Correlations Adaptation for Optimal Emissions Prediction

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Correlations Adaptation for Optimal Emissions Prediction

- Emissions correlations types
- Predicting capabilities of existing emissions correlations
- Adaptation of emissions correlations to measured data
  - o Adaptation through scaling
  - o Adaptation through optimization methods
- Establishment of generic correlations through multivariate analysis
- Adaptive performance models & emissions predictions
- Summary - Conclusions

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Emissions Correlations Types

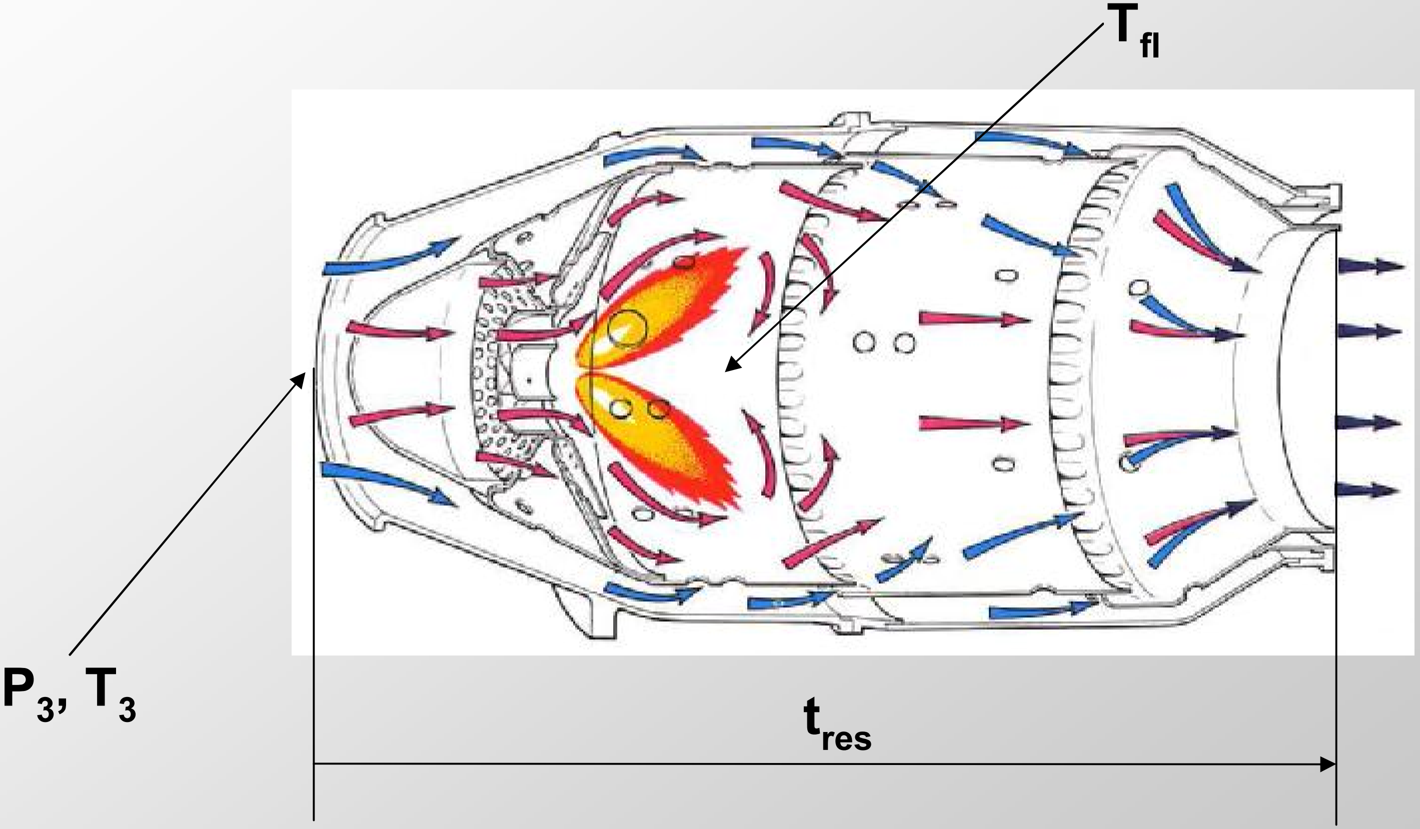
- **In most cases, emissions correlations are established through the analysis of measured data of a specific gas turbine or combustor.**

- **Most attention is given to nitrogen oxides (NOx) since they have a greater environmental impact**

- **Correlations published in open literature can be classified in two main classes: (a) Direct prediction, and (b) Ratio type**

Emissions Correlations Types

Characteristic Cycle Variables that Affect Emissions



Emissions Correlations Types

- **Direct prediction correlations use a number of cycle variables along the engine**

Odgers & Kremtcher $EINO_X = 29 \cdot e^{\left\{\frac{-21670}{T_{fl}}\right\}} \cdot P_3^{0.66} \cdot \left[1 - e^{\left\{-250 \cdot t_{form}\right\}}\right]$

- **Ratio type correlations use reference values of certain cycle variables**

Dopelheur & Lecht $\frac{EINOx}{EINOx_{ref}} = \left(\frac{P_3}{P_{3,ref}}\right)^{0.5} \left(\frac{T_{3,ref}}{T_3}\right)^{0.5} \left(\frac{T_{pz,ref}}{T_{pz}}\right)^{1.5} e^{\left[38000 \cdot \left(\frac{1}{T_{fl,ref}} - \frac{1}{T_{fl}}\right)\right]}$

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Predicting Capabilities of Existing Correlations

- **A large number of semi-empirical correlations have been identified in open literature**

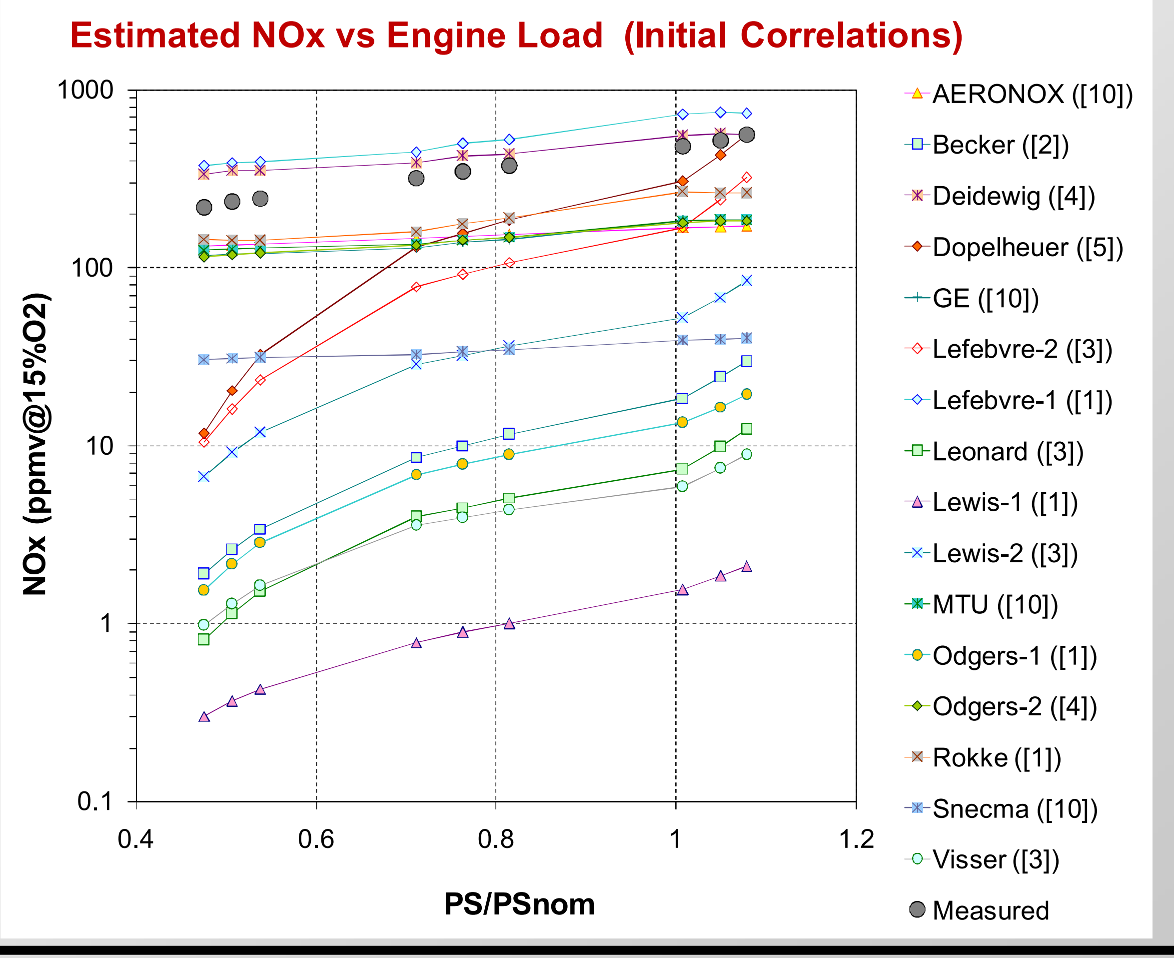
- **The predicting capability of the collected correlations has been assessed through their application in two cases:**

