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Optimal Energy Management Strategy for HEVs with Consideration of Thermal Dynamics

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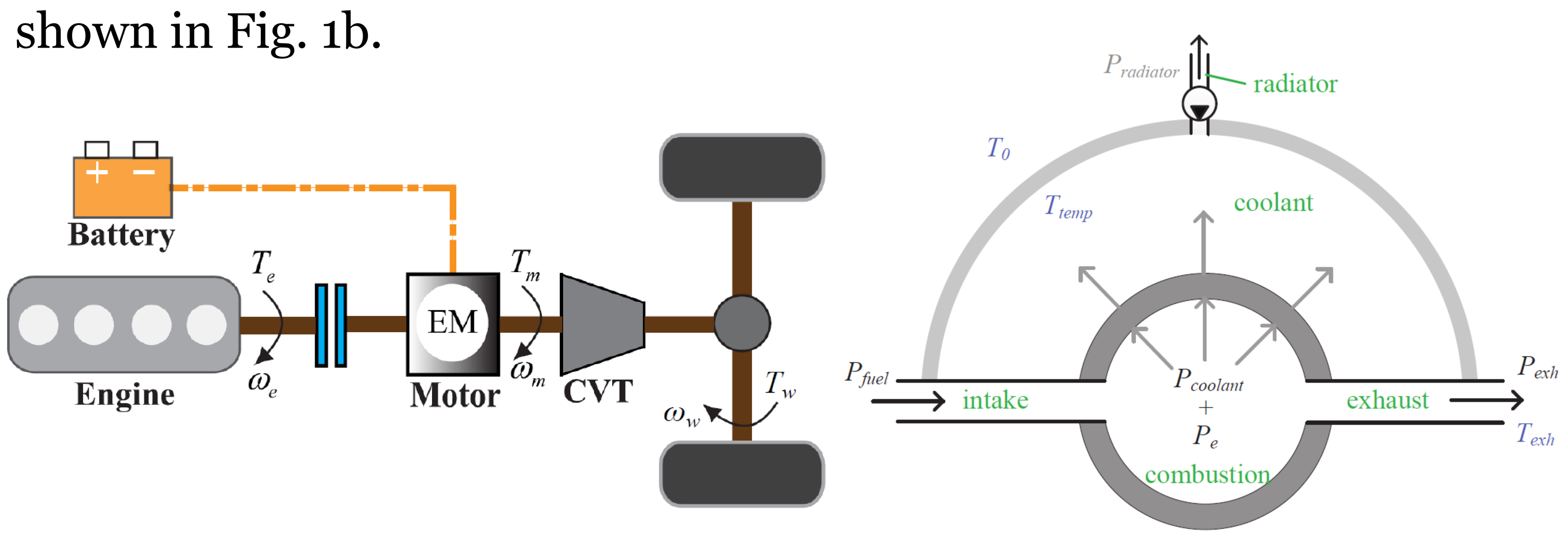
Motivation

The fuel efficiency are related to the engine temperature. The total fuel consumption of a warmed-up engine is less than that of the cold-start engine for the same driving cycle. Hybrid electric vehicle (HEV) allows the motor to work during the engine warming-up process. Optimizing torque distribution ratio can help reduce engine fuel consumption of the warm-up process. The traditional energy management strategy, which does not consider the engine temperature, is designed for a warmed-up engine. In this paper, an energy management strategy with considering engine warming-up is formulated.

Modeling

The vehicle under investigation is a parallel HEV. Its power comes from a 35 [kW] internal combustion engine and a 28 [kW] electric motor. The overall schematic of the parallel HEV is shown in Fig. 1a. A control-oriented engine thermal model is proposed to describe the main thermodynamic effects. The lumped parameter model is shown in Fig. 1b.



