

# SIMPLIFIED MODELS OF ENGINE HC EMISSIONS, EXHAUST TEMPERATURE AND CATALYST TEMPERATURE FOR AUTOMOTIVE COLDSTART

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Abstract: The initial 1-2 minutes of operation of an automotive spark-ignition engine, commonly called as the "coldstart" period, produces more than 75-80 % of the hydrocarbon (HC) emissions in a typical drive cycle. Model-based controller development requires accurate, yet simple, models that can run in real-time. Simple, intuitive models are developed to predict both tailpipe hydrocarbon (HC) emissions and exhaust temperature during coldstart. Each of the models is chosen to be sum of first order linear systems based on the experimental data and ease of parameter identification. Inputs to these models are *AFR*, spark timing and engine crankshaft speed. A reduced order thermodynamic model for the catalyst temperature is also developed. The parameters are identified using least squares technique. The model estimates for the coldstart are compared with the experimental results with good agreement. *Submitted to Fifth IFAC Symposium on Advances in Automotive Control*

Keywords: Coldstart, Engine Thermal Model, Catalyst Model

## 1. INTRODUCTION

As regulations on emissions for automotive engines become more stringent, the reduction of hydrocarbon (HC) emissions during coldstart continues to pose a relevant challenge for the industry. Developing simple models which can run in real-time is necessary to design controllers using the model-based paradigm.

A lot of interest has been shown in modeling and analysis of engine and catalyst subsystems for coldstart analysis. The initial work on physically based dynamic engine models that account for the

throttle dynamics and intake manifold dynamics can be traced back to (Powell 1979) and (Dobner 1983). It was further modified by (Moskwa and Hedrick 1987) and (Cho and Hedrick 1989). Recent work on engine subsystems modeling can be found in (Tunestal and Hedrick 2001), (Balluchi *et al.* 2001),(Shaw and Hedrick 2002),(Zavala *et al.* 2006),(Sanketi *et al.* 2006b). (Shaw and Hedrick 2002) and references therein developed models for engine-out exhaust gas temperature ( $T_{exh}$ ) and raw HC ( $HC_{raw}$ ). In this paper, simple, intuitive models for  $T_{exh}$  and  $HC_{raw}$  are developed. Each of these is modeled as a sum of first order linear systems based on the experimental data and ease of parameter identification. Inputs to these models are air to fuel ratio (*AFR*), spark

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timing and engine crankshaft speed ( $\omega_e$ ).  $AFR$ , spark and changes in  $\omega_e$  are related to the combustion stability. (See Sec. 2.1 and 2.2).

Modeling and analysis of catalysts is also important for coldstart controller design. These range from very complex ones to simplified ones which are more suitable for closed-loop control. Some of the important contributions are (Ohsawa *et al.* 1998), (Shen *et al.* 1999), (Chan and Hoang 1999), (Jones *et al.* 2000), (Brandt *et al.* 2000), (Fiengo *et al.* 2002), (Shaw *et al.* 2002), (Koltsakis and Tsinoglou 2003), (Sanketi *et al.* 2006a) and references therein. The catalyst model presented here is an improved version of the model developed in (Sanketi *et al.* 2006a). A thermodynamic energy balance is used to model the catalyst temperature ( $T_{cat}$ ). Further, thermal diffusivity calculation is used to reduce the order of the catalyst temperature model. (See Sec. 2.3).

The contribution of this paper lies in developing new simplified models for  $HC_{raw}$ ,  $T_{exh}$  and  $T_{cat}$ . Our goal is to develop a simplified model-based controller for coldstart. A MIMO sliding controller for coldstart designed using these models is presented in another paper submitted to the same symposium.

## 2. MODEL OF PLANT

The model presented here has been developed based on the influence of the  $AFR$ , engine speed and spark timing on  $T_{exh}$  and  $HC_{raw}$ .  $AFR$  and spark timing directly affect the combustion process. In addition, changes in engine speed affect the cylinder pressure and hence, the quality of combustion. Experiments indicated that the engine speed was having a more noticeable influence on  $HC_{raw}$  and  $T_{exh}$  as compared to the intake air flow rate. Also, each of the chosen inputs can be modified easily to observe the effect on  $T_{exh}$ , which simplifies the process of modeling. The  $T_{exh}$ ,  $HC_{raw}$  and  $T_{cat}$  submodels have been simulated together with an engine model presented in (Cho and Hedrick 1989) and (Sanketi *et al.* 2006b).

