# EVALUATING THE DEGREE OF ANNOYANCE CAUSED BY IMPULSIVE NOISE TYPES

Disturbing impulsive noises occurring in combustion engines have a particularly detrimental effect on the perceived quality of vehicles and are sometimes misinterpreted by customers as defects. A tool for computing objective evaluations of such disturbing noises has been developed at the Institute for Combustion Engines (VKA) at RWTH Aachen University. By using modern methods of signal analysis to break down disturbing noises into individual noise types, even better results can be obtained than when evaluations are carried out by a jury.

AUTHORS

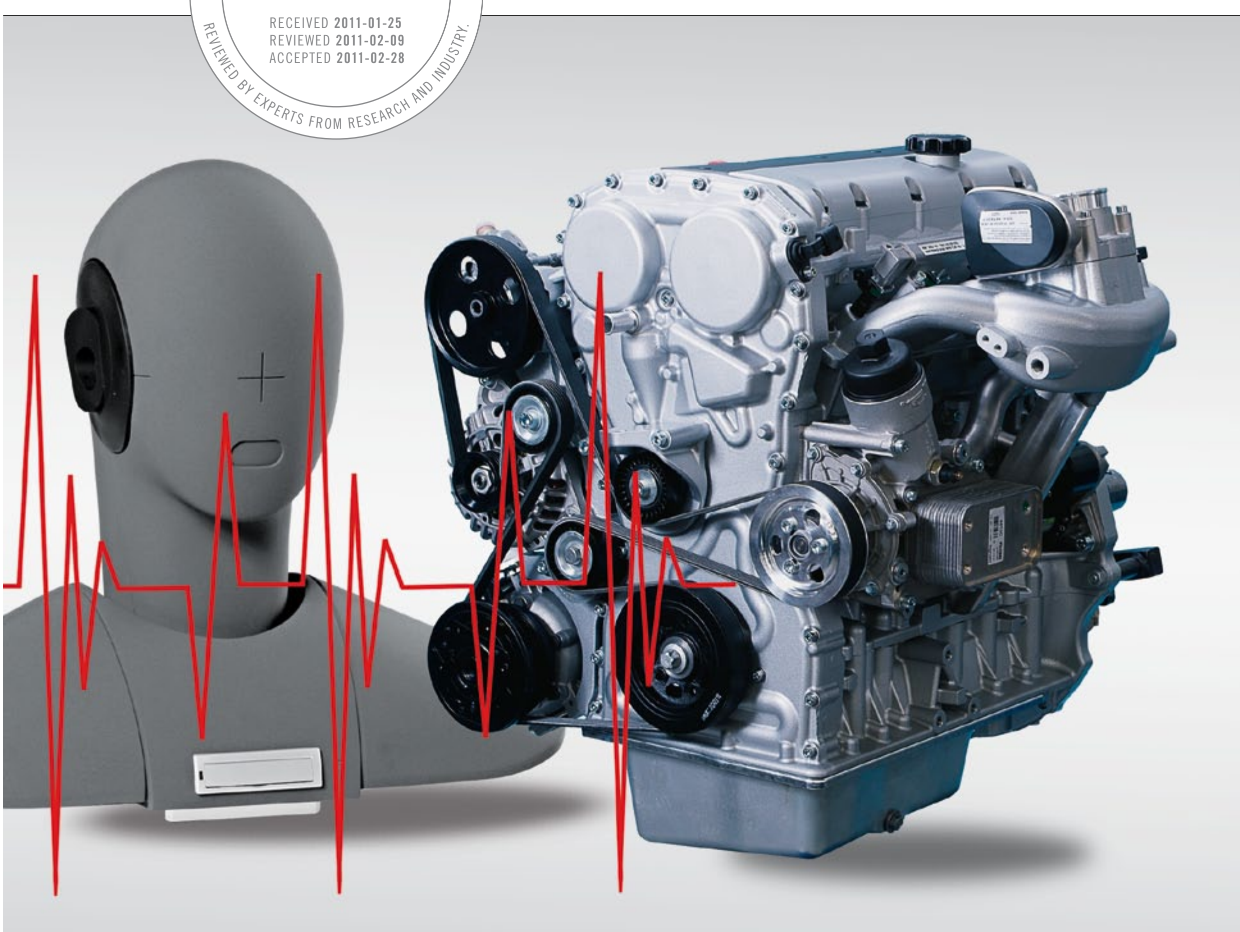
**DIPL.-ING. MARTIN ATZLER** is Research Associate at the Institute for Combustion Engines (VKA) at RWTH Aachen University (Germany).

