SCIENCE CHINA
Information Sciences

• LETTER •

September 2021, Vol. 64 199202:1–199202:3
https://doi.org/10.1007/s11432-018-9796-1

Predictive coordinated control of fuel consumption and emissions for diesel engine vehicles under intelligent network environments

Di LIU[1,2], Hong CHEN[1,2], Jinwu GAO[2], Jinghua ZHAO[2,3] & Yunfeng HU[1,2*]

[1]*State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun* 130025*, China;*
[2]*Department of Control Science and Engineering, Jilin University, Changchun* 130025*, China;*
[3]*Computer College, Jilin Normal University, Siping* 136000*, China*

Received 19 November 2018/Accepted 18 February 2019/Published online 20 July 2020

Citation Liu D, Chen H, Gao J W, et al. Predictive coordinated control of fuel consumption and emissions for diesel engine vehicles under intelligent network environments. Sci China Inf Sci, 2021, 64(9): 199202, https://doi.org/10.1007/s11432-018-9796-1

Dear editor,

Diesel engines have been widely used in vehicles because of their excellent fuel efficiency and durability. Although they only represent a small percentage of vehicle ownership, they cause the majority of on-road emissions such as NO_x and PM [1]. By analyzing the emission characteristics of diesel engines, transient engine operation such as at idle speed and start-up is found to cause substantially more to total emissions over a driving cycle compared to steady-state engine operation [2]. Therefore, the challenge of the existing technology is to improve the emission and fuel consumption performance of diesel engine under transient conditions.

With the development of intelligent transportation and intelligent vehicles, traffic information such as traffic signals, road slope, and inter-vehicle distance can be directly obtained. Based on these information, it gives us an opportunity to predict future vehicle states and plan the desired vehicle torque and velocity, such that the aggressive engine transients can be decreased. Therefore, the main contribution of this study is that a predictive coordinated control strategy is proposed for fuel consumption and emission for diesel engine vehicles based on intelligent network environments. The novelty of the proposed control scheme can be summarized as follows: (1) Intelligent network information is used to predict the vehicle dynamics, and plan the desired torque considering fuel consumption and emission limits; (2) a data-based modeling method is applied to deduce the control-oriented model; (3) a constrained optimization control method is applied to design the torque tracking controller.

Using intelligent network information, the strategy for diesel engine predictive coordinated control is described in Figure 1(a). The strategy includes an intelligent network information collection module, a torque planning module and a torque tracking control module. As for the collection of information, because it is not the focus of this study, we assume that such information can be directly obtained. Using this information, the future state of a diesel engine vehicle is predicted, and the torque planning strategy is obtained by minimizing the energy consumption under certain constraints. Then, the torque tracking control strategy is obtained by minimizing the torque tracking error and fuel consumption under the emission constraints. For automatous vehicles, the proposed method can be directly applied to the vehicle planing and control. For vehicles with driver, the proposed method can provide a best driving scheme to the driver under the current traffic environment.

Torque planning with constraints. Using the intelligent network information, the purpose of torque planning is to obtain the optimal torque (driving torque and braking torque) by minimizing the energy consumption under given traffic, emission regulation and vehicle performance constraints. The travel time is $\tau_1 \in [t, t+T]$, which means the travel time from the current traffic signal to the next traffic signal.

As a consumer, we hope that the fuel consumption (energy loss) will be minimal; then, the optimization goal of torque planning is as follows:

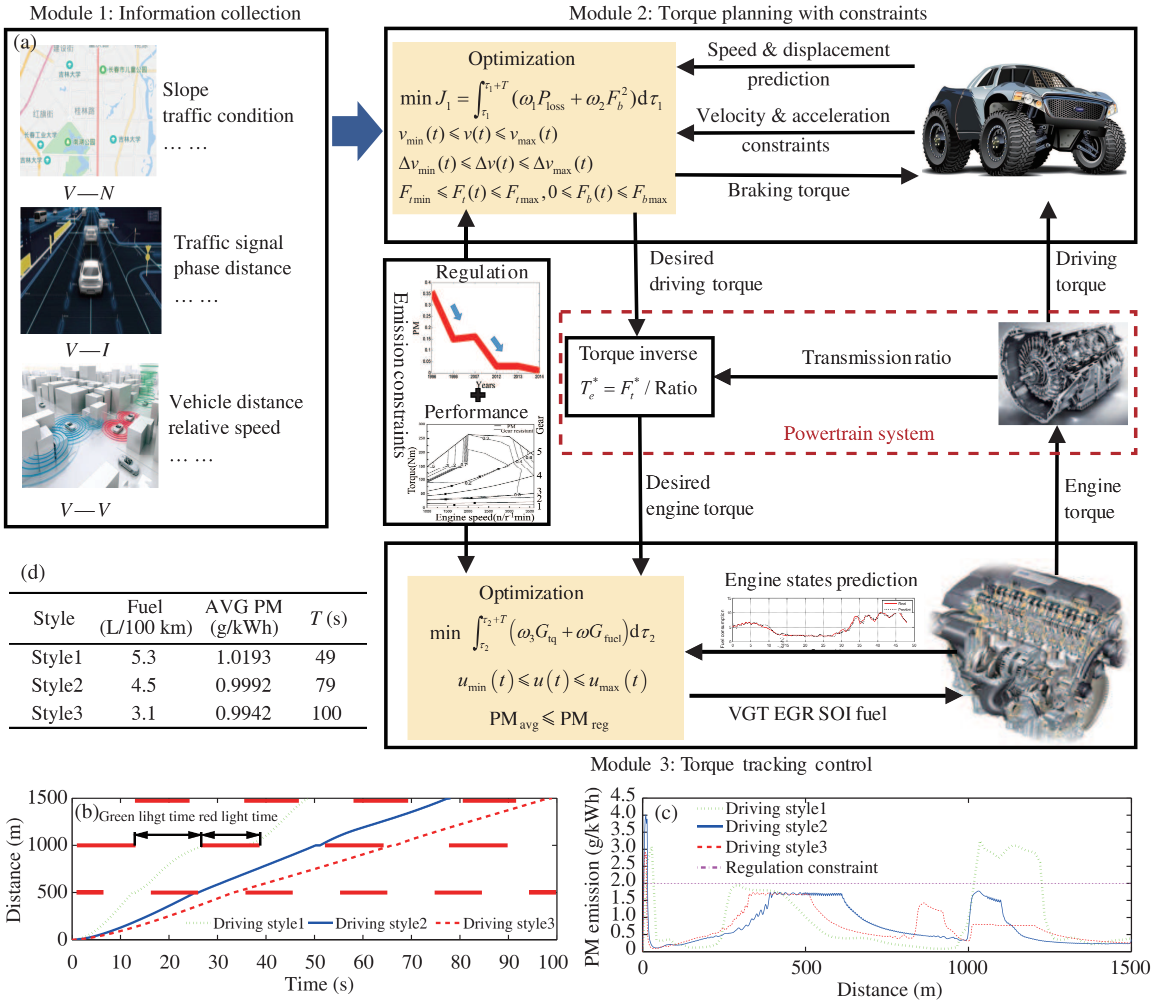
$$\min J_1 = \int_t^{t+T} \left(\omega_1 P_{\rm loss}(x_1, u_1, t) + \omega_2 F_{\rm b}^2\right) {\rm d}\tau_1, \tag{1}$$

where the meaning and the specific calculation form of $P_{\rm loss}$ can be found in [3], ω_1 and ω_2 are weight coefficients, and $x_1 = [v(t), s(t)]^{\rm T}$ is the state of the vehicle kinematics model, which is predicted by the following kinematics equations:

$$\begin{aligned} \dot{v}(t) &= \frac{1}{M}\left(F_{\rm t}(t) - F_{\rm b}(t) - \frac{1}{2}\rho c_d A_f v^2(t)\right) - c_r g, \\ \dot{s} &= v(t). \end{aligned} \tag{2}$$

The control variable is $u_1 = [F_{\rm t}, F_{\rm b}]^{\rm T}$, where $F_{\rm t}(t)$ is the driving torque, and $F_{\rm b}(t)$ is the braking torque. The end time of the next traffic signal's green light and the distance

* Corresponding author (email: huyf@jlu.edu.cn)



Style	Fuel (L/100 km)	AVG PM (g/kWh)	T (s)
Style1	5.3	1.0193	49
Style2	4.5	0.9992	79
Style3	3.1	0.9942	100

Figure 1 (Color online) Simulation results under three different driving styles. (a) Overall structural schametic flow chart; (b) driving route; (c) PM emissions; (d) analysis of experimental data.

from the current position to the next traffic signal are considered as the terminal conditions of the above optimization problem.

To ensure safety and emission limits, traffic and vehicle performance constraints should be considered in the planning module. The constraints on vehicle torque planning can be obtained as follows:

$$\begin{aligned} &v_{\min}(t) \leqslant v(t) \leqslant v_{\max}(t), \\ &\Delta v_{\min}(t) \leqslant \Delta v(t) \leqslant \Delta v_{\max}(t), \\ &F_{\rm tmin} \leqslant F_{\rm t}(t) \leqslant F_{\rm tmax},\ \ 0 \leqslant F_{\rm b}(t) \leqslant F_{\rm bmax}, \end{aligned} \tag{3}$$

where $v_{\min}$ and $v_{\max}$ are velocity constraints and $\Delta v_{\min}$ and $\Delta v_{\max}$ are acceleration constraints. Using traffic flow speed, traffic density and traffic jam information, we can obtain velocity and acceleration constraints. $F_{\rm tmin}$ and $F_{\rm tmax}$ are vehicle driving torque constraints, which are converted to engine torque constraints via the transmission ratio and are ultimately determined by the engine performance and engine emission MAP. $F_{\rm bmin}$ and $F_{\rm bmax}$ are the braking torque constraints, given according to vehicle performance.