  - **An industrial single shaft gas turbine (Siemens V64-3)**

  - **A military turbojet engine (ATAR -101F2)**

Predicting Capabilities of Existing Correlations

Predicted and Measured NOx of the Industrial Gas Turbine



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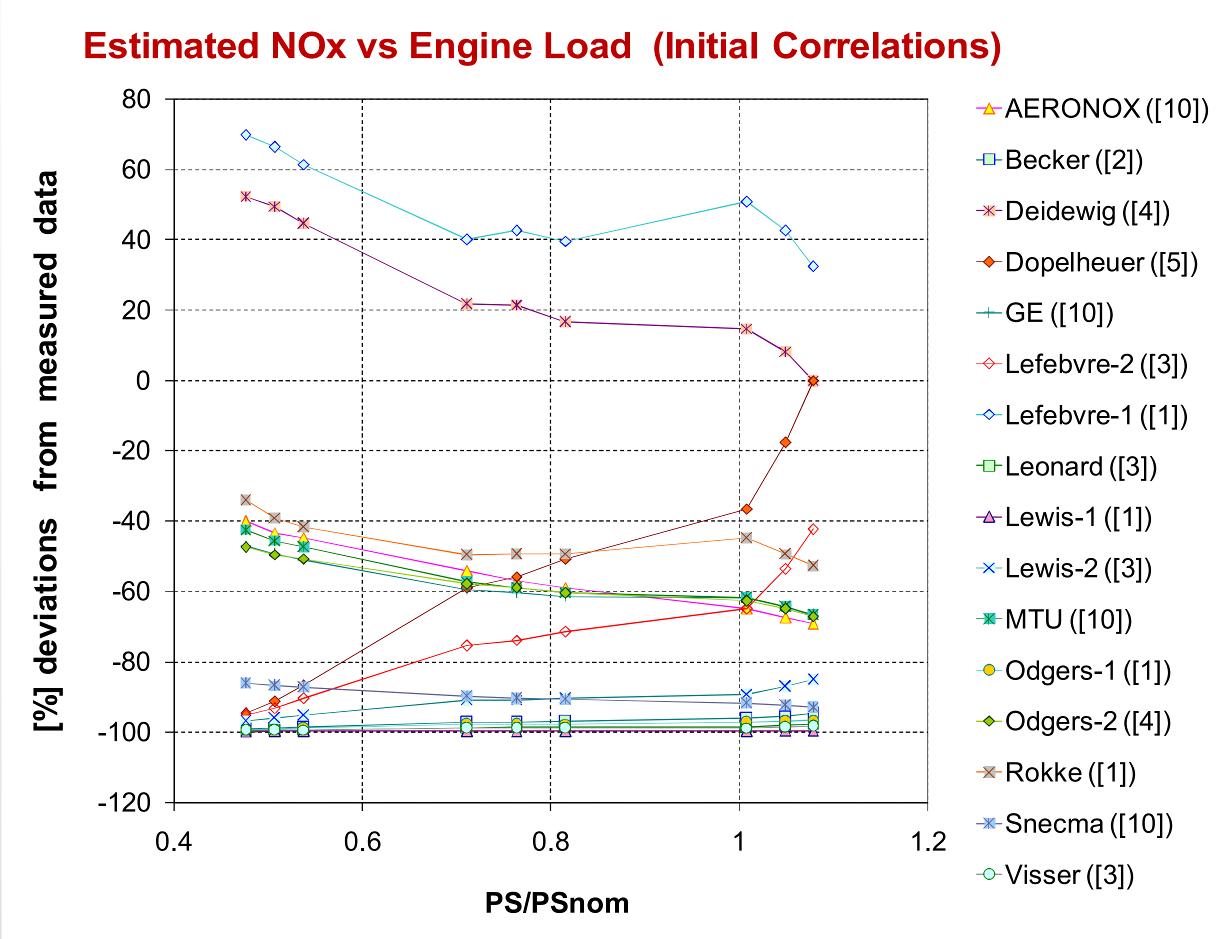
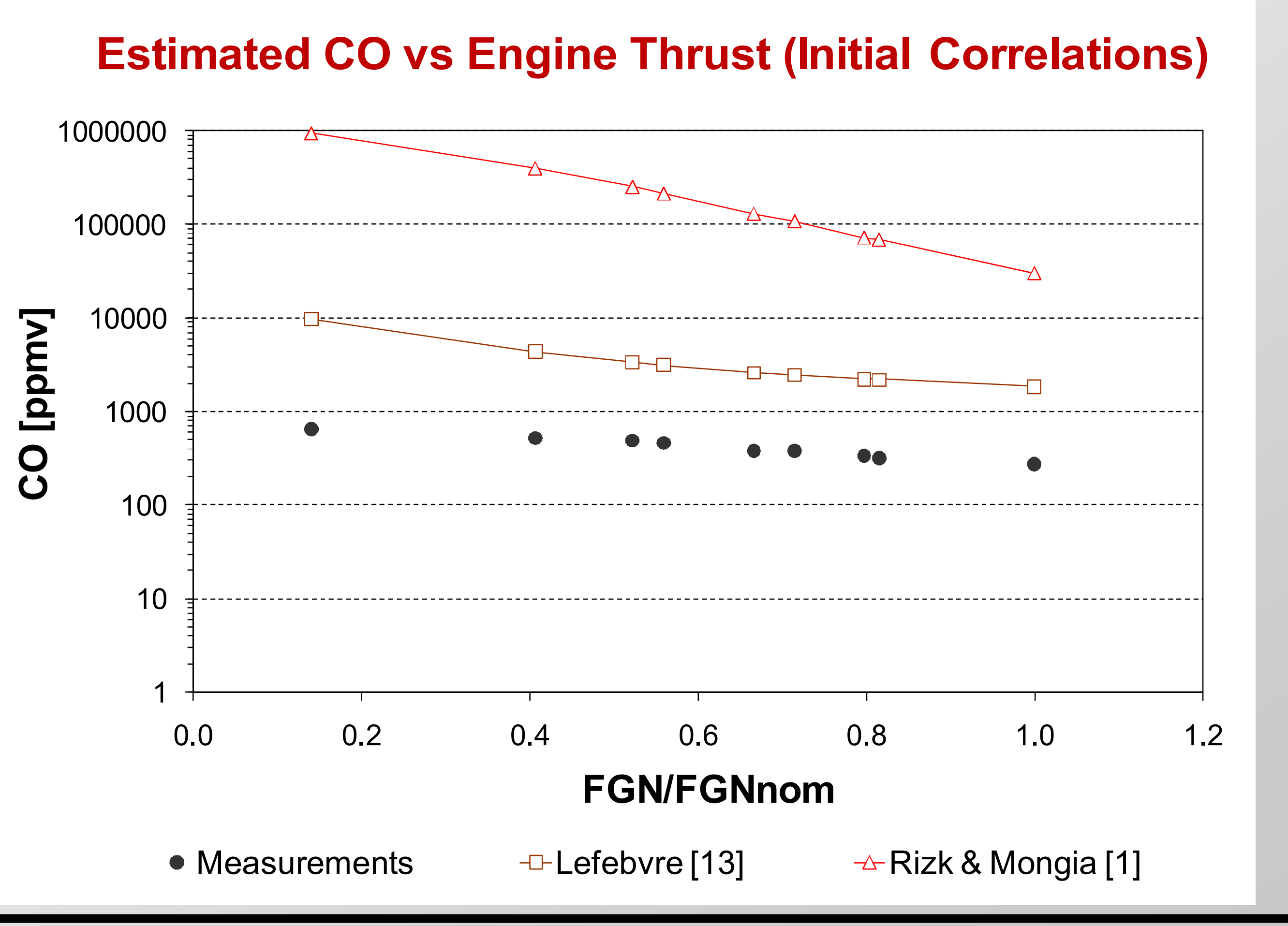
Predicted and Measured NOx of the Industrial Gas Turbine