**PROF. DR.-ING. STEFAN PISCHINGER** is the Director of the Institute for Combustion Engines (VKA) at RWTH Aachen University (Germany).

**DIPL.-ING. BERNHARD LANGE** was the Chairman of the FVV research project and works in the Department for Vehicle Acoustics at the International Technical Development Centre of Adam Opel AG in Rüsselsheim (Germany).

**DR.-ING. STEFAN HEUER** is Manager at the FEV Motorentechnik GmbH in Aachen (Germany).

THE SEAL OF APPROVAL FOR SCIENTIFIC ARTICLES IN MTZ.
MTZ
PEER REVIEW
RECEIVED 2011-01-25
REVIEWED 2011-02-09
ACCEPTED 2011-02-28
REVIEWED BY EXPERTS FROM RESEARCH AND INDUSTRY.



## 1 INTRODUCTION

The traditional method of evaluating noise quality during the development process of engines and motor vehicles is by means of subjective evaluations carried out by a jury. The disadvantages of these evaluations are that they are very time-consuming to conduct and the results are colored by the subjective impressions of the persons carrying out the evaluations. While acoustic analyses can be used to obtain objective ratings, these methods have previously been found to be of only limited value in the case of noises encompassing several simultaneously occurring impulsive noise types. The reason for this lies in the cross-sensitivity that arises from the fact that the noises concerned share similar characteristics [1]. Current methods therefore limit the validity range of the parameters to pre-defined operating conditions [2, 3]. At the Institute for Combustion Engines (VKA) at RWTH Aachen University, algorithms for analyzing the disturbing impulsive engine noises of knocking, ticking and rattling and general impulsiveness have been developed within the framework of an FVV research project. The use of modern methods of signal analysis enables a precise evaluation to be made by breaking the overall noise down into individual disturbing noises. The method of computation used enables a standardized evaluation to be carried out for stationary and transient noises regardless of such constraints as operating point or combustion process.

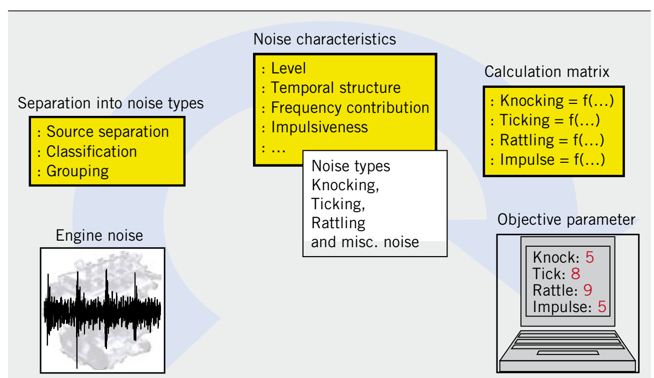
## 2 METHOD OF CALCULATION

In order to evaluate the individual disturbing noises, the overall noise is first separated into the following noise types: knocking, ticking, rattling and miscellaneous noise. The process developed in this project for splitting the overall noise into noise types represents a considerable innovation over the state of the art, since it enables the individual noises to be evaluated separately. In the next stage, the complex signals are reduced to a small number of characteristic noise attributes such as impulsiveness, temporal structure and frequency contribution. A calculation matrix describes the relationship between the attributes of the noise types and the objective parameters. This was determined by means of a regression analysis incorporating subjective evaluations carried out by a jury. The procedure for calculating the objective parameters is shown in ❶.

