inter•noise 96
25th Anniversary Congress – Liverpool

INCE: 76.9

ANALYSIS OF INTERNAL COMBUSTION ENGINE NOISE AND EXHAUST EMISSIONS USING MULTIVARIATE METHODS

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1. INTRODUCTION

Future stricter regulations on engine noise and exhaust emissions requires comprehensive optimization with respect to all engine parameters influencing the combustion process. This means that an ever increasing number of parameters need to be considered simultaneously. This can preferably be performed utilizing statistically designed experiments (SDE). From SDE can valid models be determined which enable the engineer to assess technical trade-offs in the model, which is far less expensive then by experimentation[1]. In the area of internal combustion engine research SDE has not been applied to a large extent, although some of the recent published work have used Taguchis designs to identify the most important variables and most robust settings for minimization of exhaust emissions[2]. Less work has been focused on noise.

The sound level outside the engine can be obtained from the combustion pulse via the structural attenuation of the engine [3]. A different approach is to investigate the direct relationship between the combustion pulse, engine data, noise as well as and exhaust emission data. This can be accomplished with Principal Component Analysis (PCA) and Partial Least Square (PLS) regression. While PCA only is a help in evaluating the structure of the data, PLS can be a help in finding cause-effects relationship between data generated in statistically designed experiments. PLS has also the advantage that it can help in evaluation of inter-correlated predictor variables.

The aims of the present work were therefore to evaluate the applicability of SDE and multivariate evaluation to predict the noise level outside the engine as well as levels of exhaust emissions.

2. EXPERIMENTAL SET-UP AND PROCEDURE

The engine used for the experiments was a modified 11 litre, 6 cylinder, turbocharged and intercooled direct injection diesel engine operating on ignition improved ethanol. The ignition improver used was Avocet. Data acquisition was made with a HP 715/75 computer with a maximum sampling frequency of 132 kHz. For the cylinder pulse measurements, an optical sensor was used as a trigger signal to locate the position of the piston in the cylinder. Pressure was measured by an AVL QC31C-E transducer. The sound level was measured with 1/2" microphone (B&K). For exhaust analysis, a non-dispersive infrared instrument was used for carbon monoxide (CO) and carbon dioxide (CO_2). Hydrocarbons (HC) were measured using a heated flame ionisation detector (FID). Emissions of nitrogen oxide (NO) and the sum of NO and NO_2 (NO_x) were determined by a chemiluminescence instrument.

Factorial designed experiments were used, to enable identification of both main effect and interaction effects [4], with both noise and exhaust emissions as measured responses. The factors were, injection timing, (alpha, 9-13°), amount of Avocet (1-3 %), load (10-90 %) and speed (800-2000 rpm). To facilitate design and evaluation the computerprograme Modde version. 2.01 (Umetri AB, Sweden) was used.

Table 1 shows all variables used in the analyses, including the 4 designed factors. The measured variables were divided into three subgroups depending on the variables origin. The groups were combustion pulse, the engine data, and the exhaust emissions data.

They were examined individually and then analyzed together, in order to identify potential relations. The different test were run randomly, to avoid possible drift causing spurious correlations. The programe Simca version 5.1 (Umetri AB) was used to facilitate the PCA and PLS analysis.

Table 1: Variables used in the analysis (1357)		
Combustion pulse	**Exhaust emission data**	**Engine data**
1-1338 variables	HC, NO, NO_2, NO_x, CO and CO_2	Avocet, Alpha, Pressure after inter-cooler Temp before/after turbo,Power, Temp after Fuel flow, Load,Speed, Airflow,Load,Speed, Airflow,Exhaust gas flow, Sound level

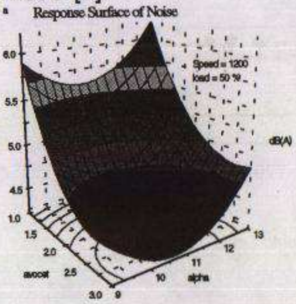
3. RESULTS AND DISCUSSIONS

Analysis of the designed experiment

Table 2 shows the scaled coefficients for the most significant factors. Scaled coefficients can be directly compared with each other, a large value indicate a strong influence, positive or negative. As could be expected, speed has the largest impact on noise. Load and amount of ignition improver (Avocet), also show some impact and only the square and interaction term with speed are significant for injection timing (alpha).