### 2.1 Exhaust Temperature Model

Through experiments, it was observed that  $T_{exh}$  was responding almost like a first order linear system to each of the input variables. Hence, the output was modeled as a set of three first order linear systems running in parallel that relate the three variables mentioned before to  $T_{exh}$ . The block diagram shown in Fig.1 illustrates the idea. It should be noted that however, the inputs have been offset around certain nominal value

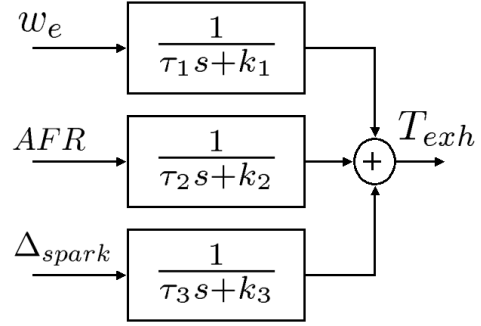


Fig. 1. Block Model for Exhaust temperature model

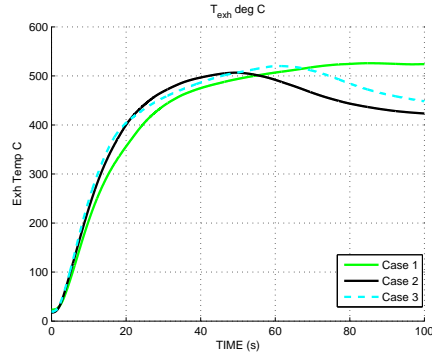


Fig. 2. Experiments showing the effect of inputs on exhaust temperature-  $T_{exh}$

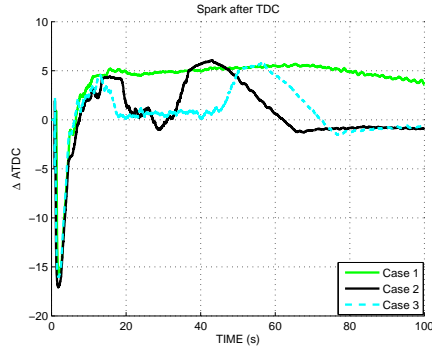


Fig. 3. Experiments showing the effect of inputs on exhaust temperature- Spark

in the model and saturations have been applied, too. Negative actuation has also to be ruled out. Though this model does not follow any physics-based combustion modeling, it is intuitive; and it is simple and suitable for engine controller design.

Figures 2 through 5 illustrate the effect of inputs on  $T_{exh}$ . Retarding the spark, increasing the engine speed and a richer  $AFR$  lead to an increase in  $T_{exh}$ .  $T_{exh}$  is slower in response to  $AFR$  and engine speed as compared to the spark timing. Also, the effect of spark timing was found to be more prominent than that of others. The parameters of the model were obtained for the coldstart period using least squares.

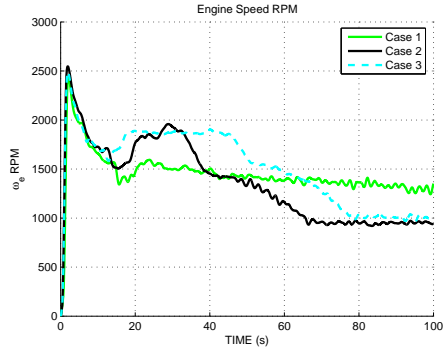


Fig. 4. Experiments showing the effect of inputs on exhaust temperature- RPM

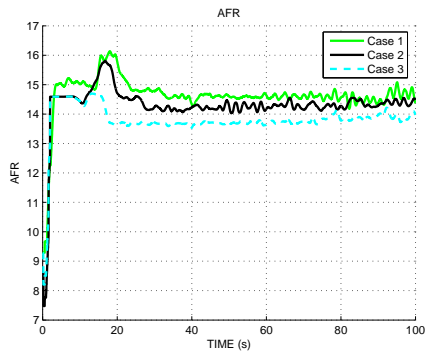


Fig. 5. Experiments showing the effect of inputs on exhaust temperature- AFR

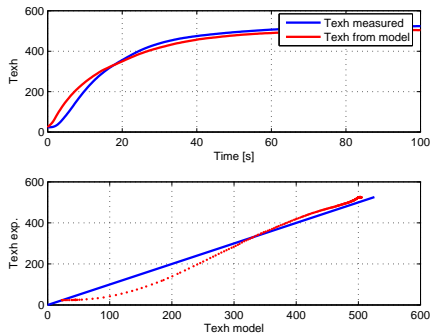


Fig. 6. Comparison between measured and computed exhaust temperature for a coldstart run