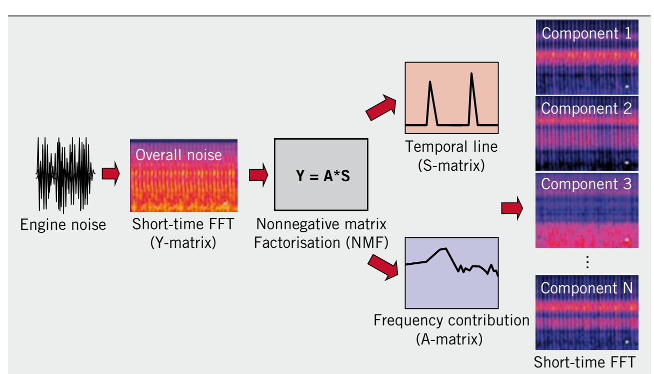
## 3 SEPARATION INTO NOISE TYPES

The separation into noise types is carried out in several stages. ❷ shows the blind source separation by means of Non-Negative Matrix Factorization (NMF) [4]. To this end, the engine noise is broken down into overlapping blocks and converted into the time/frequency domain by means of a short-time Fast Fourier Transform (FFT). The matrix obtained by the FFT is factorized into two matrices, A and S, by means of the NMF algorithm; the product of these two matrices is approximately equal to the source Y. Here, the S matrix represents the time line of the components and the A matrix their frequency contribution. In order to perform the splitting operation, the number of components N must be specified. Studies have shown that good results can be obtained for ten noise components. The short-time spectra of all NMF components are calculated by multiplying the individual vectors component by component. An inverse FFT is used to transform the spectra into the time domain and make each component audible. Since Non-Negative Matrix Factorization only produces an amplitude spectrum without phase information, the original phase of the overall noise is applied to all components. As is borne out by the literature, this produces good results for the noises generated [5, 6].

In the second stage, the NMF components are classified according to the type of disturbing noise. This classification is carried out by applying methods of signal theory analysis to extract specific attributes. These attributes are first selected on the basis of preliminary studies carried out with the aid of synthetic noises and definitely evaluated real engine noises. Here, it transpired that in order to break down the noise types, the noise levels, the spectral distribution and the regularity of the signal have to be taken into account. In order to determine class delimiters, the linear classi-




❶ Procedure for computing objective parameters




❷ Blind source separation of engine noises fication process is used on a training-dataset of samples, which have been definitely rated by a jury. The used procedure has the advantage that the resulting straight lines are simply comprehensible class delimiters. These can then be directly related to the engine acoustics and adjusted as necessary.

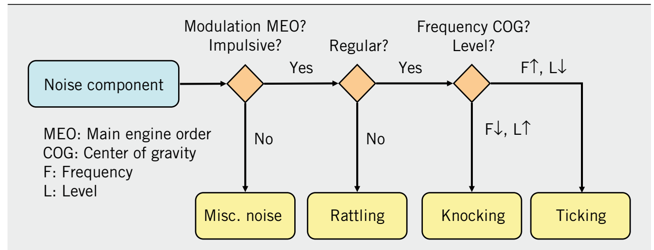
❸ shows the decision tree which is used to classify the NMF components. It represents the class delimiters determined on the basis of the training-dataset: If a component demonstrates no modulation with the main engine order and is not impulsive, it is assigned to the class of miscellaneous noise. If both characteristics apply, a decision is made on the basis of the autocorrelation function and degree of modulation as to whether or not it is an irregular rattling noise. The decision between knocking and ticking is based on the spectral center of gravity of the sound energy and the noise level.

The result of separating the noise into types is shown in ❹ for the noise of a diesel engine. For a combustion without pilot injection, the overall noise reveals strong impulsive components in the 1 kHz to 8 kHz frequency range. In the case of high-frequency components above 5 kHz, it is difficult to distinguish subjectively between the noise types of knocking and ticking. The objective separation method classifies distinct impulsive noises in the frequency range up to 8 kHz as knocking. Injector ticking is less pronounced and rattling is not registered.

The objective separation corresponds to the results for a variation of fuel injection, ❺. Pilot injection can considerably reduce diesel knocking. This also applies to the noise components in the high-frequency range, which are difficult to classify. Here, an advantage of the newly developed process becomes evident. While current methods classify all components in the frequency range above 5 kHz as ticking [7], the new procedure allows a more precise differentiation to be made. The results of the separation can be confirmed by listening to the noise components classified as knocking and ticking.

## 4 DETERMINING THE CALCULATION RULES

In order to determine the calculation rules, the number of input variables is limited to a small number of characteristic attributes. In order to select the attributes and to develop the appropriate methods of signal analysis, insights were drawn from the literature and from the studies carried out in the context of this project. It has been demonstrated that noise level, impulse amplitude and rate of repetition have a significant effect on the subjective impression. Attributes and analytical methods are selected and re-




❸ Decision tree for classifying noise components

fined in order to produce a high coefficient of determination in the regression and to reflect known facts about engine acoustics.

