are divided into several types according to the peak power ratio of motor and engine. The relatively high cost performance, low technical cost and effectiveness make mild hybrid technology and weak hybrid technology gradually favored by OEMs and component suppliers. The 48V system is the focus of research and development in mild hybrid technology[5].

The 48V system can achieve two-thirds of the fuel-saving effect at one-third of the technical cost of the strong hybrid system and the research is relatively cost-effective[6]. In the market environment where fuel vehicles are the main, it has important research value. This paper studies the 48V mild hybrid vehicle and hopes to lay the foundation for the further study of the 48V system of vehicle.

In section 2, the structure of 48V system, the selection and performance experiments of motor, and the type selection and parameter identification of battery model are provided. In section 3, a single-target optimization strategy based on threshold, which is to reduce fuel consumption is proposed. Section 4 provides simulation results and analysis. Finally, a short conclusion is given in section 5.

2. SYSTEM CONFIGURATION

2.1 *48V System Structure*

The EU is promoter and practitioner of the automotive 48V system and has even proposed the requirement to popularize the 48V start-stop system by 2020[7][8]. Hybrid vehicles are usually divided into five configurations according to the position of the motor in the drive train: P0, P1, P2, P3 and P4. The three structures P0, P1 and P2 are suitable for 48V system. By comparing and analyzing in terms of cost, technical difficulty and fuel economy, the most suitable P0 scheme is chosen as the system structure of this research.

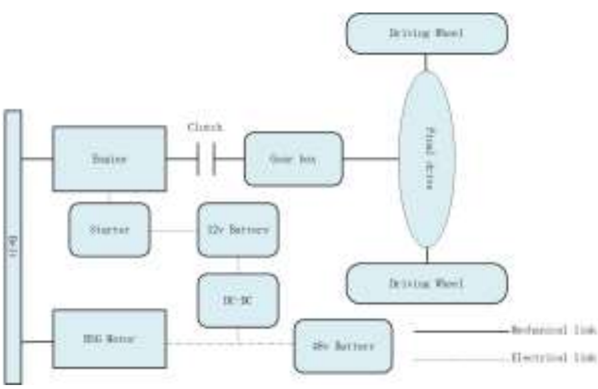

Fig 1. 48V system structure

In the figure, the BSG replaces the position of the original generator, and the original 12V starter is still retained. The purpose is to start the engine with a 12V starter under cold temperature. The BSG motor can charge the 12v battery through the DCDC module. If the bidirectional DCDC module is used, the battery can also supply power to the 48V battery and start BSG motor.

2.2 *Key component selection and parameter identification*

The motor is an important component in the 48V mild hybrid system. The motor must start the engine quickly when the engine is stopped, provide power assistance for the engine and recover braking energy when necessary. By comparing and analyzing several kinds of motor commonly used in automobiles, it is known that AC asynchronous motor (ASM) has stronger overload capability, wider speed range and lower cost, and is suitable as a start-stop motor for 48V mild hybrid system.

The 48V battery pack in the 48V mild hybrid system powers the motor and is used to store some of the energy when necessary. After comparing and analyzing performance of several common batteries, ternary lithium battery is selected.

This research is to improve a certain fuel vehicle, equipping it with a 48V mild hybrid system. According to the vehicle and engine parameters of the prototype, the vehicle's dynamic performance index is calculated. Providing that, after equipping the vehicle with 48V system, the maximum speed is increased by 5% and the maximum grade is increased by 12%, final motor parameters are achieved.

For the selected motor, the motor parameter calibration experiment is performed on the bench. The efficiency MAP diagram and external characteristics of the motor can be obtained.

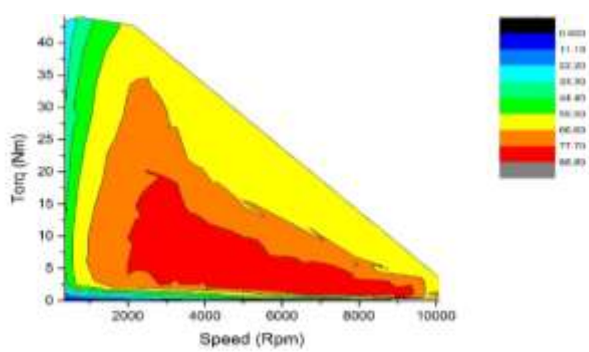

Fig 2. Efficiency MAP diagram of the motor

For the battery of the 48V mild hybrid system, the voltage has been determined. The battery pack is in the form of series and the remaining basic parameters are mainly the battery capacity and discharge capability. Battery capacity directly affects system cost, while discharge capability directly determines the system's output power. According to the design that vehicle equipped with 48V system can climb at the maximum ramp whose gradient is increased by 12% at speed of 19km/h, reaching 300m, the battery capacity is calculated to be 9.6Ah and the maximum discharge current is 208A. The 48V battery pack requires 14 batteries in series.