Fig.6 shows the comparison of the model versus experimental data for an engine coldstart run. The second part of the figure shows an error of about  $50C$ , however, the first part of the figure illustrates that it is due to a small delay in the transient rise of the temperature. This will not have a significant effect on the catalyst efficiency profile. Fig.7 shows the comparison between the model and the experimental values for exhaust temperature over several coldstart experiments. Errors of about  $50-60 C$  are consistently found in the transient part of the temperature profile. A steady state error of about  $80 C$  is also found in one of the data sets. Overall, the mean error was

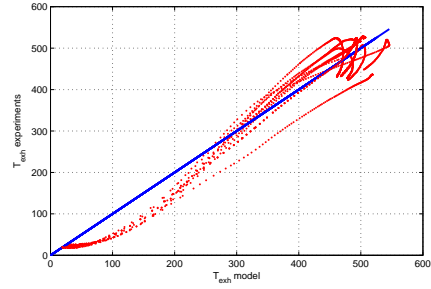


Fig. 7. Comparison between measured and computed exhaust temperature for several coldstart runs

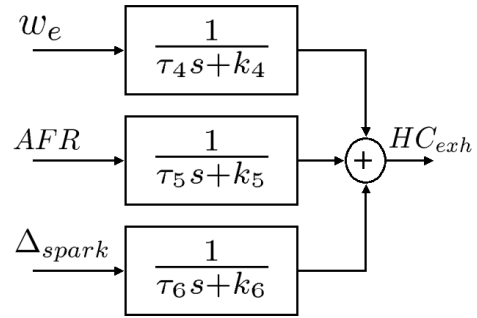


Fig. 8. Block Model for hydrocarbon emissions model

$4.9414 C$  with a standard deviation of  $34.8981 C$ .

## 2.2 Hydrocarbon Emissions Model

The raw hydrocarbon emissions  $HC_{raw}$  was also modeled as a sum of first-order linear systems, very similar in concept to that of  $T_{exh}$ . It makes sense since both  $HC_{raw}$  and  $T_{exh}$  are products of the same process. As in the case of  $T_{exh}$ , three linear subsystems describe the interaction between  $AFR$ , engine speed and spark timing with the hydrocarbon emissions. However, the input offsets are different than those used for the  $T_{exh}$  model. Fig.8 illustrates the concept of the model.

Figures 9 through 12 illustrate the effect of inputs on  $HC_{raw}$ . Retarding the spark above certain value, decreasing the engine speed and a richer  $AFR$  lead to an increase in  $HC_{raw}$ .  $HC_{raw}$  is much faster in response to  $AFR$  as compared to the engine speed and the spark timing. Also, the effect of  $AFR$  was found to be more prominent than others. The parameters of the model were obtained for the coldstart period using least squares.

Fig.13 shows the comparison between the model and the experimental hydrocarbon emissions for a coldstart run and Fig.14 shows the comparison of the model and experimental hydrocarbon