Predicting Capabilities of Existing Correlations

Predicted and Measured CO of the Military Turbojet



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Emissions Adaptation Through Scaling

- **Emissions correlations predictions are 'scaled' with a multiplier coefficient so that the average of the scaled emissions is closer to the actual one**

$$C_{mult} = \frac{\sum_{i=1}^{n} e_i^{pred} / e_i^{meas}}{n}$$

e^{meas} : measured emissions

e^{pred} : predicted emissions

n : number of experimental data points

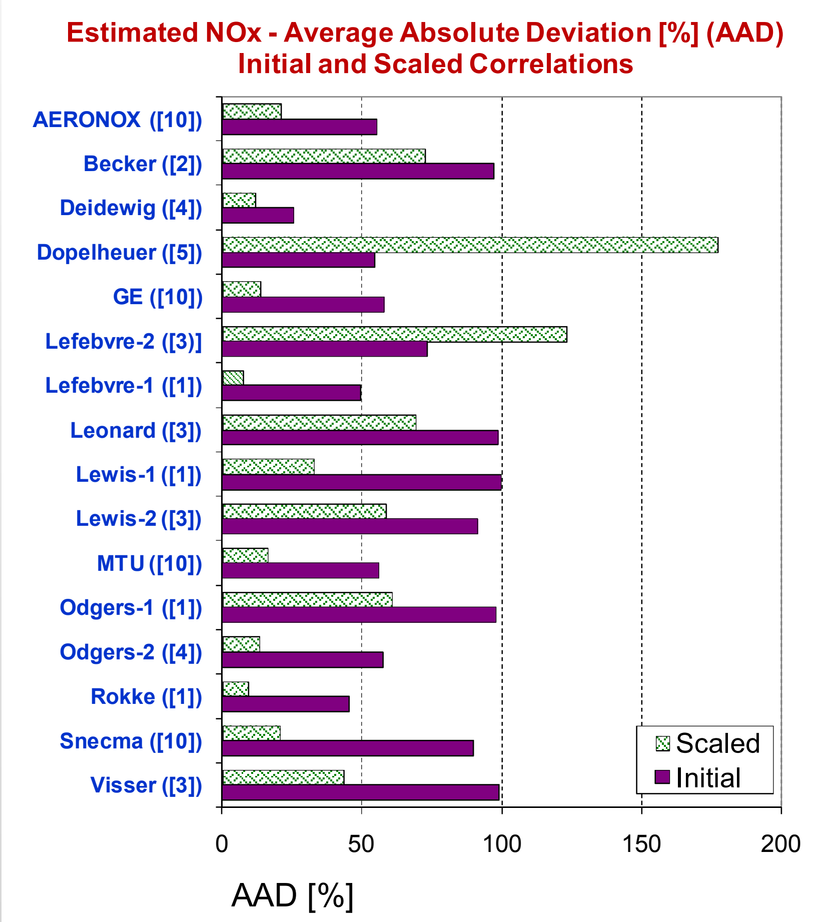
Emissions Adaptation Through Scaling
Industrial Gas Turbine Test Case

$$AAD = \frac{\sum_{i=1}^{n} \left| \left(e_i^{pred} / e_i^{meas} - 1 \right) \right|}{n}$$

e^{meas} : measured emissions

e^{pred} : predicted emissions

n : number of experimental data points



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Emissions Adaptation Through Optimization Methods

Adaptation coefficients are introduced in emissions correlations

Direct Type Correlation (Odgers & Kretchmer)

$$EINO_x = a \cdot 29 \cdot e^{\left\{\frac{-b \cdot 21670}{T_{fl}}\right\}} \cdot P_3^{c \cdot 0.66} \cdot \left[1 - e^{\left\{-d \cdot 250 \cdot t_{form}\right\}}\right]$$

Cycle Variables	Adaptation Coefficients
P_3, T_{fl}, t_{form}	a, b, c, d

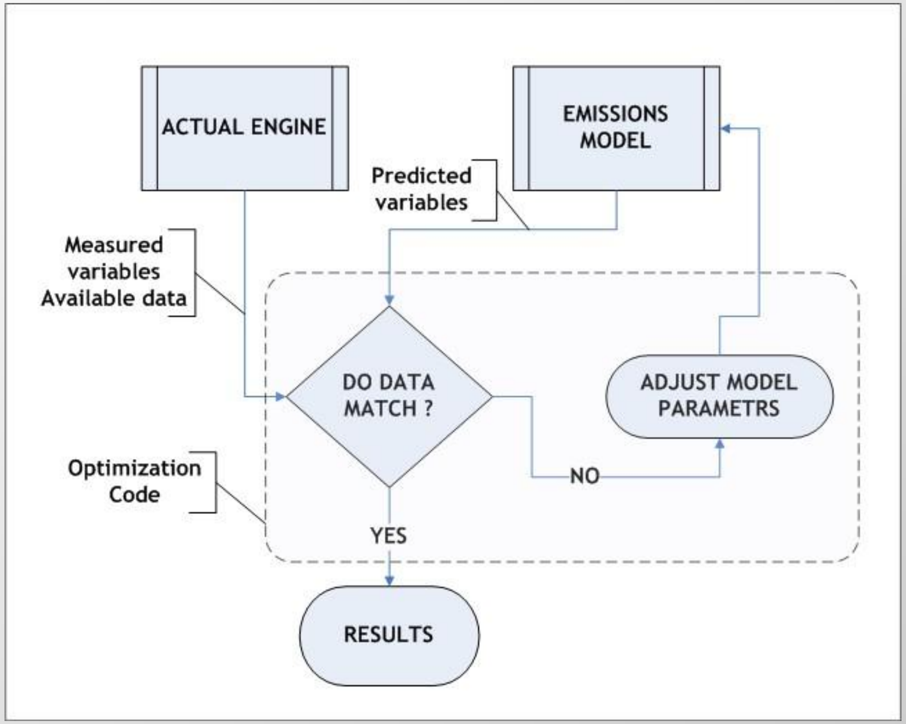
Ratio Type Correlation (Dopelheur & Lecht)