For 48V battery pack modeling, thevenin model is used for lithium-ion battery's low self-discharge rate. The model parameters of the 1-RC circuit are obtained by HPPC experiments and the temperature is kept at a constant temperature of 25 degrees.

3. A SINGLE-TARGET OPTIMIZATION STRATEGY BASED ON THRESHOLD

3.1 The target of control strategy

Since the 48V mild hybrid vehicle belongs to non-plug-in hybrid type, to save fuel consumption, the engine must work at high efficiency region and reduce idle time, and motor should recover braking energy. The core of hybrid vehicle's control strategy is to coordinate the working state of the engine-motor-battery group in order to achieve the best energy utilizing efficiency.

The fuel consumption of 100 kilometers is selected as the optimization objective, it is made up of three parts as shown below.

$$Q = Q_{idle} + Q_{run} - Q_{braking\_recovery}$$

Where Q, Q_{idle}, Q_{run} and $Q_{braking\_recovery}$ denote the fuel consumption of 100 kilometers, the fuel consumption of engine running at idle state, the fuel consumption of engine running at normal state and recovered energy during braking. This equation provides the optimized directions of fuel consumption.

According to the instant speed and torque of engine, the fuel consumption can be calculated by internal function provided in Cruise software.

There are varieties of strategies being researched. The logic threshold control strategy is simple and practical and has been widely used in mass-produced hybrid vehicles. In comparison, the optimal control strategy can optimize the engine operating point and the control effect is good, but the calculation is large and the practicality is not as good as the logic threshold strategy. The multi-objective optimization strategy uses multiple targets as the optimization control object and often can obtain the comprehensively optimal control effect, but the practicality is not strong and the calculation amount is large. This paper proposes a single-target optimization of fuel consumption strategy based on threshold.

3.2 Single-target optimization strategy based on threshold

Based on principles of reducing fuel consumption, meeting power demand, optimizing engine working curve and reducing idle time, the strategy is divided into four parts, which are engine start-stop control strategy (Start-Stop), power assisting control strategy (eBoot), braking energy recovery control strategy (Brake-Regeneration) and SOC balance control strategy (SOC-balance). These four strategies use threshold values of relevant parameters as working mode switching points.

For engine start-stop control strategy, the engine stop is enabled when the relevant conditions of the vehicle safety, start-stop system-related accessory status, engine demand and other driving demand are met. Engine start conditions include two categories: driver triggered start and non-driver triggered start.

For power assisting control strategy, the motor can provide additional power for the vehicle or absorb extra power of engine when necessary, thereby adjusting the load rate of the engine, reducing the fuel consumption and effectively improving the dynamic performance.

The power assisting mode is mainly triggered by the driver. When the accelerator pedal stroke is greater than 0, the start/stop main switch is turned on and there is no other system fault, the 48V system works in the power assisting mode, that is, the eBoot is enabled. On the equal fuel consumption rate map, drawing equal power curves at regular values, a series of points where two groups of curves are tangent can be obtained and the optimal economic for the engine is available by fitting these points[9][10].

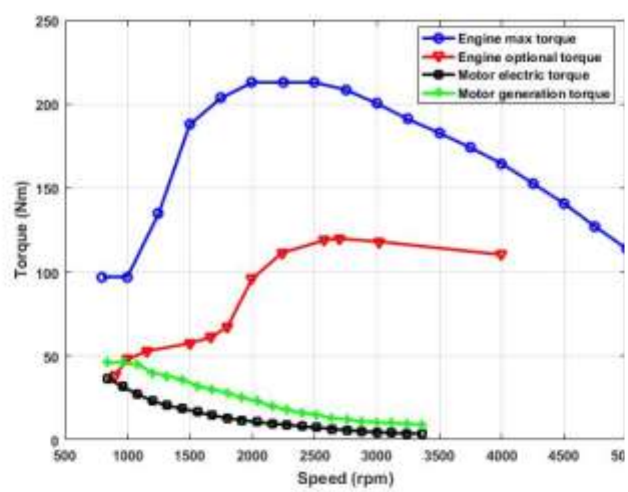

Fig 3. Engine and motor characteristic curves

As shown in the figure 3, drawing the engine external characteristic curve, the engine optimal economic curve and the motor external characteristic curves. These four curves subdivide the power assisting mode into three operating modes: hybrid driving mode, pure motor driving mode and travel charging mode. In pure motor driving mode, the engine does not stop. The gear ratio between the motor and the engine is 3:1.