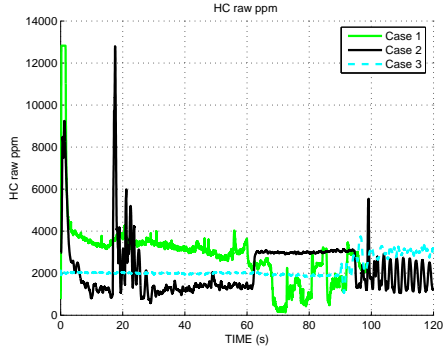


Fig. 9. Experiments showing the effect of inputs on raw emissions-  $HC_{raw}$

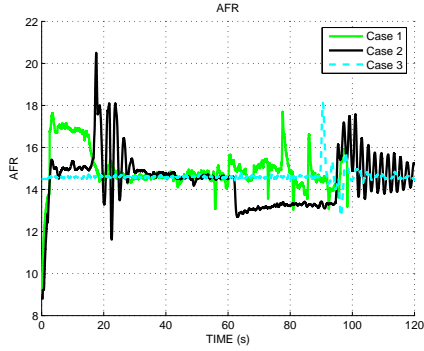


Fig. 10. Experiments showing the effect of inputs on raw emissions-  $AFR$

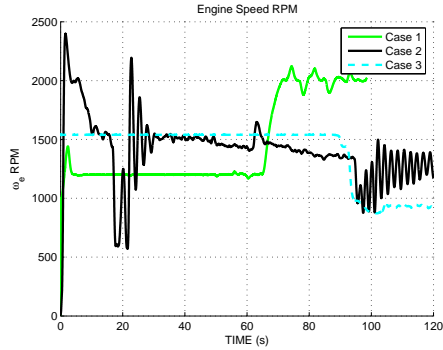


Fig. 11. Experiments showing the effect of inputs on raw emissions-  $RPM$

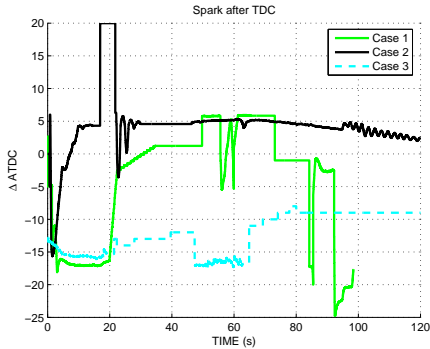


Fig. 12. Experiments showing the effect of inputs on raw emissions- Spark

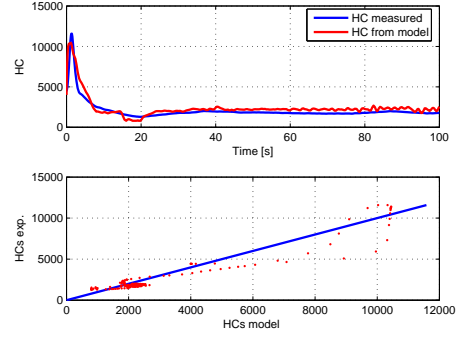


Fig. 13. Comparison between measured and computed hydrocarbon for one coldstart run

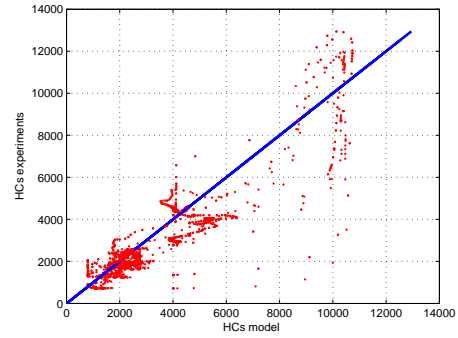


Fig. 14. Comparison between measured and computed hydrocarbon for several coldstart runs

emissions in ppm over several experiments. The largest errors occur during the transients close to the peak of the emissions which is the period when the signal changes more rapidly, whereas the errors are lower at steady state. Overall, the mean error was 388.7233 ppm with a standard deviation of 959.3685 ppm.

### 2.3 Catalyst Model

This part describes the physics that governs the catalyst warm up including the water condensation and evaporation effect. The simplified catalyst model has a structure similar to that described in (Sanketi *et al.* 2006a). Here, a thermal diffusivity calculation is used to show that the gas comes in equilibrium with the solid before it leaves the catalyst, thus making unnecessary the use of different states for the catalyst solid temperature and the gas temperature.

A single cell of the catalytic converter is analyzed. The time scale required for the gas and the honeycomb mass to come in equilibrium is given by

$$t_{diff} = \frac{d^2}{\alpha} \quad (1)$$

where, the characteristic length  $d$  for diffusion is equal to half the cell side length and  $\alpha$  is thermal diffusivity of the gas. This was compared with

the time required for the gas to travel through the catalyst, which was calculated using the average exhaust gas flow rate in a typical coldstart. The calculations were performed at three different temperatures spanning the coldstart. The results are shown in Table 1.

Table 1. Time for travel and diffusion time scale

No.	Gas Temp. (K)	Time Travel (s)	Diffusion Time Scale (s)
1	350	0.1114	0.0559
2	550	0.0709	0.0269
3	700	0.0557	0.0183

From table 1, it can be seen that the time taken by the gas to travel through the catalyst is two to three times the time scale for the gas to come into equilibrium with the catalyst solid mass. Hence, for our analysis, we can assume that the gas and the solid mass of the catalyst are at the same temperature and modeling the catalyst requires only one temperature state instead of two.

