Applying AI Technologies to Vehicle Sensor Modeling

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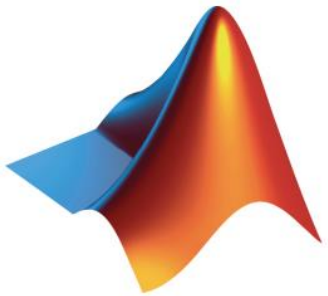

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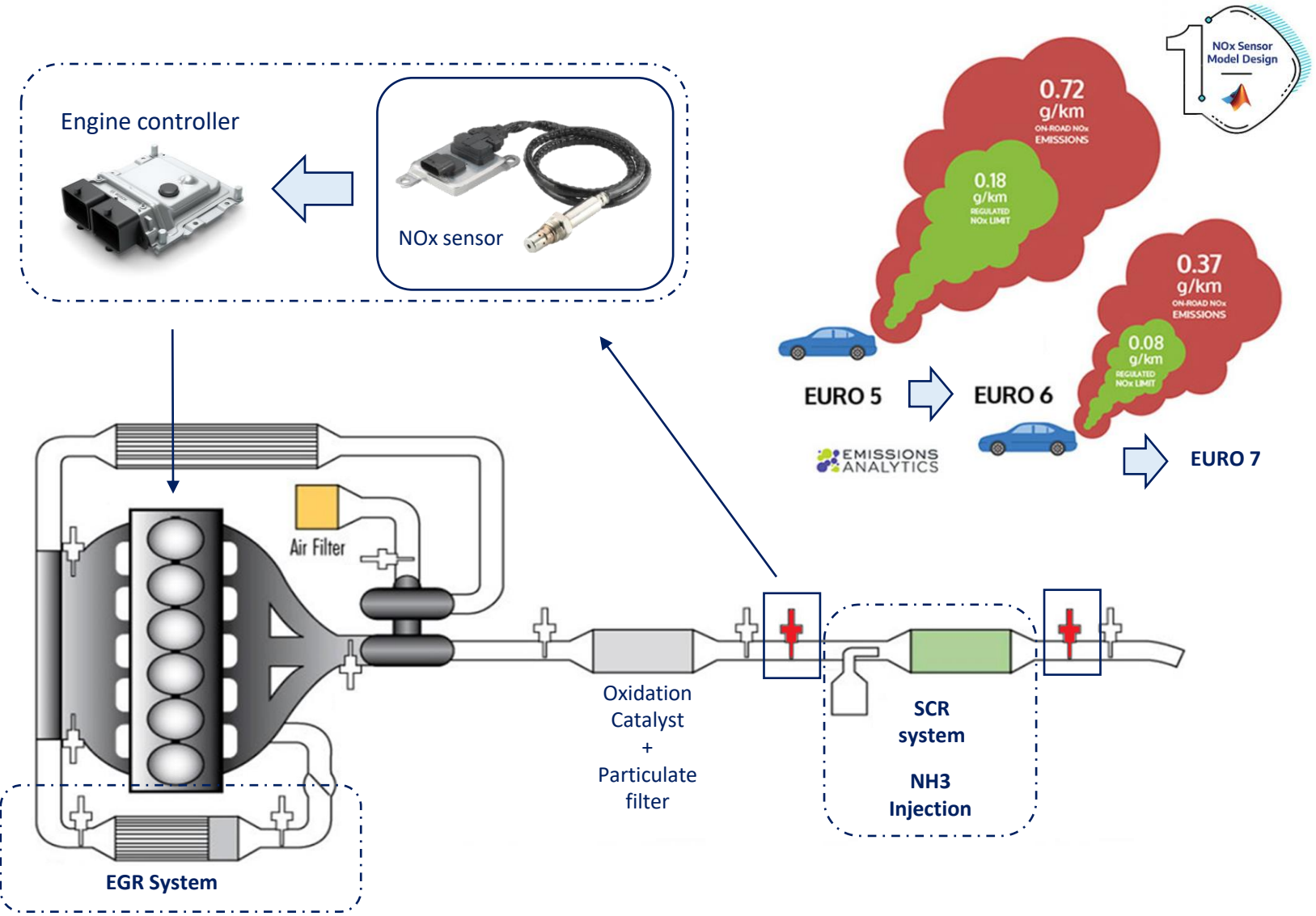
Vehicle NOx Emission