(a) (b)

Fig. 1: (a) Powertrian structure of parallel HEV, (b) Lumped parameter model for engine thermal dynamics

According to the first law of thermodynamics, the engine thermal dynamics is written as,

$$\dot{T}_{temp} = \begin{cases} \frac{1}{C_t} P_{coolant} - \frac{G_t}{C_t}(T_{temp} - T_0) & T_{temp} < 80 \\ 0 & T_{temp} \geq 80 \end{cases}$$

The dynamics of the battery state of charge is given by

$$\dot{SOC} = -\frac{V_{oc} - \sqrt{V_{oc}^2 - 4P_b R}}{2RQ_b}.$$

The temperature-dependent fuel consumption rate is calculated by,

$$Q_f(T_e, \omega_e, T_{temp}) = \gamma_{pf}(T_{temp}) Q_{f,w}(T_e, \omega_e)$$

$$Q_{f,w}(T_e, \omega_e) = \sum_{i=0}^{2} \sum_{j=0}^{2} \iota_{i,j} T_e^i(k) \omega_e^j(k)$$

$$\gamma_{pf}(T_{temp}) = \begin{cases} 1 + a_t(80 - T_{temp}) & T_{temp} < 80 \\ 1 & T_{temp} \geq 80 \end{cases}$$

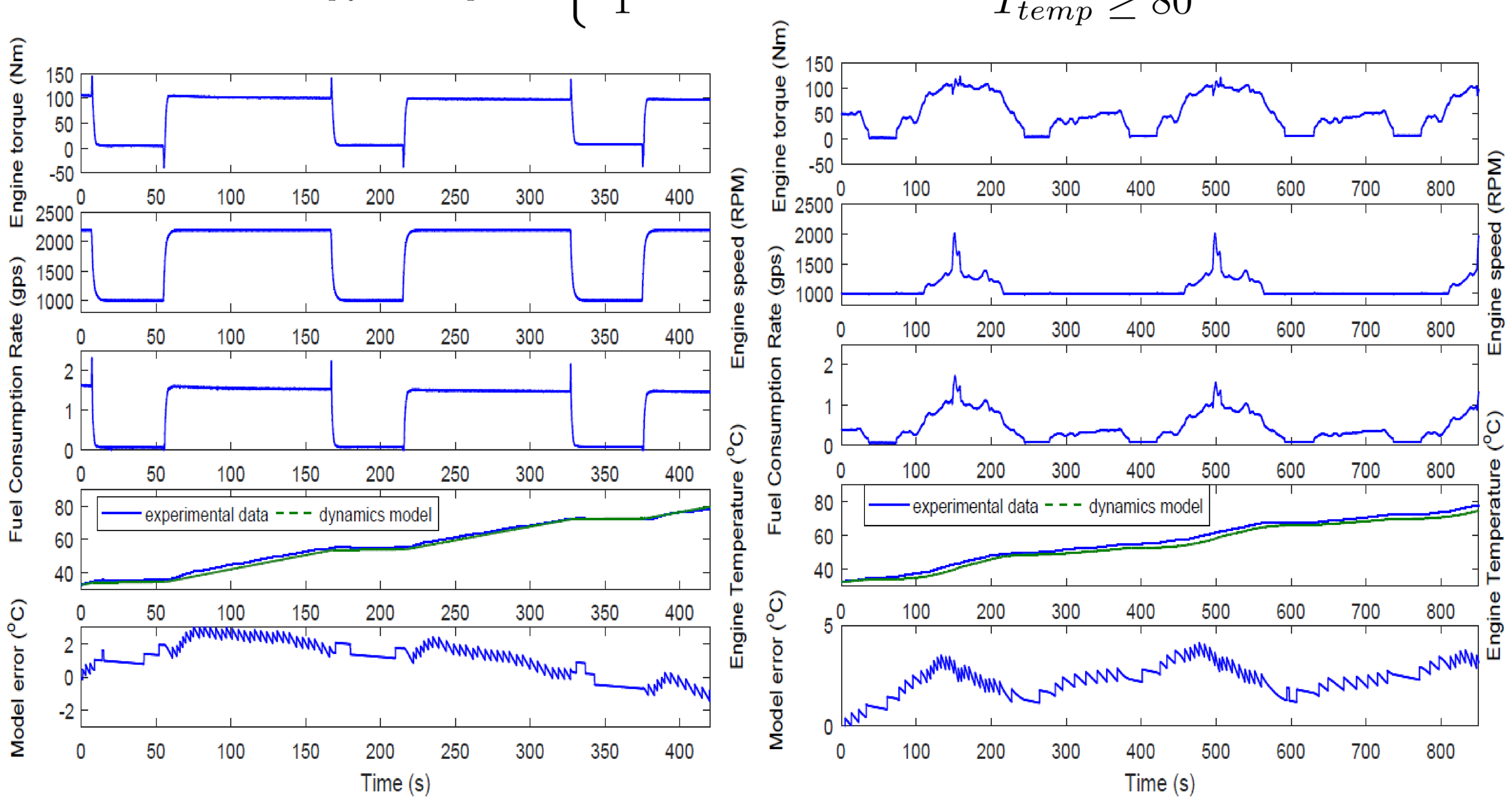


Fig. 2: Model identification and validation for engine thermal dynamics

Optimal control problem formulation

The control objective is to minimize the total fuel consumption for a specified driving cycle. Over the driving cycle, the terminal value of the battery state of charge is forced to be equal to the initial value of the battery state of charge. There are two states in the optimal problem. One is the engine temperature. The other is the battery state of charge. The optimal input is the torque distribution factor. To sum up, the energy management of the warming-up process is formulated as a constrained optimization problem,