$$\frac{EINO_x}{EINO_{x_{ref}}} = a\left(\frac{P_3}{P_{3_{ref}}}\right)^{b \bullet 0.5}\left(\frac{T_{3_{ref}}}{T_3}\right)^{c \bullet 0.5}\left(\frac{T_{pz_{ref}}}{T_{pz}}\right)^{d \bullet 1.5} e^{\left[f \bullet 38000 \cdot \left(\frac{1}{T_{fl,ref}} - \frac{1}{T_{fl}}\right)\right]}$$

Cycle Variables	Adaptation Coefficients
P_3, T_3, T_{pz}, T_{fl}	a, b, c, d

Emissions Adaptation Through Optimization Methods

Adaptation coefficients estimation through the minimization of appropriate cost function (CF)

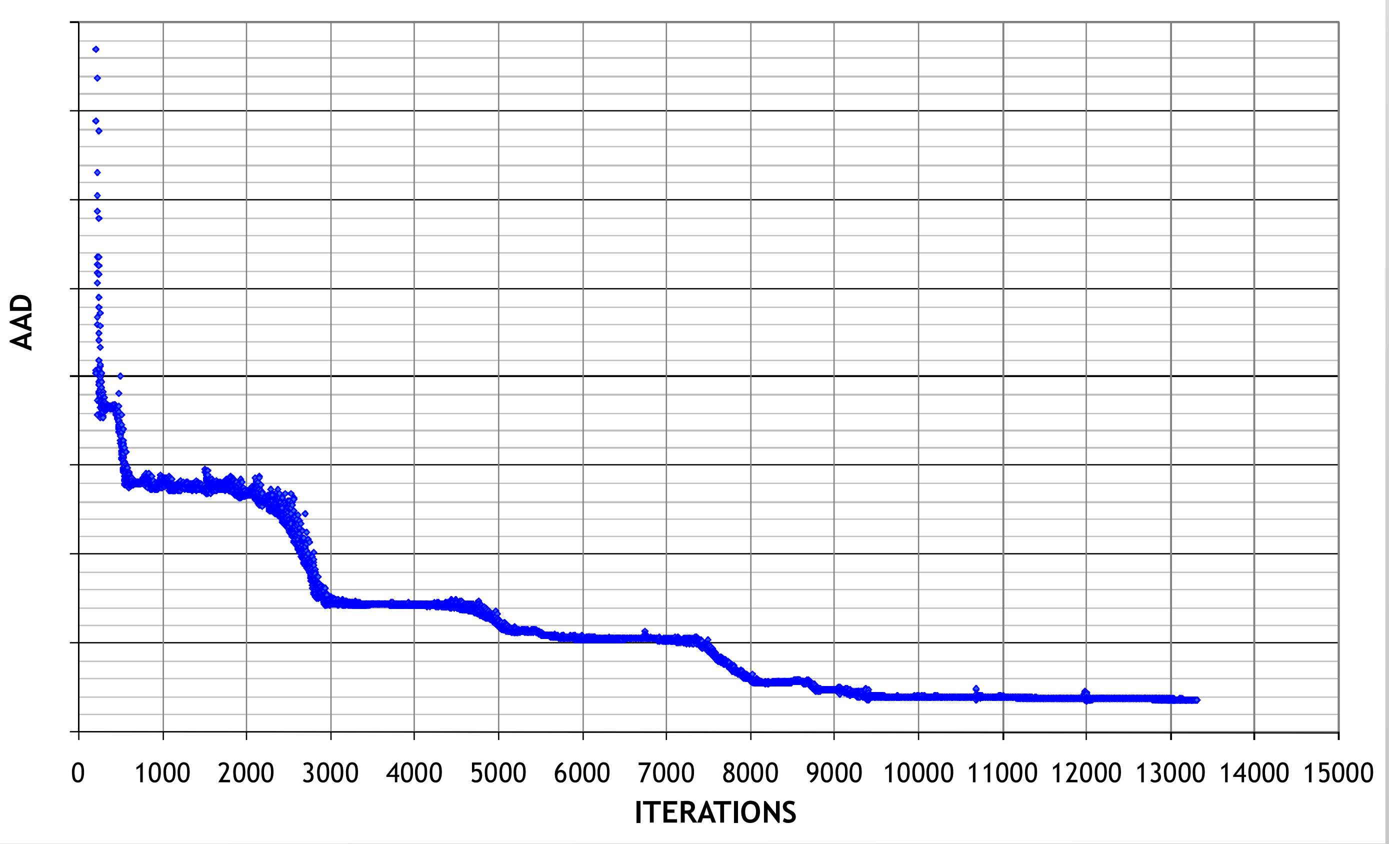


Employed Cost Function $$CF = \sum_{i=1}^{i=n} \left[\left(e_i^{pred} - e_i^{meas} \right) \cdot w_i \right]^2$$