NOx Control Technologies:

- EGR - Exhaust Gas Recirculation system
- Retard injection/ Change Compression Ratio
- SCR - Selective Catalytic Reduction of NOx:
  - Ammonia (NH3-SCR)
  - Hydrocarbons (HC-SCR)

Benefits from having virtual sensor model:

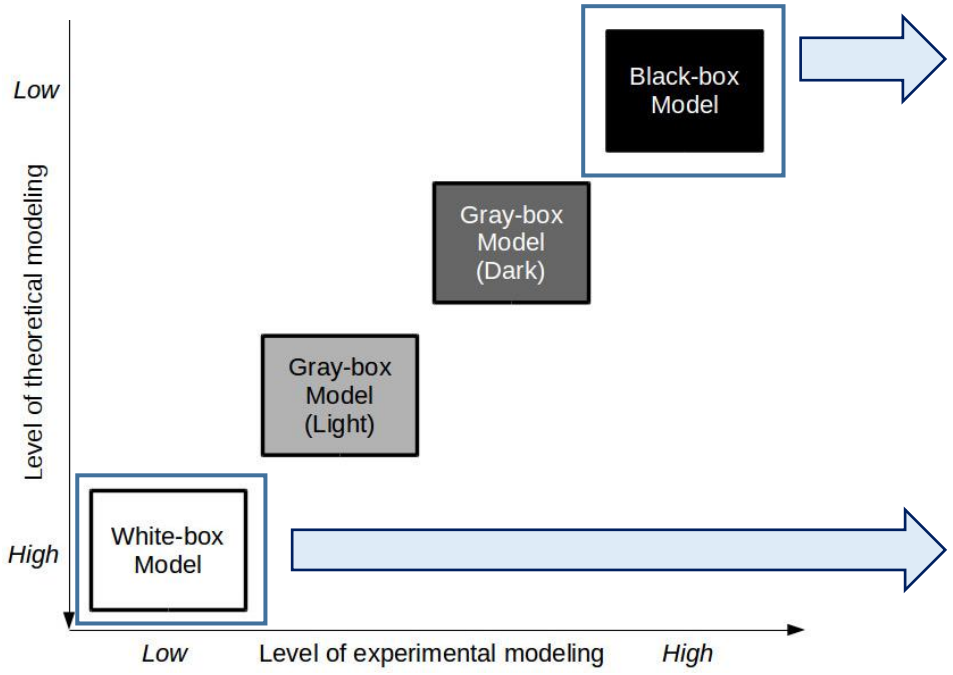
- Redundancy and Reliability
- Optimization of the number of physical sensors
- Diagnoses



Vehicle NOx Sensor Modeling

Physics modeling issue/concerns

Getting AI help



Artificial Intelligence (AI) modeling

- Machine Learning
- Deep learning
- Artificial Neural Network

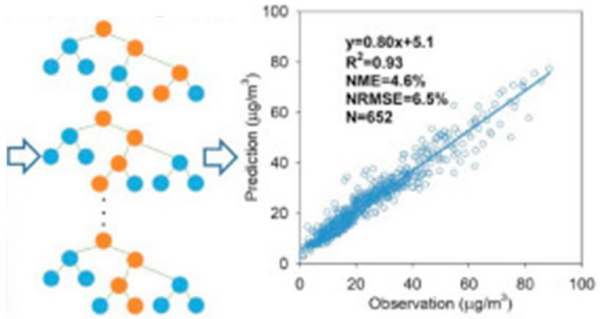
Training based technology

- correlate the I/O of the system to find a mathematical relationship between them.