Table 2 : Significant scaled coefficients												
	speed(sp)	load(lo)	avocet(av)	alpha(al)	sp^2	lo^2	av^2	al^2	spxlo	spxal	loxav	Q^2
sound	4.44	0.81	-0.64	-			0.4		0.32	-0.4		0.93
logHC	0.25	-0.07	-0.11		0.2		0.12		-0.1		0.11	0.69
NO_x	6.51	130.3	-4.1	34.9	-30	22	12.7	15			15.7	0.89

Figure 1 indicates that the lowest sound level is obtained at 11°(alpha) and 2.3 % Avocet. Q^2 is a measure of the predictive capacity of the model [5].



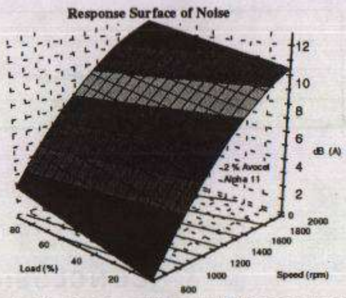


Fig. 1 : Sound Level Vs Alpha and Avocet *Fig. 2 : Sound Level Vs Speed and Load*

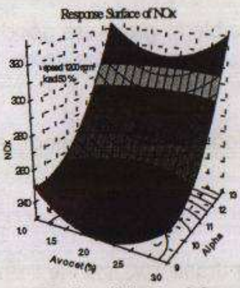


Fig. 3: NO_x Vs Alpha and Avocet

Fig 2: Shows the interaction effect between speed and load.

Fig. 3: Shows a minimum for NO_x at about 2.2 % Avocet and alpha 9 °.

Analysis of the total variable correlations

The PCA plots indicated that the sound level, airflow, exhaust gas flow and speed were correlated. It was noticed that load, NO, NO_x and power were also correlated.

Different PLS models with noise as Y and different variable groups as X-variables were then evaluated. The best model was obtained with only engine data (Q^2 0.93). The three groups combined resulted in a model with Q^2 of 0.84 as did the model based on only combustion pulse data (Q^2 0.84). The model based on only exhaust emission data gave the worst model (Q^2 0.67).

Validation of the prediction model: The best model (Q^2 0.93) was then validated both internally and externally. The internal validation was performed by splitting the data in two data sets, a learning set and a test set. To the external validation a new experimental data set was imported.

The model was proven to be good by both validation sets, and the difference between the observed and the predicted value was around 0.5-2.5 dB(A). See figure 4.

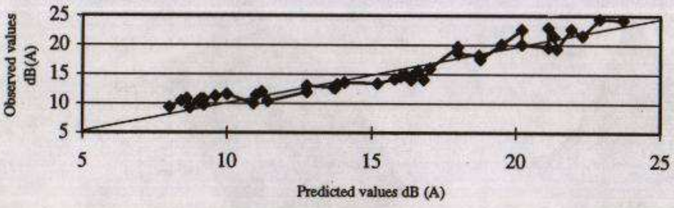


Fig. 4 : Observed Versus Predicted Sound Level

CONCLUSIONS

The noise and HC are mostly influenced by speed while NO_x emissions depends mostly on load.

By SDE and multivariate evaluation it was possible to generate good prediction models for noise and some exhaust components from the group of engine data.

The work has demonstrated the importance and applicability of experimental design and multivariate methods for modeling and minimization

ACKNOWLEDGMENT

The authors would like to acknowledge the support from Scania CV, and the financial support from the Swedish Transport and Communications Research Board (KFB) and the Swedish Work Environment Fund.

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