(a) When the SOC of battery meets: $SOC_{low} < SOC < SOC_{high}$, the battery pack can be charged and discharged. The instantaneous operating point of the engine can be adjusted according to the optimal economic curve of the engine. T_{req}, T_{opt}, T_e and T_g respectively denote the required torque of vehicle, the optimal economic torque of engine, the maximum electric torque of motor and the maximum generation torque of motor at certain speed.

(1) If $T_{req} > T_{opt} + 3T_e$, the torque of motor is T_e and the engine provides insufficient part. It is hybrid driving mode.

(2) If $T_{opt} < T_{req} < T_{opt} + 3T_e$, engine operates on optimal economic curve and motor supplies remaining part. It is hybrid driving mode.

(3) If $T_{opt} - 3T_g < T_{req} < T_{opt}$, engine operates on optimal economic curve and the generation torque of motor is $(T_{opt} - T_{req})/3$. It is travel charging mode.

(4) If $T_e < T_{req} < T_{opt} - 3T_g$ the generation torque of motor is T_g and torque of engine is $T_{req} + 3T_g$. It is travel charging mode.

(5) If $0 < T_{req} < T_e$, motor provides the whole required torque and engine doesn't stop or provide power. It is pure motor driving mode.

(6) When the vehicle is accelerating or climbing, the working state of engine isn't optimized and motor supplies assisting torque of T_e after the stroke of accelerator pedal reaching a certain value. It is hybrid driving mode.

(b) When $SOC < SOC_{low}$, the battery can only be charged. At this time, the generation torque of the motor can be appropriately adjusted according to required torque and optimal economic torque.

(c) When $SOC > SOC_{high}$, the battery can only be discharged. At this time, the motor's electric torque can be appropriately adjusted according to required torque and optimal economic torque.

The torque distribution strategy of the power assisting control strategy is shown in Figure 4.

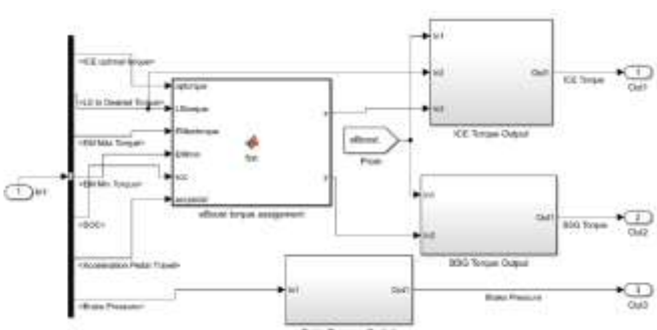

Fig 4. The torque distribution strategy during power assisting

Braking energy recovery is to store the energy of friction loss when the vehicle brakes. The SOC of battery affects the braking energy recovery efficiency. The control strategy during braking is shown in Figure 5.

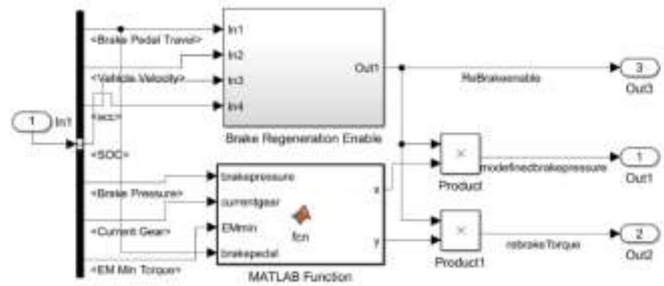

Fig 5. The torque distribution strategy during braking

The SOC balance control strategy is to adjust SOC of battery pack within a certain range. The enabling condition of this strategy is that other strategies are not enabled. The variation range is set to 5% on the basis of initial value. According the remaining capacity, the working state of motor is dynamically adjusted.

4. SIMULATION AND RESULT ANALYSIS

4.1 Co-simulation

Through the co-simulation of AVL Cruise software and MATLAB/Simulink, the fuel economy and dynamical performance of 48V mild hybrid vehicle and prototype under cyclic conditions can be compared in simulated environment.