Emissions Adaptation Through Optimization Methods

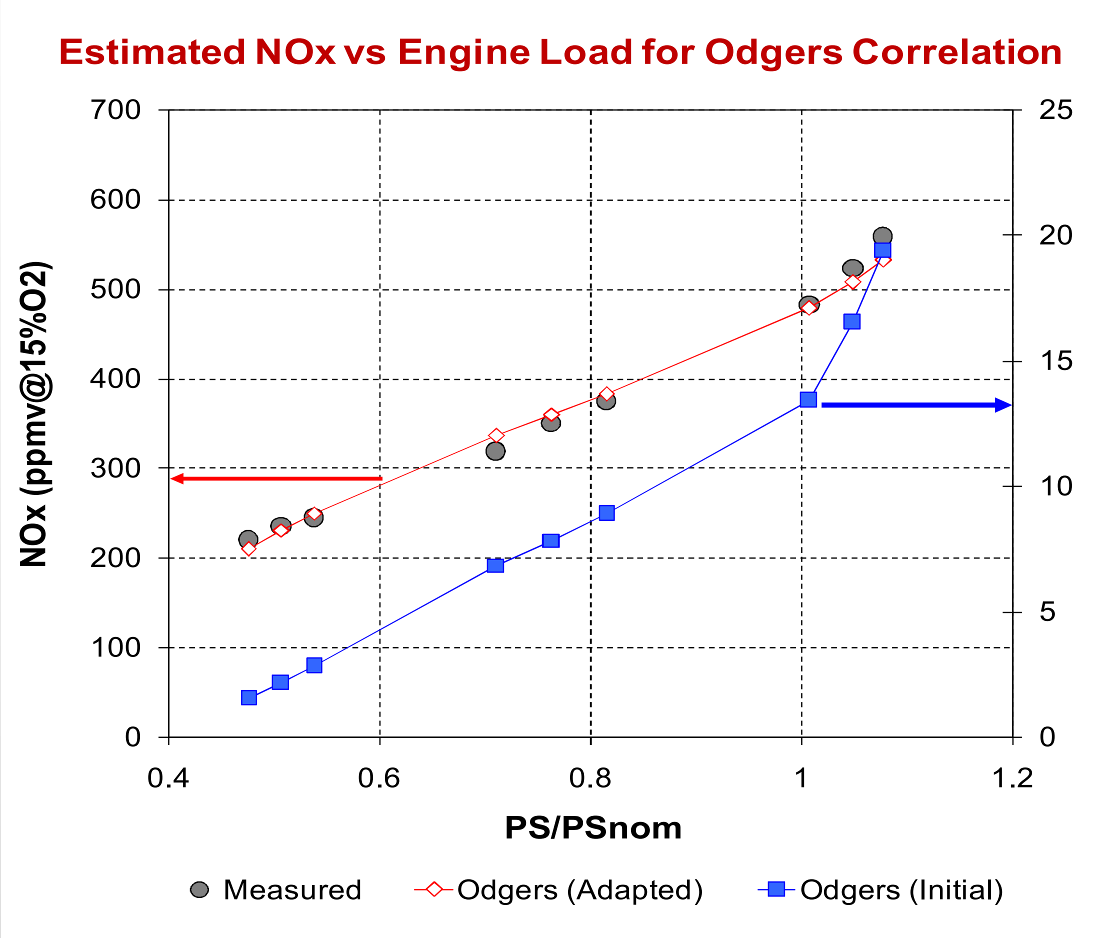
Convergence History Example

Adaptation of NOx Correlation to Industrial Gas Turbine Data



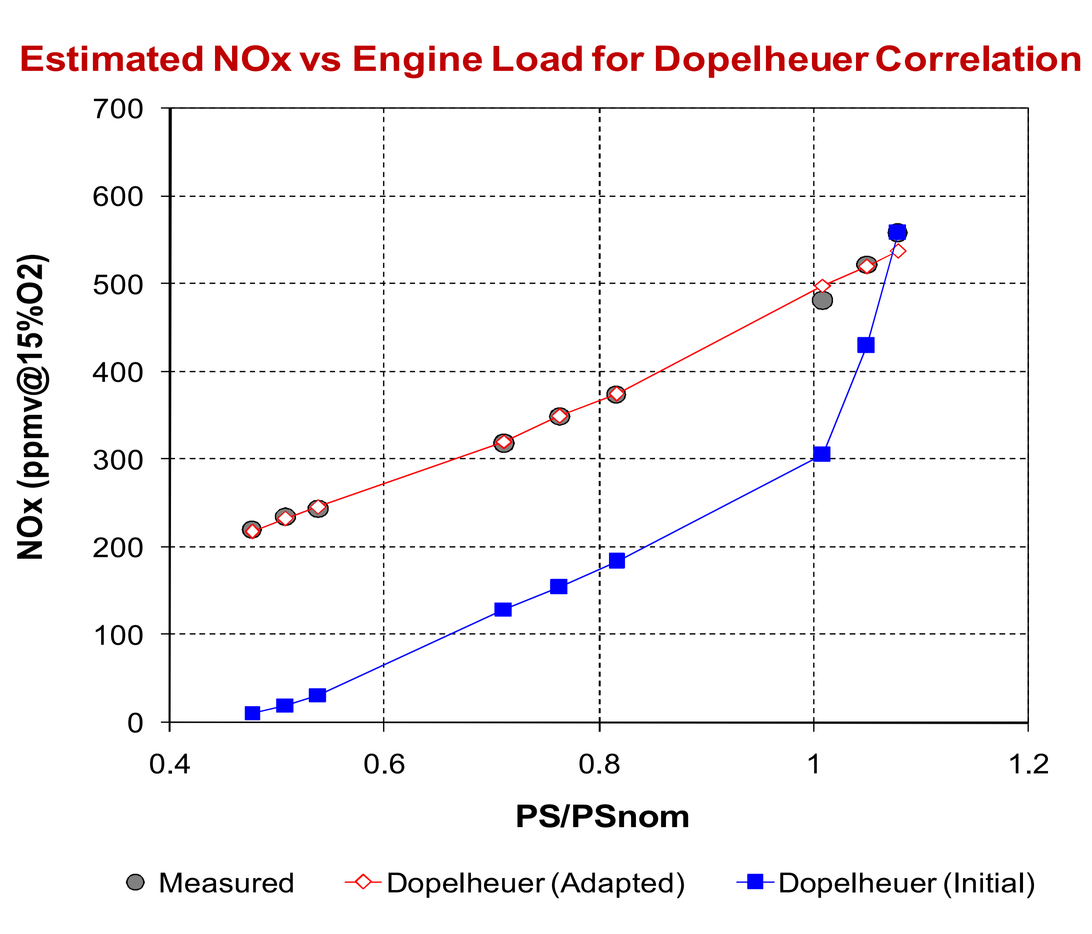
Emissions Adaptation Through Optimization Methods

