Multi-objective optimization of a CRDI assisted diesel engine with predictive regression model developed by uniform design

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Abstract. This paper is dedicated to find a unique solution for the optimization of engine performance and emissions which have a trade-off between NOx-soot-BSFC. To develop regression models for engine performance and emissions, multiple nonlinear regression with uniform design is employed. And the accuracy of the predictive models has revealed the good performance and high efficiency of uniform design. The multi-objective optimization with weighted sum method is conducted for multi-objective optimization and weights which represent relative importance of different objective can be suitably varied to meet the different desire of engine designers. Finally, four optimization objectives have conducted and validated which confirmed the feasible of this optimization approach.

1. Introduction

Diesel engine has been widely used in industry and transportation due to the advantages of reliability, durability, fuel economy and efficiency. Nonetheless, there are increasing challenges caused by the regulations and market demands, but the common rail diesel injection system with more flexibility injection control has expanded the optimization space for engine performance and emissions [1-3] . Common rail diesel injection systems can reduce the specific fuel consumption and soot emission but with a penalization of higher NOx emissions, and this trade-off scenario has been investigated in many studies [4-7].

To study engine performance and emissions, model-based approach has been extensively employed due to its simplicity, flexibility and low cost compared to the traditional experimental methods [8-12]. Fabio Scappin et al.[9]described a zero-dimensional model which evaluated the engine performance by means of an energy balance and a two zone combustion model using ideal gas law equations over a complete crank cycle. Zhijun Peng and Ming Jia[11]developed a three-dimensional computational fluid dynamics model to investigate the effect of late intake valve closing on combustion and emissions with premixed charge compression ignition combustion in a diesel engine.

Uniform design as an experimental design is motivated by the need for effective designs in computer experiments in the 1970s [13], has been successfully applied in industry, system engineering, pharmaceutics and natural sciences due to its economical and minimum experimental runs to study multi factors with high levels simultaneously[14-16]. But the application of uniform design in the diesel engine field is quite rare so far, this paper has developed multi nonlinear regression predictive models for engine performance and emissions using the uniform design, and the performance of this experimental design has been validated.

In order to optimize performance and emissions, previous studies mainly optimized the objectives one by one which could not get the unique solution when optimized multi objectives simultaneously. So many studied have been conducted to optimize the engine using multi-objective optimization in recent years [5, 7, 8, 17-20].

In this paper, the multi-objective optimization method is integrated with uniform design to optimize the fuel injection and induced air parameters. To get the responses of the diesel engine to the parameters of fuel injection and induced air which are managed in accordance with the uniform design, a thermodynamic model which has been validated by experiment data has been developed in GT-power. Then the objectives regression models are developed by multiple nonlinear regression method, and the final part of the paper is the multi-objective optimization of the engine operation, the objectives are NOx and soot emissions, break specific fuel consumption(BSFC) and max in-cylinder pressure which have their respective weights and constraints according the different purpose of optimization.

2. Materials and methods

2.1 Modeling and validating engine.

The thermodynamic model has employed Direct-injection diesel jet combustion model and a fuel injection model developed by the injector flow map which is obtained by injector manufacturer. The core approach of the combustion model is to track the fuel jet as it breaks into droplets, evaporates, mixes with surrounding gas, and burns.

The thermodynamic model is validated at the 90% load condition of a CRDI assisted diesel engine with turbocharges used for marine propulsion, and there are seven cases for calibration which are listed in Table1.

Table 1 Cases for model validation

case	Operation paremeters			
	Rail pressure (*bar*)	Injection Timing (°*ATDC*)	Charger Pressure (*bar*)	Charger Temperature (*K*)
1	1500	-12	3.94	318
2	1500	-14	3.8	317
3	1500	-16	3.68	316
4	1500	-18	3.64	315
5	1400	-18	3.8	316
6	1300	-18	3.91	316
7	1200	-18	4.02	317

In-cylinder pressures of the model in the cases (1-3) with same rail pressure and changing injection timing and the cases (5-7) with same injection timing and changing rail pressure is compared with the experimental date, shown in Figs. 1-2. And Fig.3 shows the validation of the BSFC and soot emission. The good agreements to the experimental date indicate the feasibility of the model for the study.