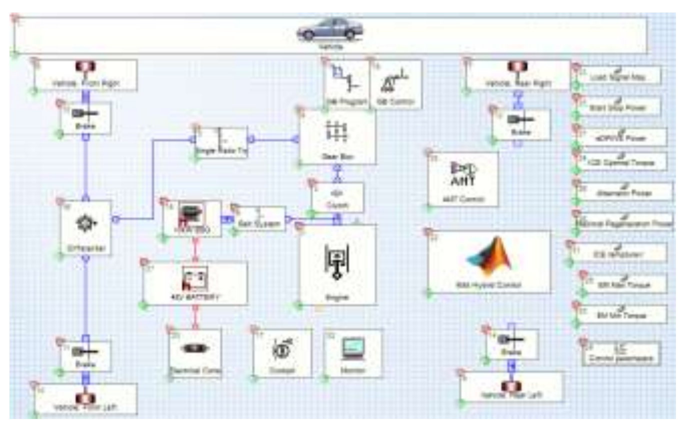

Fig 6. 48V mild hybrid vehicle

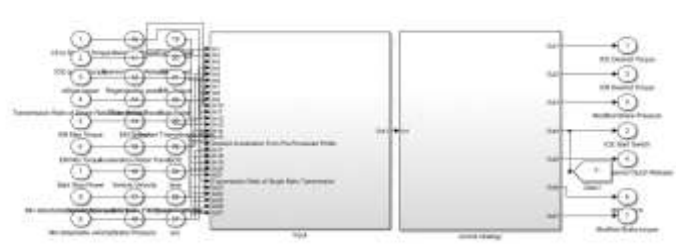

Fig 7. Control strategy model of single-target optimization based on threshold

4.2 *Simulation Analysis of Fuel Economy under NEDC Condition*

Figure 8 is comparison of the cumulative fuel consumption of the three situations under a NEDC operating cycle. It can be seen from the figure that under one NEDC cycle condition, the fuel consumption of the prototype is 0.7114L, and the fuel consumption of the 48V mild hybrid vehicle under the logic threshold control strategy is 0.6343L. While under single-target optimization control strategy for the 48V mild hybrid vehicle, the fuel consumption is 0.6181 L.

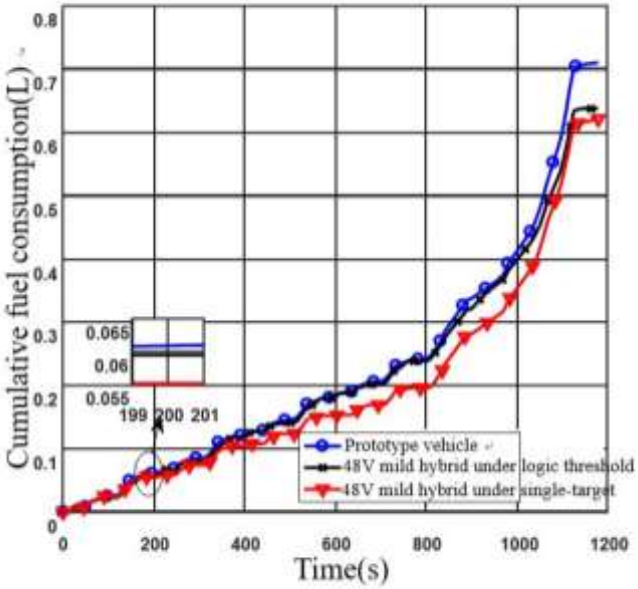

Fig 8. Comparison of cumulative fuel consumption

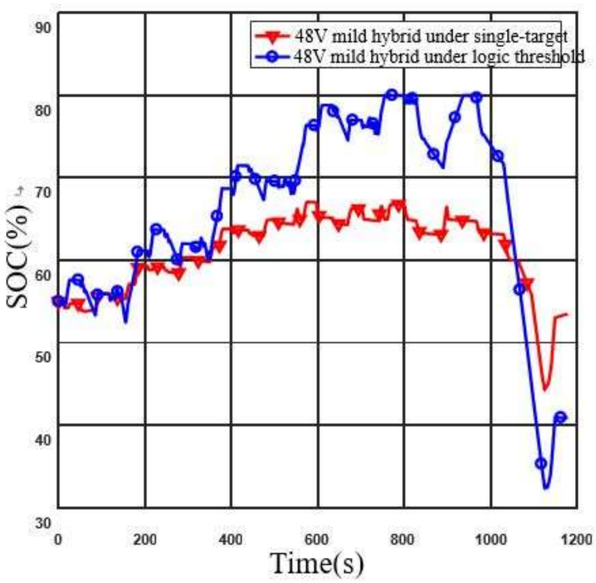

Fig 9. SOC curve

It can be seen from the figure 9 that the initial SOC values of both are 55%. After a NEDC operating cycle, the battery SOC of the 48V mild hybrid vehicle under the logic threshold control strategy becomes 40.93%, and the SOC changes sharply; for the battery SOC of 48V mild hybrid vehicle under the single-target optimization control strategy, the battery SOC becomes 53.51%, and the SOC changes smoothly.