$$\min J = \min_{[\alpha]} \int_{t_0}^{t_0+T} Q_f(P_e, \omega_e, T_{temp}) dt$$

s.t.

$$\dot{SOC} = -\frac{V_{oc} - \sqrt{V_{oc}^2 - 4P_b R}}{2RQ_b}$$

$$\dot{T}_{temp} = \begin{cases} \frac{1}{C_t} P_{coolant} - \frac{G_t}{C_t}(T_{temp} - T_0) & T_{temp} < 80 \\ 0 & T_{temp} \geq 80 \end{cases}$$

$$P_{coolant} = (p_a \omega_e + p_b)\alpha_f Q_f(T_e, \omega_e, T_{temp})$$

$$Q_f(P_e, \omega_e, T_{temp}) = \gamma_{pf}(T_{temp}) Q_{f,norm}(T_e, \omega_e)$$

$$Q_{f,norm}(T_e, \omega_e) = a_1 \omega_e + a_2 \omega_e^2 + a_3 \omega_e^3 + a_4 \omega_e T_e + a_5 \omega_e^2 T_e + a_6 \omega_e T_e^2$$

$$\gamma_{pf}(T_{temp}) = 1 + a_t(80 - T_{temp})$$

$$T_e = \begin{cases} (1-\alpha) T_{tot} & T_{tot} > 0 \\ 0 & T_{tot} \leq 0 \end{cases}$$

$$T_m = \alpha T_{tot}$$

$$T_b = \begin{cases} 0 & T_{tot} > 0 \\ (1-\alpha) T_{tot} & T_{tot} \leq 0 \end{cases}$$

$$P_b = \begin{cases} T_m \omega_m / \eta_m & T_m > 0 \\ T_m \omega_m \eta_g & T_m \leq 0 \end{cases}$$

$$T_{e,min}(\omega_e) \leq T_e \leq T_{e,max}(\omega_e)$$

$$T_{m,min}(\omega_m) \leq T_m \leq T_{m,max}(\omega_m)$$

$$T_{b,min} \leq T_b \leq T_{b,max}$$

$$\alpha_{min} \leq \alpha \leq \alpha_{max}$$

$$SOC_{min} \leq SOC \leq SOC_{max}$$

$$SOC(t_0) = SOC(t_0 + T)$$

Experimental results

The experiments are carried out on Sophia engine test bench, including model identification and validation for engine thermal dynamics and comparison for simulation and experimental results. The experimental results are shown in Fig. 2 and Fig. 3.