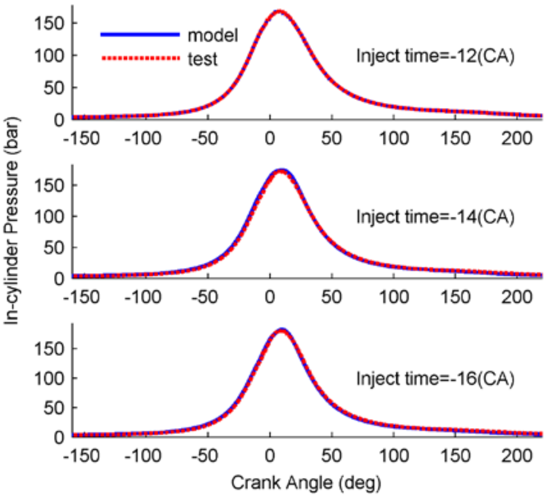


Fig. 1 Validation of in-cylinder pressure with same rail pressure

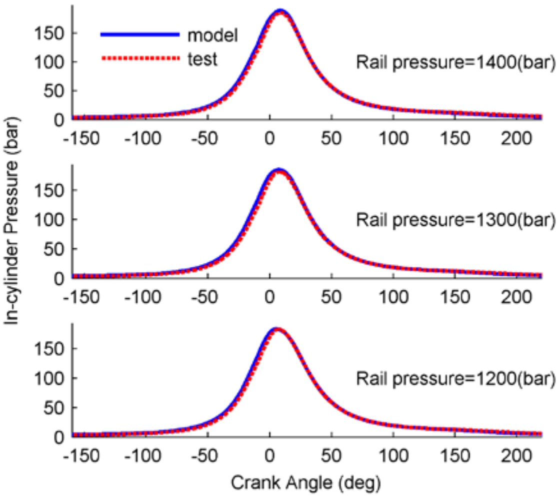


Fig. 2 Validation of in-cylinder pressure with same injection timing

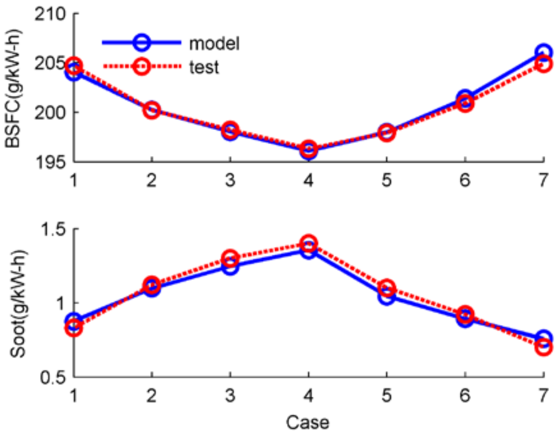


Fig. 3 Validation of BSFC and Soot emission

2.2 Uniform design.

Uniform design has been widely used especially for computer experiments since it was proposed by Fang [13].The uniform design intends to scatter its design points evenly on the experimental domain. Uniform design can minimize the number of runs to the levels of the factors, so it has absolute advantages compared to full-factorial design and orthogonal design when experiments have multiple factors with high levels simultaneously. This study employed a uniform design with four factors and seventeen levels which shown in Table 2, in the table each column indicates the levels of a factor.

Table 2 Uniform design

Trial No	Column				Trial No	Column			
	1	2	3	4		1	2	3	4
1	1	7	11	13	10	10	2	8	11
2	2	14	5	9	11	11	9	2	7
3	3	4	16	5	12	12	16	13	3
4	4	11	10	1	13	13	6	7	16
5	5	1	4	14	14	14	13	1	12
6	6	8	15	10	15	15	3	12	8
7	7	15	9	6	16	16	10	6	4
8	8	5	3	2	17	17	17	17	17
9	9	12	14	15					

This purpose of this paper is to optimize the fuel injection and induced air parameters at one load condition of the engine. According to the experimental date and optimization purpose, the experimental design considered the speed of the engine and fuel injection quantity as a constant value and the upper and lower bounds of input variables are shown in Table 3.