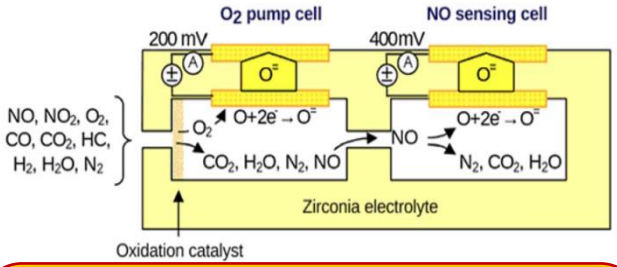
Theoretical modeling – Eq. derived from physics

- Electrical systems
  - Ohm's law
  - Kirchhoff's law
- Hydrodynamics
  - Bernoulli's law
  - conservation of mass law
- Thermodynamics
  - ideal gas law
  - entropy

NOx sensor – Machine Learning



NOx sensing element in longitudinal section view



Challenges: Complex Physical Modeling (Electrochemistry and Semiconductors)

- Normally cannot run in real time (high computation effort)
- Hard to obtain physical parameters
- Model Accuracy

Machine Learning technique

Machine Learning is a subset of Artificial Intelligence (AI), in which the machine learns how to complete a certain task without being explicitly programmed to predict.

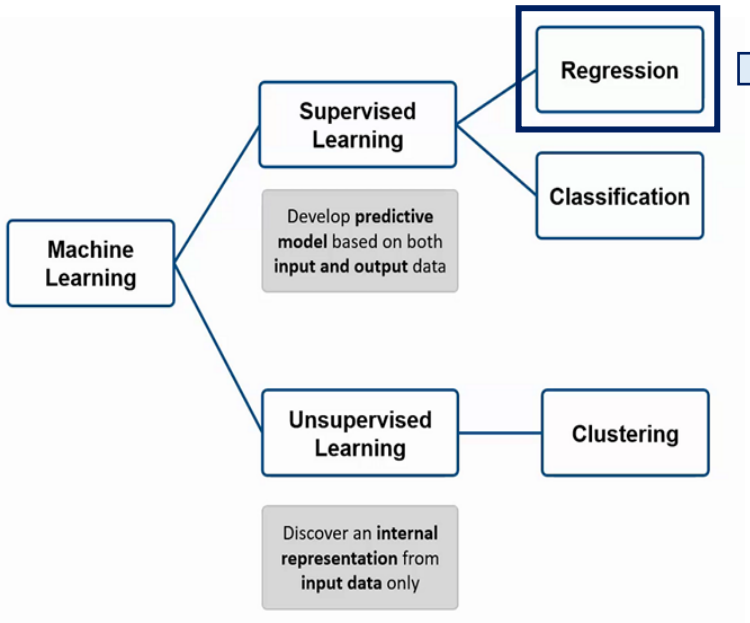


Figure 1 - Machine Learning methods. (MathWorks, 2021)

Supervised Learning

Find the relationship between the NOx (output) and the variables which have influence on the output.

Regression models

The NOx sensing is a typical time series problem.

Common techniques include:

- Decision trees
- Support vector machines
- Step-wise Linear
- Lasso
- and others...

Decision Tree - Non-Parametric Regression

- One of the most used supervised learning
- Easy to implement and interpret
- Goes from observations to conclusions about the target value

What does the tree look like?