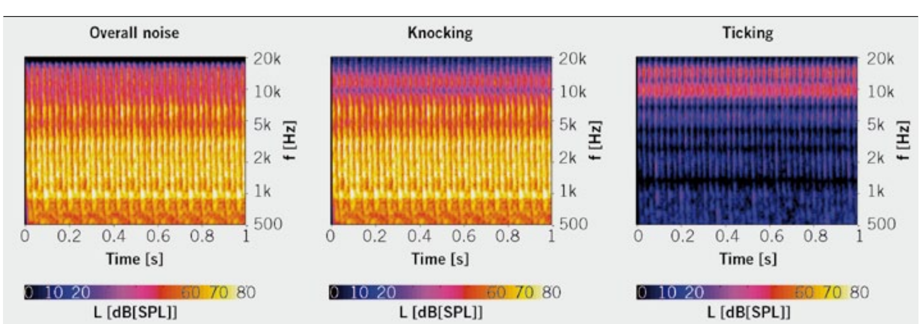
The computation of the objective parameters is based on a regression model. It describes the relationship between the extracted noise attributes and the subjective ratings of the jury. The evaluation of the disturbing noise is carried out on the basis of standardized parameters independently of constraints such as engine speed or combustion process. In order to minimize the effect of uncertainties in the jury, a selection is made from a data set of 150 engine noises. Only such noises are included which have on the one hand been uniformly evaluated by a jury and which on the other hand contain only small proportion of other types of disturbing noise.

❻ shows the results of the regression analysis for the noise type "knocking". The deviation between jury evaluation and parameters is less than one rating point for all noises; the coefficient of determination $R^2$ is 0.86. This can be considered a good result, especially in view of the fact that standardized parameters are used irrespectively of engine speed, load and engine size. The parameters are calculated by means of the following equation:

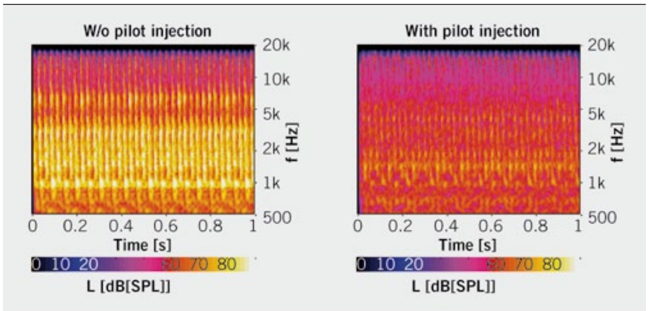
**EQ. 1**

$$Y_K = 20.35 - 0.17 * \frac{L_A}{\text{dB(A)}} + 0.1 * \frac{L_{Diff}}{\text{dB(A)}} - 0.19 * \frac{L_I}{\text{dB}} - 0.11 * \frac{\Delta t_I}{\text{ms}} - 2.93 * Mod_{0.5EO}$$

The rating $Y_K$ is made up of a constant component, the noise level for the noise type knocking $L_A$ in dB(A), the difference between the noise level and the overall noise $L_{Diff}$ in dB(A), the impulse level $L_I$ in dB, the interval between two consecutive impulses $\Delta t_I$ in ms and the dimensionless half engine order modulation $Mod_{0.5EO}$.




❹ Separating the noise of a diesel engine into noise types




❺ Noise for the variation of fuel-injection


❻ Regression for the noise type "knocking"

The impulse level was developed within the framework of the research project. The calculation bases on the autocorrelation function of the signal and it describes the ratio between the correlated power of the impulses and the non-impulsive noise share. With the exception of the difference level, all parameters have a negative coefficient, i.e. higher values give a poorer evaluation. The calculation rules for ticking and rattling were developed in a similar way to the example shown.

In addition to stationary noises, the process developed in this project can also evaluate prolonged transient noises. For reasons of computing efficiency and memory limitations, it is not possible to use the NMF algorithm for long noise signals. In the case of prolonged noises, the input signal is therefore divided into short blocks of 4 s each with an overlap of 50 %. A quasi-stationary result is computed and stored for each block. The initial engine speed is entered as an input variable and the subsequent speed curve is calculated on the basis of the noise signal. This means that it is not necessary to record the engine speed during the measurement.