Table 3 Input variable bounds

Variables	Unit	Lower bound	Upper bound
Rail pressure	*bar*	1200	1600
Injection timing	°*ATDC*	-18	-10
Charge pressure	*bar*	3.6	4
Charge temperature	*K*	310	326

2.3 Multiple nonlinear regression.

A best predictive regression model should contain all the important input variables and exclude the insignificant factors to maintain the accuracy and simplicity of the model at the same time. According to the previous study and the input variable bounds, it showed that except of the main effects of the four input variables, the interaction effect of rail pressure and injection timing had significant effect to the response of the engine. Besides, the effects of the rail pressure and injection timing were nonlinear, so the square terms of these two variables were introduced into the regression model.

The multiple nonlinear regression model is given as Eq. 1.

$$\hat{y} = \beta + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 \tag{1}$$

Where $\hat{y}$ is dependent response variable; x_1, x_2, x_3, x_4 are the input variables rail pressure, injection timing, charger pressure and charger temperature respectively.

2.4 Multi-objective optimization.

The multiple objective optimization has been formulated to a single objective problem by the weighted sum method which was defined as follows.

$$F_{\mathrm{ws}} = \sum_{i=1}^{n} w_i F_i(x_1, x_2, x_3, x_4) \tag{2}$$

Subject to:

$$\begin{aligned} & g_i(x_1, x_2, x_3, x_4) \le 0, i = 1, 2, \cdots k \\ & h_i(x_1, x_2, x_3, x_4) = 0,\ j = 1, 2, \cdots m \end{aligned} \tag{3}$$

Where F_{ws} is the objective vector; $F_i(x_1, x_2, x_3, x_4)$ is the *i*th objective to be minimizing or maximizing, w_i is the weights of *i*th objective; $g_i(x_1, x_2, x_3, x_4)$ is the inequality constraint condition; $h_i(x_1, x_2, x_3, x_4)$ is the equality constraint condition; (x_1, x_2, x_3, x_4) is the input variables.

The weights which represent the relative importance of the different objective are determined by the designers according to the optimization target.

3. Results and discussion

3.1 Multiple regression model validation.

To validate the predictive accuracy of regression model, 100 operating points which are generated by the quasi random sequence between upper and lower bounds. The points of uniform design (*star*) and points for validation (*circle*) are shown in Fig. 4. It can be seen that the points are all scatter evenly in the design space which can represent the overall status of the engine responses.

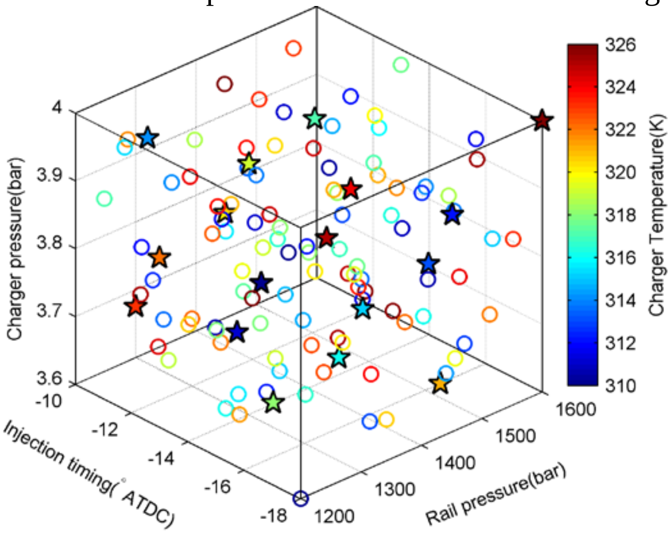


Fig. 4 Operating points of uniform design and validation

In order to evaluate the prediction performance of the regression models, the correlation coefficient (R), root mean square error (RMSE) and mean absolute percentage error (MAPE) are calculated between the predicted and target values which are defined respectively as follows:

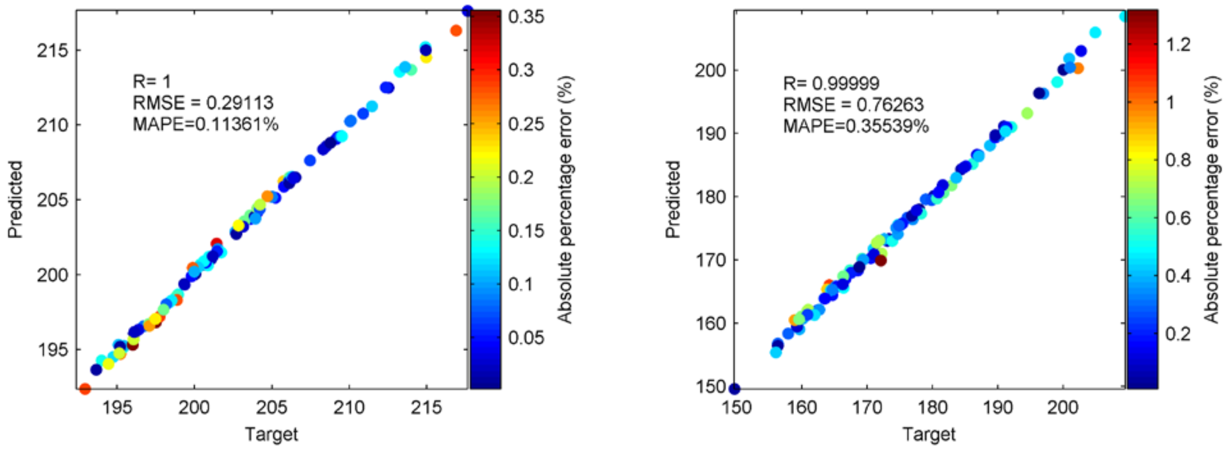
$$R = sqrt\left(1 - \left(\frac{\sum_{i=1}^{n}(t_i - o_i)^2}{\sum_{i=1}^{n}(o_i)^2}\right)\right) \tag{4}$$

$$RMSE = sqrt\left(\frac{1}{n}\sum_{i=1}^{n}(t_i - o_i)^2\right) \tag{5}$$

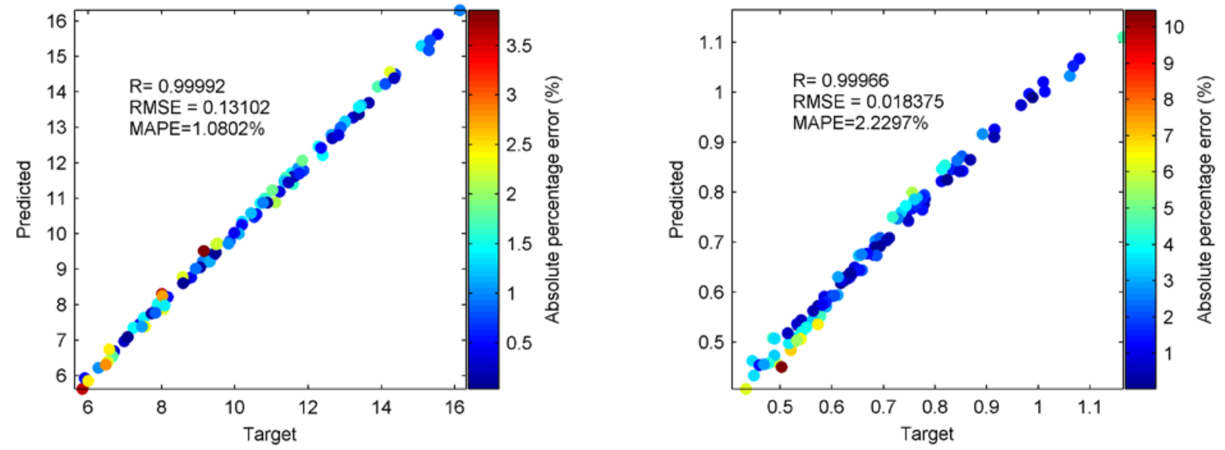
$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left(\left|\frac{t_i - o_i}{t_i}\right|\right) \times 100 \tag{6}$$

Where *n* is the number of points; *t* is the target value and *o* is the predicted output value.

Fig.5 shows the performance and accuracy of each regression model, it can be observed that the correlation coefficients of regression models are almost equal to 1, the root mean square error and mean absolute percentage error are very small, all these have well confirmed the accuracy of the models. Besides, the excellent performances of these regression models have revealed that the uniform design has a good performance and remarkable efficiency of developing predictive regression model for diesel engine study.