#### 2.4 Model Equations

The catalyst temperature depends on the heat obtained from the feedgas flowing into the catalyst, the amount of heat generated due to oxidation of pollutants from the feedgas ( $\dot{Q}_{gen}$ ) and the heat transfer to the surroundings ( $\dot{Q}_{out}$ ). In addition to these heat transfers, heat is lost due to evaporation of the moisture in the catalyst ( $\dot{Q}_{ev}$ ). This moisture is accumulated in the initial few seconds of operation due to condensation of vapor on the cold surface of the catalytic converter. When the temperature reaches the saturation temperature of the condensed vapor, the vapor starts evaporating. Due to the heavy heat loss in evaporation, the catalyst temperature remains almost constant or increases at a very low rate. Thus, there is a plateau in the temperature profile. The catalyst temperature dynamics can be summarized as follows.

During the plateau:

$$\dot{T}_{cat} = \frac{1}{m_{gas}C_v + MC} [\dot{m}_{exh}C_p(T_{exh} - T_{tp}) - \dot{Q}_{out} + \dot{Q}_{gen} - \dot{Q}_{ev}] \quad (2)$$

otherwise

$$\dot{T}_{cat} = \frac{1}{m_{gas}C_v + MC} [\dot{m}_{exh}C_p(T_{exh} - T_{tp}) - \dot{Q}_{out} + \dot{Q}_{gen}] \quad (3)$$

$$\dot{Q}_{ev} = \dot{m}_{ev}\Delta\bar{h}_{ev} \quad (4)$$

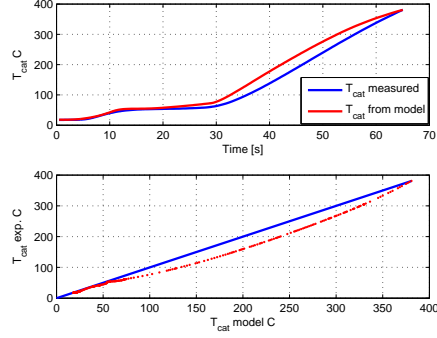


Fig. 15. Comparison between measured and computed  $T_{cat}$  for several coldstart runs

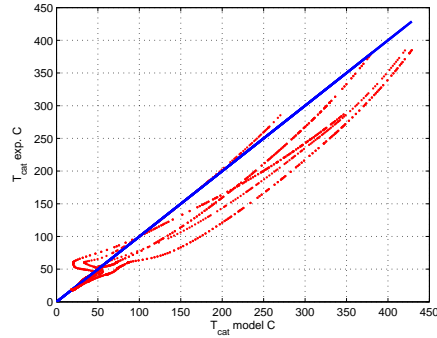


Fig. 16. Comparison between measured and computed  $T_{cat}$  for several coldstart runs

where,  $\dot{m}_{exh}$  is the exhaust gas flow rate,  $M$  is the solid mass of the catalyst,  $m_{gas}$  is the mass of the gas inside the catalyst,  $\dot{m}_{ev}$  is the mass rate of evaporation and  $\Delta\bar{h}_{ev}$  is the enthalpy of evaporation at the corresponding saturation temperature. It is not straightforward to find  $\dot{Q}_{ev}$  directly. Hence, it is calculated implicitly using a method that is similar to that used in (Sanketi *et al.* 2006a). It employs a parameter adaptation algorithm that uses the  $T_{cat}$  measurement to find  $\dot{Q}_{ev}$  through  $\dot{Q}_{out}$ . Readers are encouraged to read (Sanketi *et al.* 2006a) for details.

Fig.15 shows the comparison of the model versus experimental data for an engine coldstart run. Fig.16 shows the comparison between the model and the experimental values for exhaust temperature over several coldstart experiments. Overall, the mean error was 10.4227 C with a standard deviation of 22.2439 C.

### 3. CONCLUSIONS

Simplified control-oriented models of engine-out hydrocarbon emissions ( $HC_{raw}$ ), exhaust temperature ( $T_{exh}$ ), and catalyst temperature ( $T_{cat}$ ) were presented.  $HC_{raw}$  was modeled as a sum of first order linear systems with three different inputs namely, air-fuel ratio  $AFR$ , spark timing and engine speed  $\omega_e$ . Such a model structure was based

on the experimental data and ease of parameter identification. The structure of the  $T_{exh}$  model was chosen similar to that of  $HC_{raw}$ . A reduced order thermodynamic model for the catalyst temperature was developed using thermal diffusivity analysis. The parameters were identified using least squares methodology. The model estimates during the warm-up agreed well with the experimental results. A MIMO sliding controller for coldstart designed using these models is presented in another paper submitted to the same symposium.

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