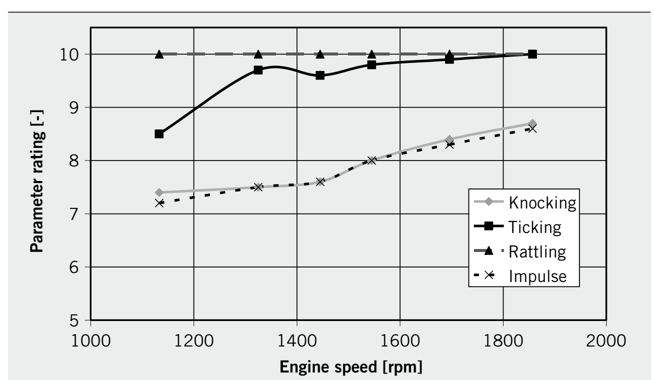
The output of the objective parameters takes place in the form a function plotted against time and can be exported together with the calculated engine speed curve. For example, ❼ shows the curves calculated for the objective parameters of transient noises depicted as a function of the engine speed during run-up. The individual noise blocks for the noise types knocking, ticking, rattling, miscellaneous noise and overall impulse noise can be combined and exported as audio files. In addition, minimum values and mean values are exported as characteristic parameters for the purposes of evaluating the overall transient noise.

## 5 EVALUATION OF THE CALCULATION METHOD

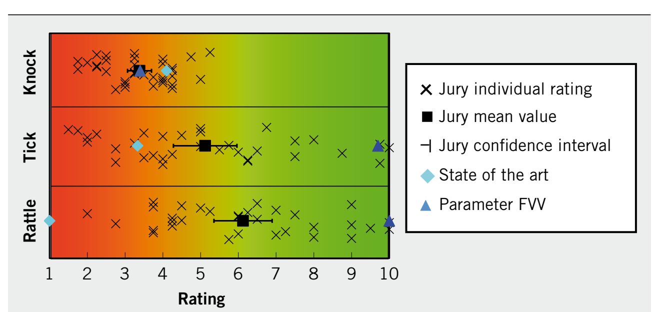
For the purposes of regression analysis, uniformly evaluated noises with a predominant disturbing noise are used. The method of calculation produces good results for these noises, with deviations amounting to less than one rating point. The extent to which the method developed is suitable for the evaluation of any form of unknown noise was investigated by means of a blind test. This database contains engine noises with pronounced impulsiveness but different characteristics. These noises were not used for determining the calculation matrices and therefore act as a measure of the prediction quality and robustness of the parameters.

As an example, ❽ shows the evaluation for the noise of a diesel engine running at medium speed. The chart shows the individual evaluations of the subjects (black crosses), the mean values of the subjective evaluations (black squares) and the extent of the 95 % confidence interval as a measure of the deviation amongst the individual evaluations. The objective parameters calculated according to the current state of the art (light blue diamonds) [1] are shown in comparison to the new calculation indices (dark blue triangles).

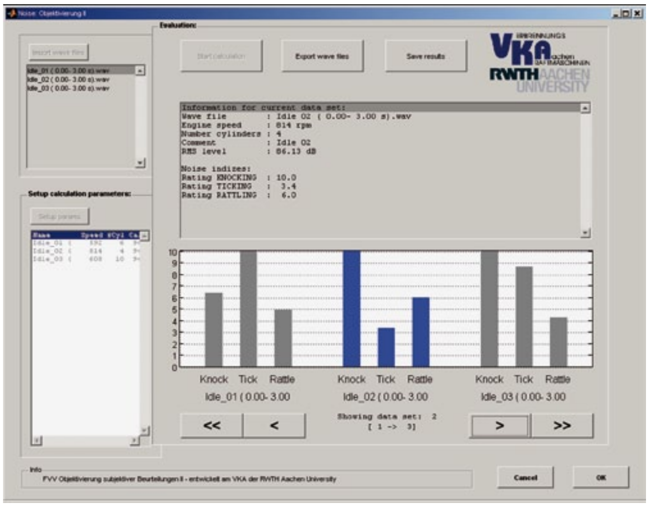
The jury's uniform evaluation of the knocking noise is accurately depicted by both parameters. For the non-uniformly evaluated ticking and rattling noises, greater differences are observed. While parameters based on the current state of the art produce ratings of 3 and 1 respectively as a result of cross-sensitivity to knocking, the parameters developed in this research project are non-sensitive and give these noises a rating of 9.5 and 10 respectively.