(a) BSFC (b) Max in-cylinder pressure



(c) NOx (d) Soot

Fig. 5 Comparison of predicted values and targets

3.2 Multi-objective optimization.

The main optimization purpose of this study is to find a better trade-off between NOx, soot emissions and break specific fuel consumption, and the max in-cylinder pressure is considered as a constraint condition. According to the 100 operating points of last subsection, the trade-off characteristics between NOx, soot and BSFC are shown in Fig.6.

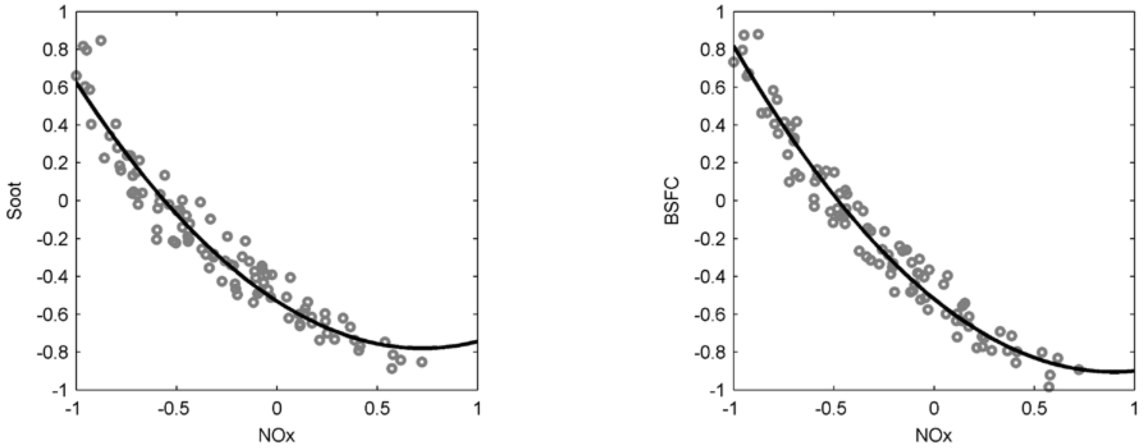
As shown in Fig.6, it can be observed that the decrease of the NOx emission always produces an increase in soot emission and BSFC, but soot emission and BSFC show a similar response trend, the reducing of the soot emission is always accompanied by the improvement of BSFC.

The optimization objective is defined as follow:

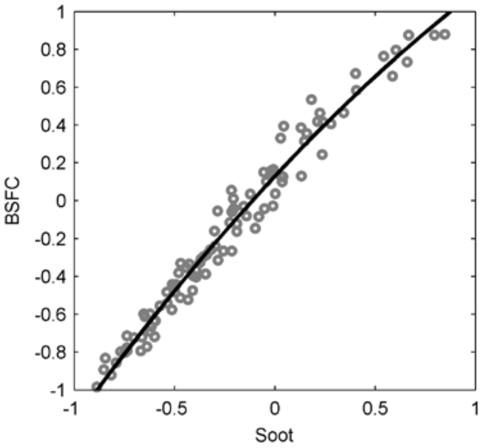
$$\begin{cases} \min(w_1 NOx + w_2 soot + w_3 BSFC) \\ Max\, incylinder\ pressure - limit \le 0 \end{cases} \tag{7}$$

Where w_1, w_2, and w_3, are the weighting value for each optimization objective, *limit* is the constraint value of max in-cylinder pressure.

The weights for the objectives can be suitably varied to meet the different desire of the engine designer. This paper has conducted four optimization objectives which are shown in Table 4.



(a) NOx-Soot (b) NOx-BSFC



(c) Soot-BSFC

Fig.6 Trade-off characteristics between NOx, soot and BSFC

Table 4 Optimization objectives

Objective	w_1	w_2	w_3	*Limit*
1	0.7	0.15	0.15	0.1938
2	0.15	0.7	0.15	0.1938
3	0.15	0.15	0.7	0.1938
4	0.5	0.25	0.25	0.1938

Fig. 7 shows the optimization results of these four objectives in Table 4, and the circles with smaller size are the engine responses of the 100 operating point which used for regression validation, these responses reveal the overall status of the engine responses in the study bounds. It can be observed that the multi-objective optimization with weighted sum method is an effective approach to find an optimal solution for engine performance and emissions optimization with trade-off relation.