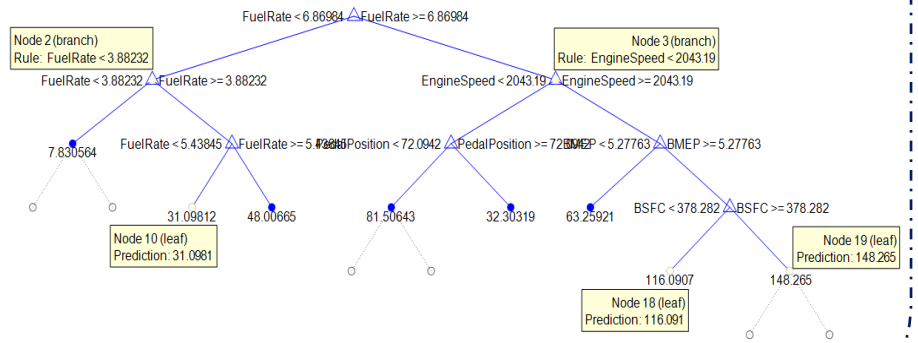
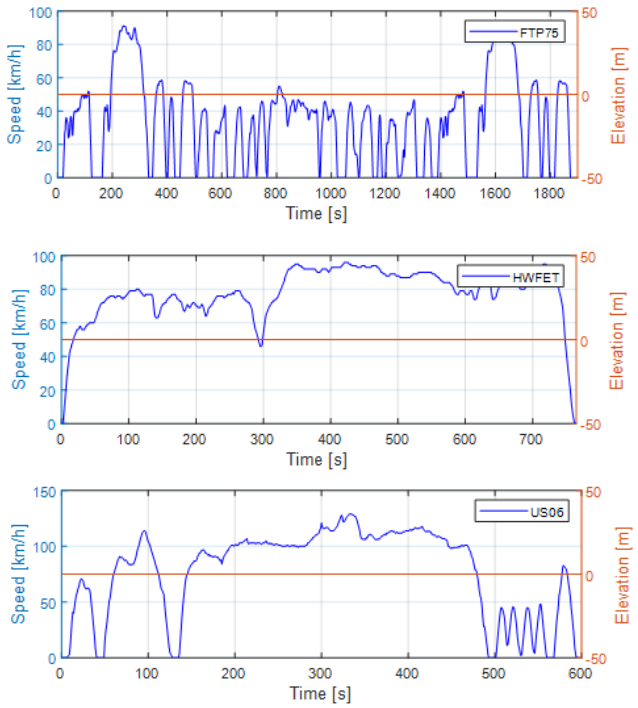


Figure 2 - Decision tree - Non-Parametric Regression

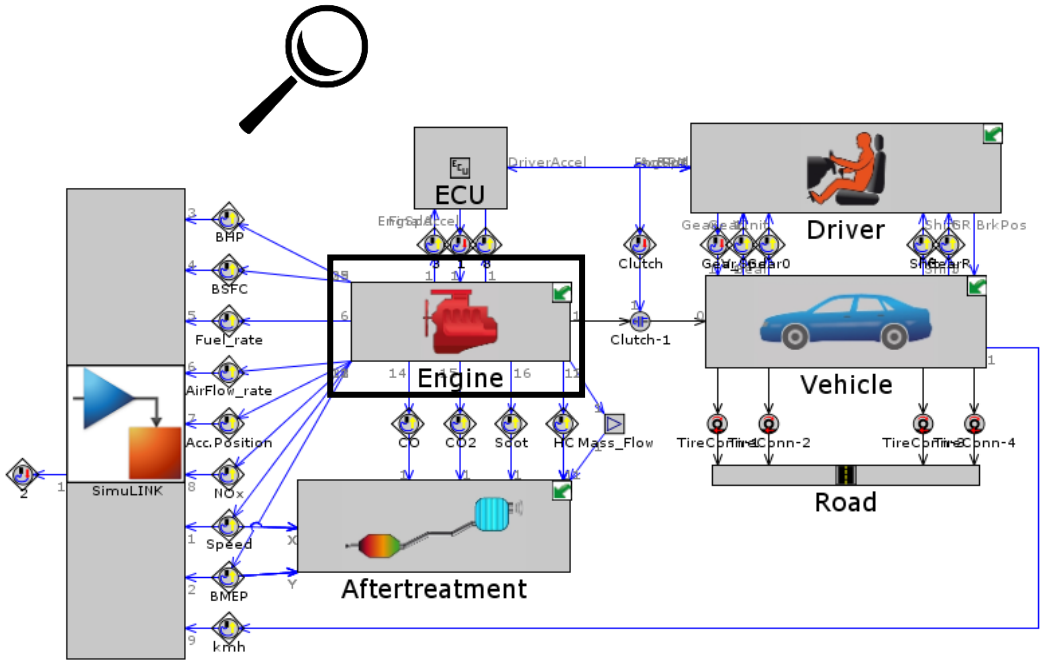
1 - Data source

Detailed GT-Suite vehicle model

Standardized Driving Cycles:
FTP75 – HWFET – US06



GT-Suite vehicle model



Vehicle: Front-wheel drive passenger car with 5-speed transmission.