❼ Evaluation of transient noises




❽ Blind test of the objective parameters




❾ Graphical user interface

Compared to the current state of the art, the cross-sensitivity between the various types of disturbing noise was considerably reduced while prediction quality was high. It is evident that the new method understandably produces some greater deviations in the case of indistinct noises. This effect is rated positive because the new procedure, based on a strict separation into noise types, is outperforming a reproduction of a jury's mean value. The performed separation and evaluation could be verified by listening tests of the separate noises, carried out by the work group supporting this project and consisting of acoustics experts.

## 6 CALCULATION TOOL

The method developed was implemented in the form of a calculation tool with a graphic user interface, ❾. This contains the algorithms for blind source separation, extraction of characteristic attributes and classification according to noise types, determination of noise attributes by means of modified analytical methods and the subsequent computation of the objective parameters. The application therefore requires no additional analysis programs.

The audio files for the engine noises, recorded at a distance of 1 m, are imported in WAV format. The results of the calculations are depicted in the form of bar graphs in the display pane. In addition, the results and the composition of the ratings from the various parameters can be stored in tabular form. Beside the evaluations for knocking, ticking and rattling noises, a value is also calculated for the overall annoyance level of impulsive noise. The separate noise type instances can be exported as audio files in WAV format.

## 7 SUMMARY

The method presented in this article enables objective ratings to be obtained for the impulsive disturbing noise components of stationary and transient noises of combustion engines. As an important innovation compared with the current state of the art, it separates the overall noise into the noise types of knocking, ticking, rattling and miscellaneous noise. This enables a robust evaluation to be made even if different types of disturbing noise occur at the same time. This can be regarded as a very good result especially in view of the fact that standardized parameters are used irrespectively of engine speed, load, combustion process and engine size.

Evaluating the calculation method by means of a blind test reveals high prediction quality with a considerably lower degree of cross-sensitivity than is known for the state of the art. The output of individual noise types as audio files represents a further innovation. By listening to the separated disturbing noises, the work group supporting the project and consisting of acoustics experts were convinced that the method of calculation not only reproducibly emulates a jury evaluation. It even outperforms the same by selectively addressing the characteristics typical of the noises evaluated. In the case of noises which had not been uniformly evaluated by the jury, it was possible to perform a distinct and reproducible classification according to noise type. This represents a considerable benefit for practical application.

The new approaches developed within the framework of this project offer potential for solving further scientific tasks. Accordingly, the Institute for Combustion Engines will in future extend the method to tonal and hissing noises. In a further research project, cylinder pressure signals will be used to predict audible engine noises.

### REFERENCES

**[1]** Pischinger, S.; Lange, B.; Heuer, S.; Hoppermanns, J.: Objektivierung subjektiver Geräuschbeurteilungen. In: MTZ 67 (2006), No. 11
**[2]** Ingham, R.; Otto, N.; McCollum, T.: Sound Quality Metric for Diesel Engines. SAE Technical Paper Series 1999-01-1819, 1999
**[3]** Heinrichs, R.; Bodden, M.: Perceptual and Instrumental Description of the Gear Rattle Phenomenon for Diesel Vehicles. 6th International Congress on Sound and Vibration, 1999
**[4]** Lee, D.D.; Seung, H.S.: Algorithms for Non-Negative Matrix Factorization. Neural Information Processing Systems, 2000
**[5]** Smaragdis, P.: Non-Negative Matrix Factor Deconvolution: Extraction of Multiple Sound Sources from Monophonic Inputs. International Symposium on Independent Component Analysis and Blind Source Separation (ICA), 2004
**[6]** Virtanen, T.O.: Monoaural Sound Source Seperation by Perceptually Weighted Non-Negative Matrix Factorization. Technical Report, Tampere University of Technology, Institute of Signal Processing, 2007
**[7]** Pischinger, S.; Lange, B.; Hoppermanns, J.: Objektivierung subjektiver Geräuschbeurteilungen. Abschlußbericht FVV Forschungsvorhaben No. 841, 2006

## THANKS

This article is the academic result of a research project assigned by the Forschungsvereinigung Verbrennungskraftmaschinen e.V (FFV), Frankfurt and carried out at the Institute for Combustion Engines at RWTH Aachen University (VKA) under the directorship of Professor Stefan Pischinger. The work was supported by finance from the FVV's own funds. The project was assisted by a work group of the FVV under the supervision of Dipl.-Ing. Bernhard Lange of Adam Opel AG. Our thanks are due to this work group for its considerable support.