Torque tracking control strategy. According to both the system characteristics of a diesel engine and control requirements, the desired driving torque is translated into the desired engine torque by a given gear ratio, which is decided by a pre-designed gear controller in GT-Power. Then an appropriate torque tracking control strategy should be adopted to achieve the desired torque.

According to the characteristics of the diesel engine, the control input is chosen as $u = [m, \gamma, \theta, \beta]^{\rm T}$, and the output is chosen as $y = [T_e, {\rm PM}, b_i]$. In this study, the control-oriented model is deduced based on the subspace identification method, which is a very practical modeling method depending on the system input-output data [4]. The input-output data are obtained from a diesel engine model built in GT-Power. The travel time is $\tau_2 \in [t, t+T]$, and the control target can be constructed as follows:

$$\begin{aligned} &\min\ J_2 \\ &= \int_t^{t+T} (\omega_3 G_{\rm tq}(x_2, u_2) + \omega_4 G_{\rm fuel}(x_2, u_2)){\rm d}\tau_2, \end{aligned} \tag{4}$$

where x_2 is the state of the system obtained through subspace identification, $G_{\rm tq}$ is the torque tracking error, $G_{\rm fuel}$ is the fuel consumption function, and ω_3 and ω_4 are weight coefficients.

The constraints on the input are based on the execution limit and the execution speed of the injector, the EGR valve, and the VGT valve. The constraints on the output are derived from emission regulations. Considering the above, the constraints on the diesel engine torque tracking control can be obtained as follows:

$$\begin{aligned} &u_{\min}(t) \leqslant u(t) \leqslant u_{\max}(t), \\ &\mathrm{PM}_{\mathrm{avg}} \leqslant \mathrm{PM}_{\mathrm{reg}}, \end{aligned} \tag{5}$$

where $u_{\min}$, $u_{\max}$ are control input constraints, $\mathrm{PM}_{\mathrm{avg}}$ is the mean PM emissions within the measurement range, and $\mathrm{PM}_{\mathrm{reg}}$ is the emission limit given by regulations.

Co-simulation. To verify the effectiveness of the proposed method, a vehicle plant with a 1.6 L diesel engine was built in GT-Power. The controller is implemented in Matlab, and a co-simulation is performed. In this application, the model predictive control method is used to solve the optimal problem. Selection of parameters and constraints in the simulation can be found in the appendix.

In Figure 1(b) and (c), the blue solid line denotes an optimized standard driving style (without idle speed state), the red dotted line denotes an optimized mild driving style (without idle speed state and rapid acceleration state), and the green dotted line denotes the driving style under idle speed and large acceleration.

From the data analysis in Figure 1(d), the mild driving style's time consumption is the highest, but the fuel consumption and average PM emission are the lowest. The radical driving style can reach the destination quickly; however, the other indices are the worst. Between these two styles, the standard driving style does not require as much time and achieves an acceptable fuel consumption and average PM emission.

Conclusion. This study highlights an integrated control scheme of fuel combustion and emission for diesel engine vehicle under intelligent network environment. Based on the intelligent network information, the desired vehicle driving force is planned by minimizing fuel consumption and considering constraints. Then the data-based method is applied to deduce the control-oriented model, and the torque tracking controller is carried out to meet the planned torque. Finally, a co-simulation is presented to verify the effectiveness.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. U1864201, 61703177, 61773009) and Jilin Provincial Science Foundation of China (Grant Nos. 20180101037JC, 20180101067JC).

Supporting information Figures and Tables. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Zhang H, Wang J. Improved NO and NO_2 concentration estimation for a diesel-engine-aftertreatment system. IEEE/ASME Trans Mechatron, 2018, 23: 190–199

2 Giakoumis E G, Zachiotis A T. Investigation of a diesel-engined vehicle's performance and emissions during the WLTC driving cycle-comparison with the NEDC. Energies, 2017, 10: 240

3 Guo L, Gao B, Gao Y, et al. Optimal energy management for HEVs in eco-driving applications using bi-level MPC. IEEE Trans Intell Transport Syst, 2017, 18: 2153–2162

4 Lu X, Chen H, Gao B, et al. Data-driven predictive gearshift control for dual-clutch transmissions and FPGA implementation. IEEE Trans Ind Electron, 2015, 62: 599–610