Predicted and Measured NOx of the Industrial Gas Turbine



Emissions Adaptation Through Optimization Methods

Predicted and Measured NOx of the Industrial Gas Turbine



Emissions Adaptation Through Optimization Methods

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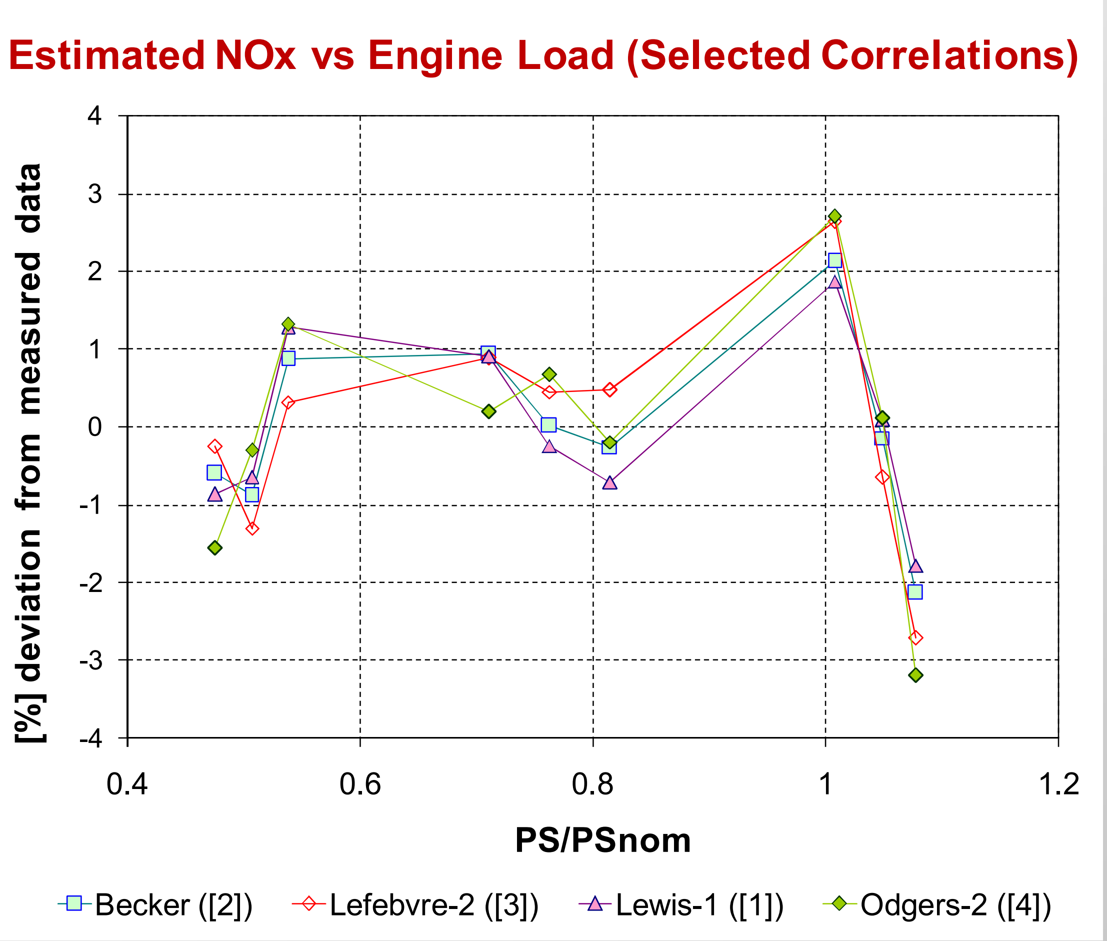
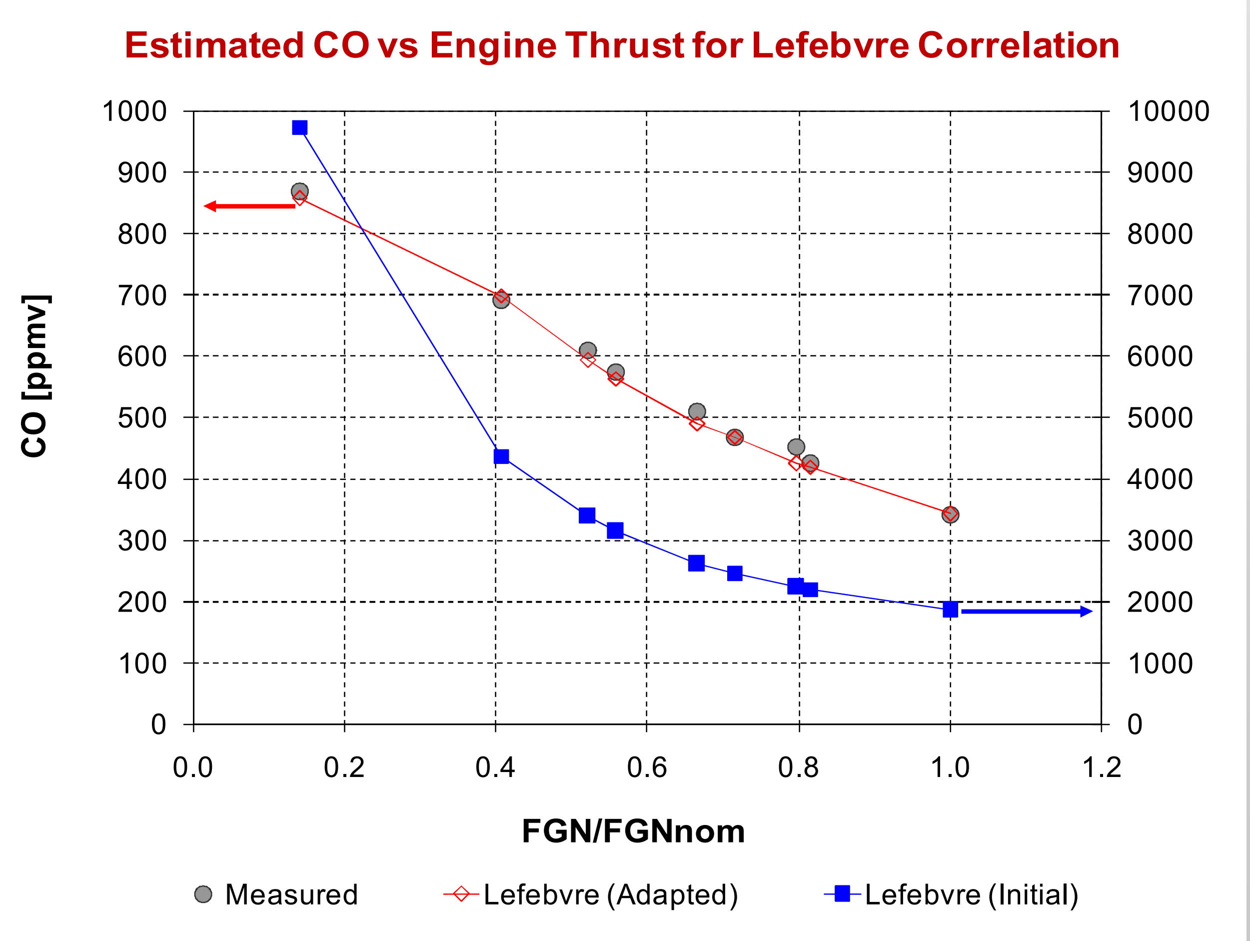


Emissions Adaptation Through Optimization Methods

Predicted and Measured CO of the Military Turbojet



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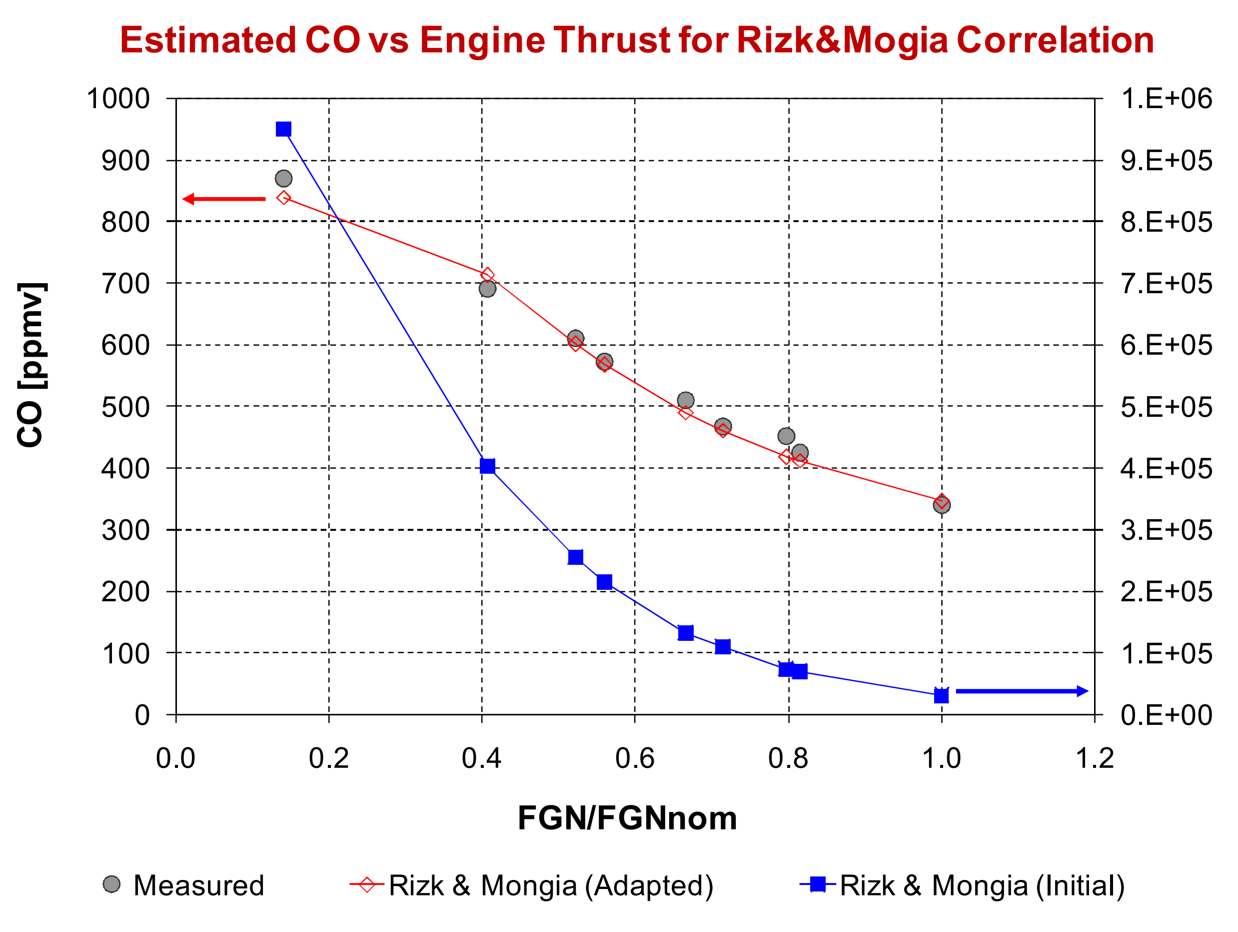