Engine: 2.0L turbo-charged Map-Based Engine.

Gearing shift: set as a function of vehicle speed (driving cycle)

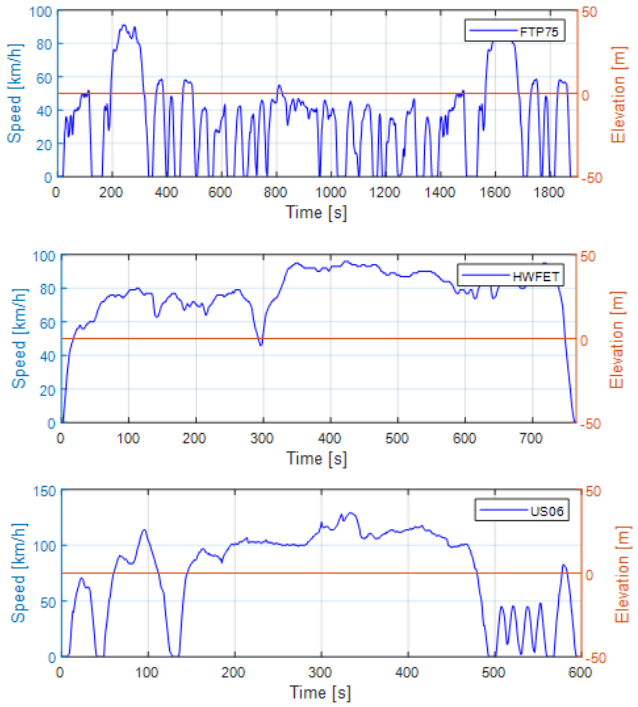
Driver controls: Accelerator and brake position transient input for the drive cycle.