4.3 *Simulation Analysis of dynamical performance under NEDC Condition*

In the dynamical performance simulation part, only the results of the prototype and the 48V mild hybrid under single-target optimization control are compared.

Figure 10 shows the acceleration time comparison between the two. As can be seen from the figure, the 0-100km/h acceleration time of the 48V mild hybrid car is 12.52s, while that of prototype vehicle is 13.87s. The acceleration performance is increased by 9.7%.

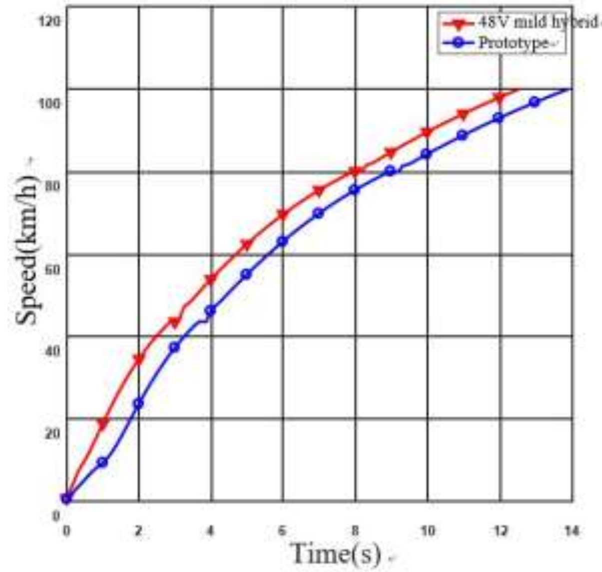

Fig 10. 0-100km/h acceleration time comparison

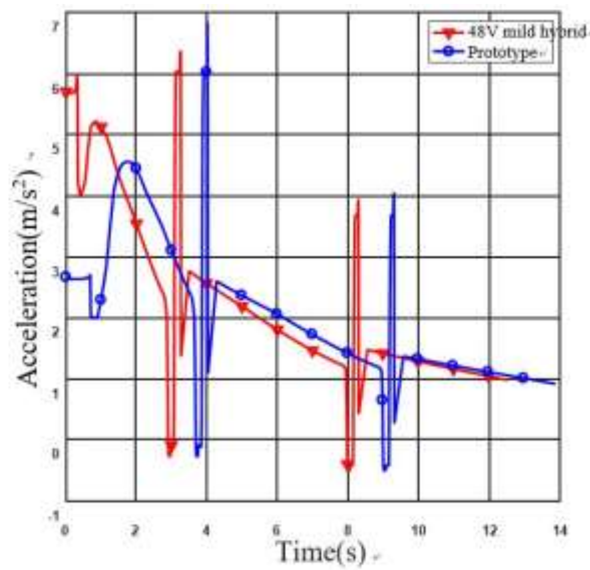

Fig 11. Comparison of acceleration

The comparison of acceleration curves also shows that the 48V mild hybrid vehicle under single-target optimization control strategy has better acceleration performance than the prototype vehicle. The 48V mild hybrid vehicle has higher acceleration at low speed, thus it can start the vehicle faster.

As for the comparison of climbing performance, the maximum climbing grade of the prototype vehicle is 54.15% when the vehicle speed is 19Km/h. The maximum climbing grade of the 48V mild hybrid vehicle under single-target control strategy is 66.59% when the vehicle speed is 16Km/h. The improvement of climbing performance is 23%.

5. CONCLUSIONS

This paper analyzes the fuel economy potential of 48V mild hybrid vehicles. According to the research focus of the paper, a single-target optimization control strategy based on threshold is proposed, mainly including engine start and stop, power assisting, brake regeneration and SOC balance.

Using the co-simulation of Cruise and Simulink, the results show that compared with the original car, the 48V mild hybrid vehicle has an improvement ratio of more than 10% in fuel economy. The acceleration time from 0 to 100Km/h is shortened by 9.7% and the maximum grade is increased by 23%. The effect of emission performance improvement is remarkable. Moreover, the simulation results show that compared with the control strategy based on logic threshold, the control strategy proposed in this paper is better in reducing the fuel consumption of the whole vehicle and maintaining the SOC balance of the battery pack.

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