It also can be seen that optimization results mainly depend on the proportion between weight of NOx and the weighted sum of soot emission and BSFC, and the proportion between soot emission and BSFC has very little effect on the optimization result as shown in Fig. 7 that the objective 2 and 3 are almost overlapped.

Finally, the optimization results are validated by the thermodynamic model, and Fig. 8 shows the comparison between the optimization values of each response parameter and the model test results. The comparison shows a good consistency between the optimization and test results.

When compares the response parameters of these four optimization objectives, it can reveal the trade-off characters between the responses. As shown in Fig. 8, the responses of NOx and max in-cylinder pressure also show a similar trend besides of the responses of soot and BSFC. And the comparison of four optimization objectives also proves that the weighted sum method can determine the relative importance of the different responses effectively.

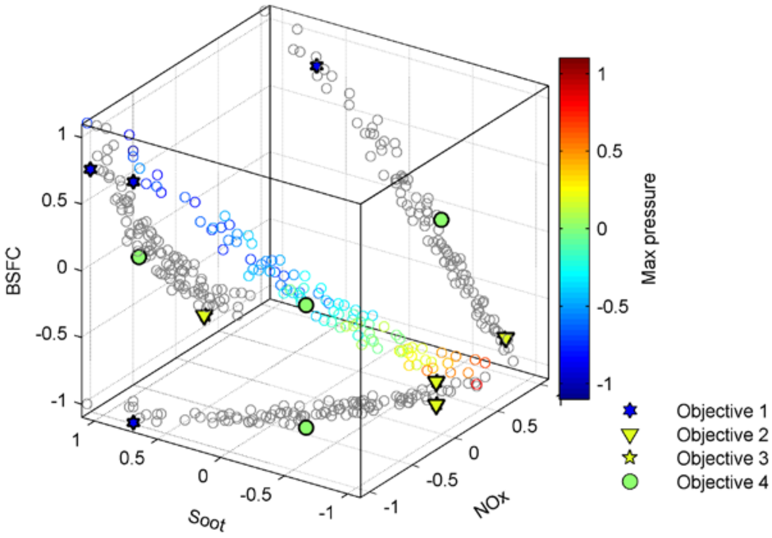


Fig.7 Optimization results of different objectives

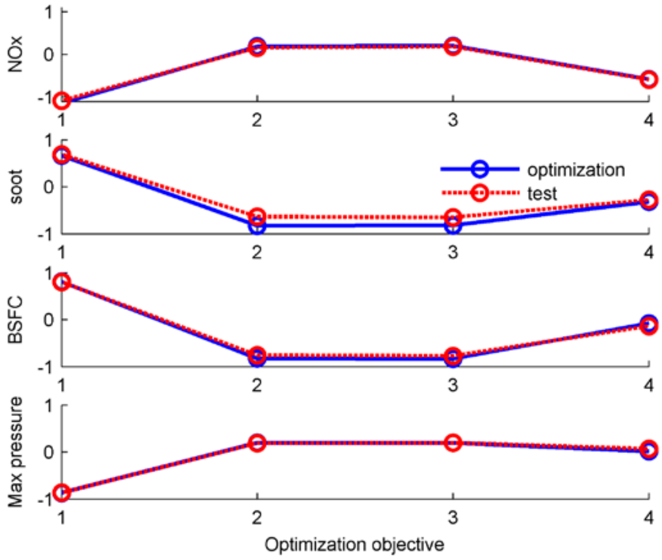


Fig.8 Comparison of optimization and model test results

4. Summary

The present study had integrated uniform design method and multi-objective optimization with weighted sum method for diesel engine performance and emissions optimization. Uniform design which could provide appropriate experimental data while minimizing the number of runs had shown a remarkable performance and efficiency for developing regression predictive model for diesel engine study. The trade-off characters of the optimization objectives NOx, soot emissions and BSFC had been analyzed, the improvement of NOx emission always accompanied by the penalization of soot emission and BSFC, but the soot emission and BSFC showed a similar trend. To find a unique solution which can optimized all the objectives at the same time according to the desire of the designers, the multi-objective optimization with weighted sum method had been conducted. And the analysis and validation of the optimization results had confirmed the feasibility and accuracy of this approach.

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