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Establishment of Generic Correlations Through Multivariate Analysis

- **Generic emissions correlations can be formulated taking account the parameters that influence the emissions generation mechanism**

Investigated Generic Emissions Correlation

$$NOx = a \cdot e^{b \cdot T_3} \cdot P_3^n \cdot far^c$$

$$NOx = a \cdot e^{b \cdot T_{fl}} \cdot P_3^n \cdot far^c$$

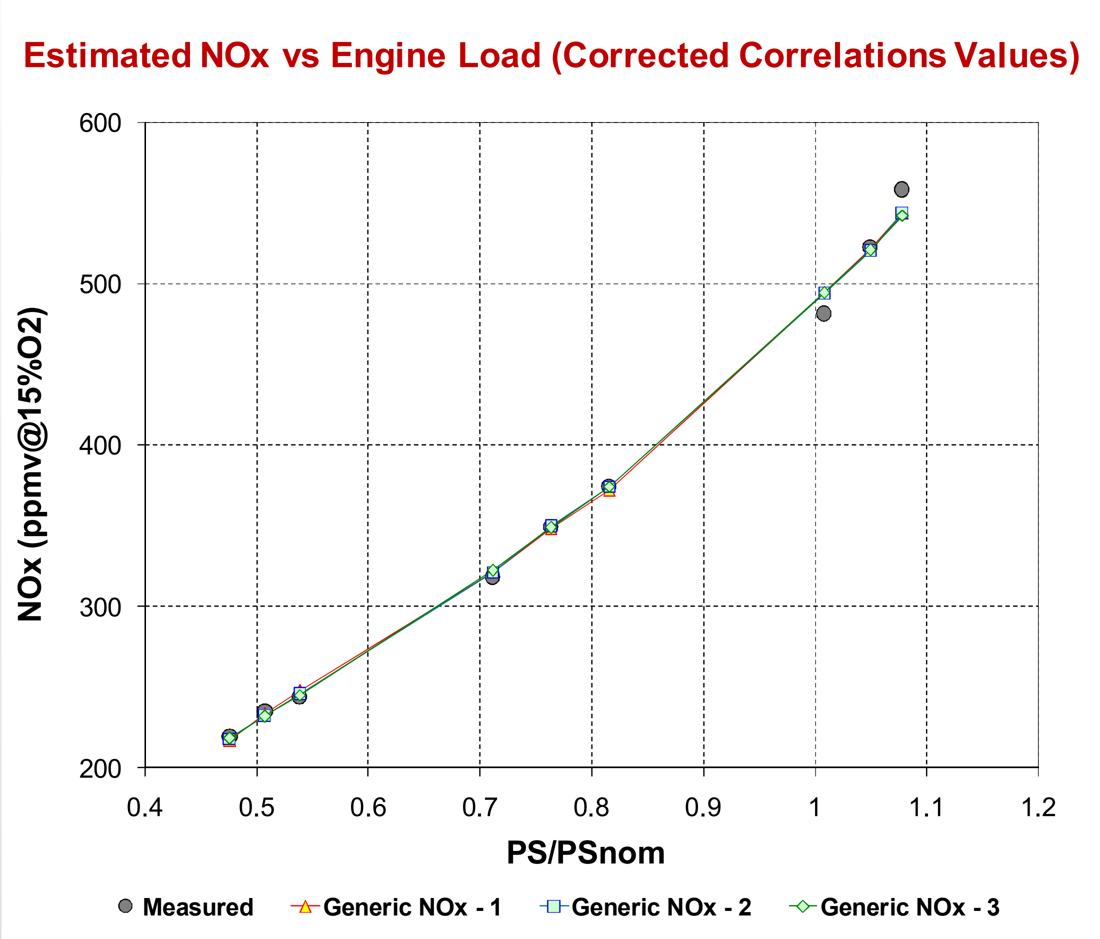
$$NOx = a \cdot e^{b \cdot T_{fl}} \cdot P_3^n \cdot m_{air}{}^c$$

- **The coefficients of these correlations can be determined from available emissions data using a multivariate analysis based on their linear transformation**

$$NOx = a \cdot e^{b \cdot T_{fl}} \cdot P_3^n \cdot far^c \Rightarrow \ln\left(NOx\right) = \ln a + b \cdot T_{fl} + n \cdot \ln\left(P_3\right) + c \cdot \ln\left(far\right)$$

Establishment of Generic Correlations Through Multivariate Analysis

Predicted and Measured NOx of the Industrial Gas Turbine



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Adaptive Performance Models & Emissions Prediction