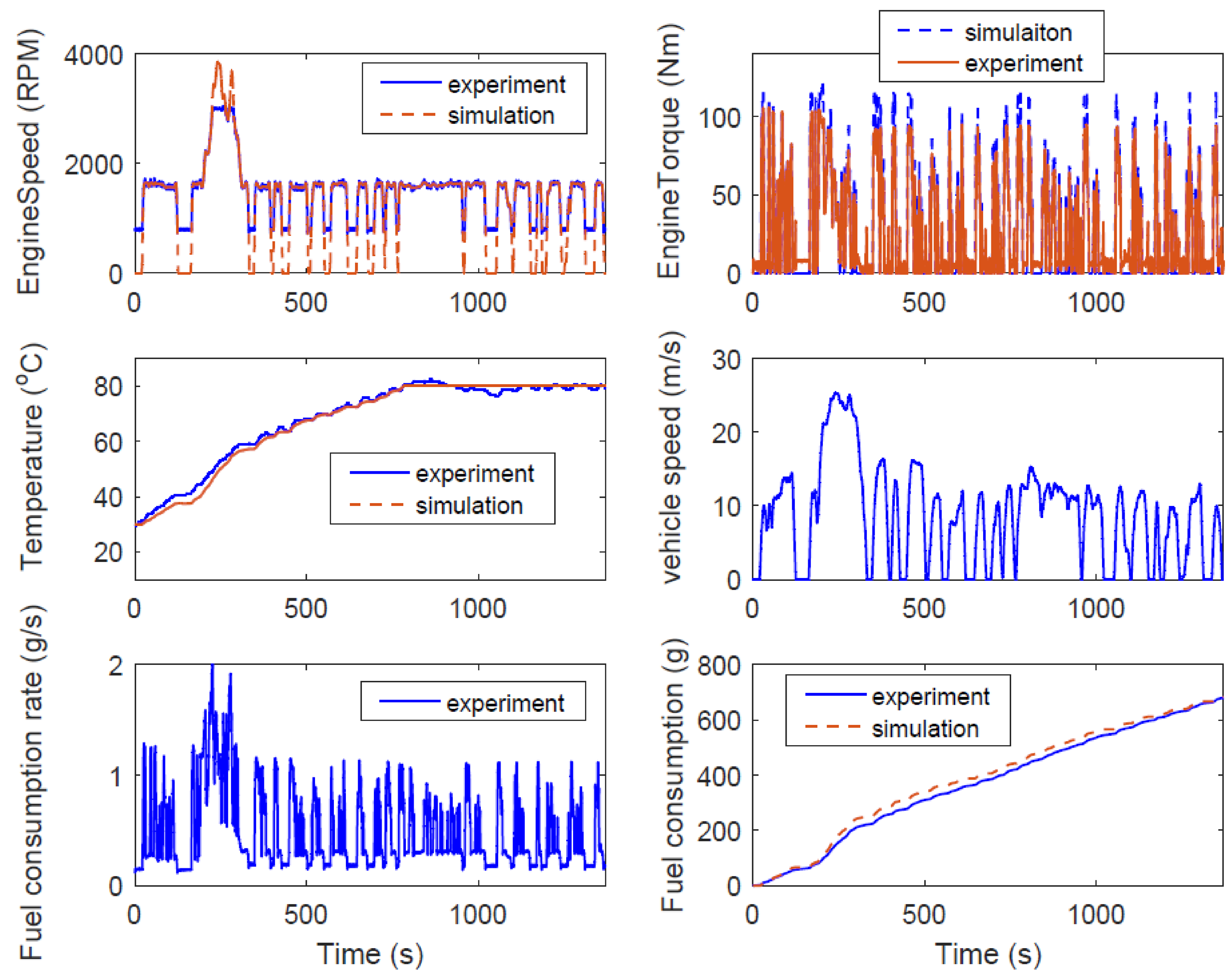


Fig. 3: Comparison for simulation and experimental results (UDDS cycle)

Conclusion

The proposed engine thermal dynamics yields a practical estimate of the main thermal behavior. The experimental results and simulation results have a high degree of similarity. As for the engine thermal model, presenting the main thermal behavior of the engine is adequate to the energy management of HEV.