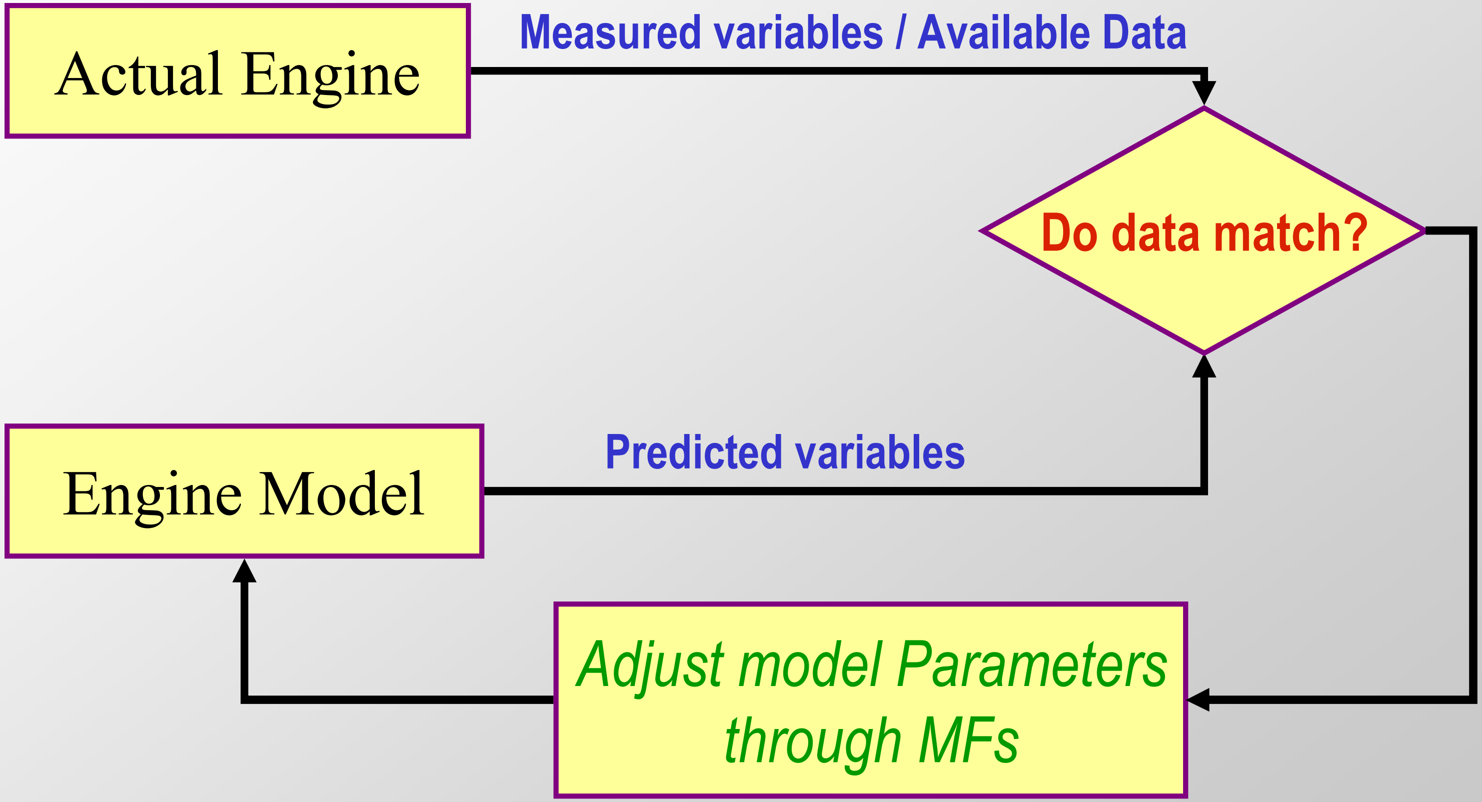
- **The accuracy of employed variables affects the accuracy of emissions predictions**

- **Engine performance model can be used in cases where the experimental study is impractical and/or expensive**

- **Adaptive engine performance models gives the possibility of accurate reproduction of cycle variables for a wide range of operating conditions**

Adaptive Performance Models & Emissions Prediction

Elements of Adaptive Models



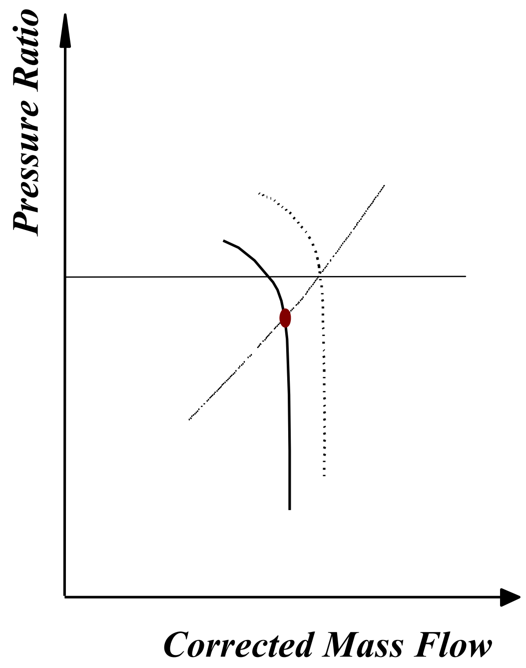
Adaptive Performance Models & Emissions Prediction

The Meaning of Modification Factors

$$f_k = \frac{x_{p,k}}{x_{p,ref,k}}$$

$x_{p,k}$: Actual value for parameter

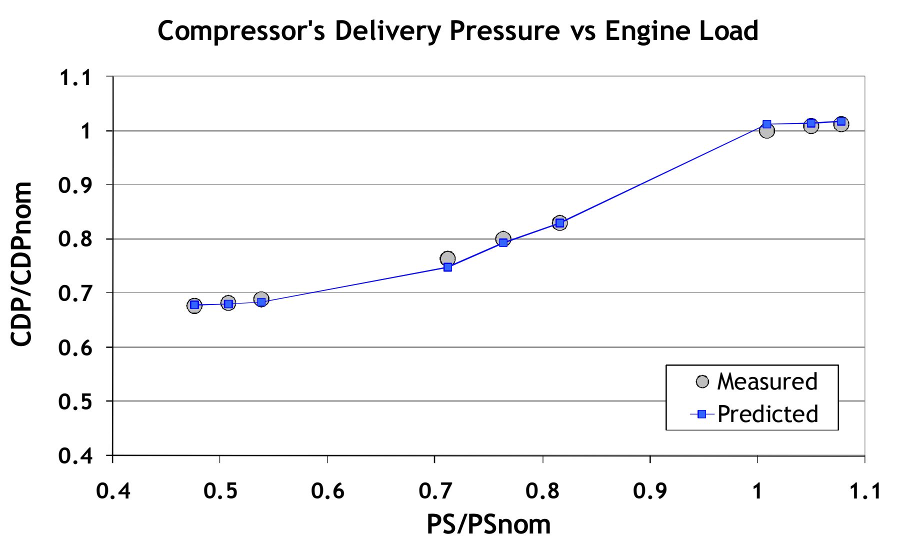
$x_{p,ref,k}$: Reference value for parameter

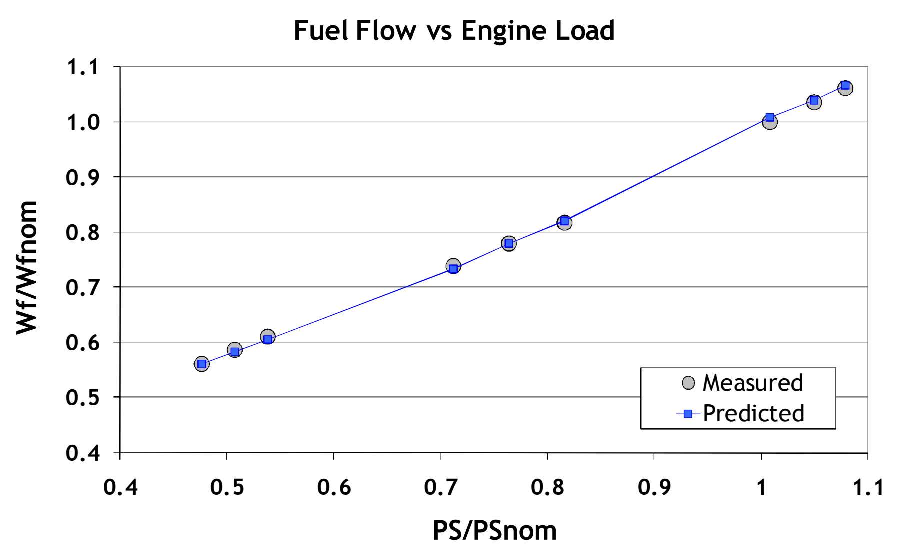


Transformation of component performance maps

Adaptive Performance Models & Emissions Prediction

Industrial Gas Turbine Adaptive Model Predictions





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Summary - Conclusions

- **Existing emissions correlations can be adapted to emissions data of a particular engine for prediction to an acceptable degree of accuracy**
- **Generic correlations can be formulated and adapted to available emissions data with a high degree of accuracy**
- **Adaptive performance models can be used for accurate regeneration of employed cycle variables**