Virtual Data
Exported from GT-Suite

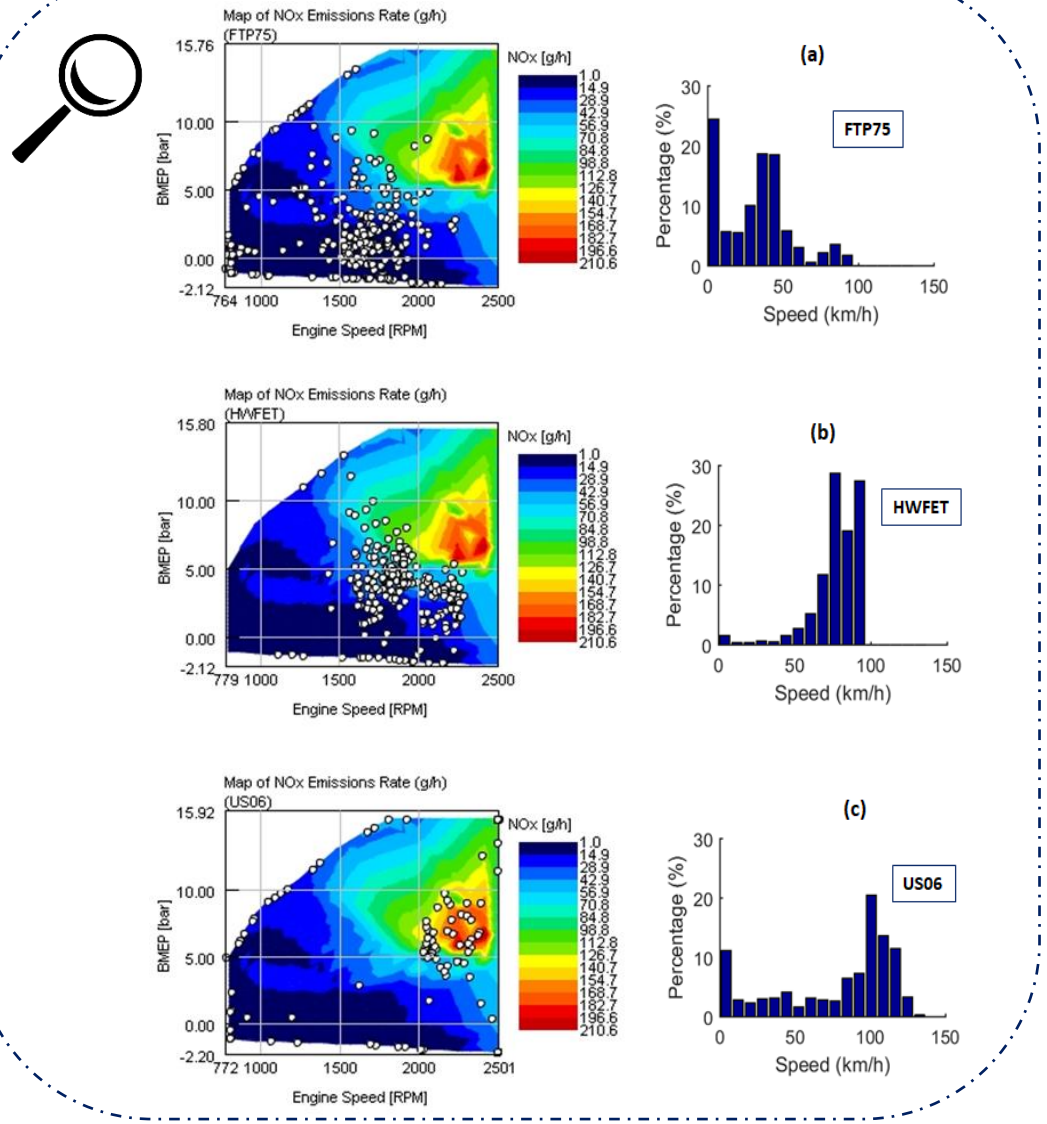
1 - Data source

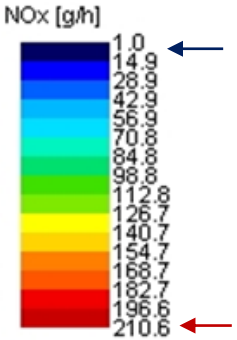
Detailed GT-Suite vehicle model

Standardized Driving Cycles:
FTP75 – HWFET – US06



Map of NOx
Engine operation points





Lowest NOx emission

Highest NOx emission

Virtual Data
Exported from GT-Suite

- Engine speed
- Fuel rate
- Air flow
- Pedal position
- ...

2 - Data Preprocessing

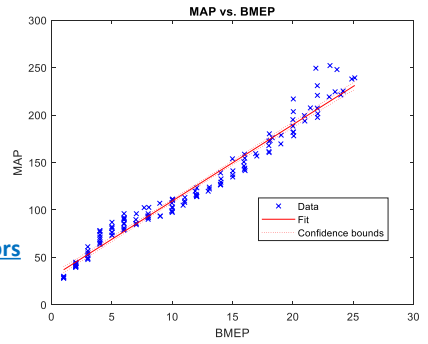
- Data correlation
- Model input and outputs

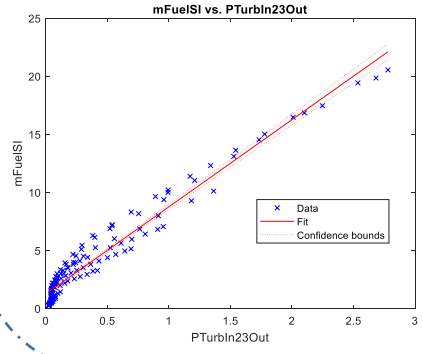
MathWorks tools were used at all steps: from data processing to the model training and validation.

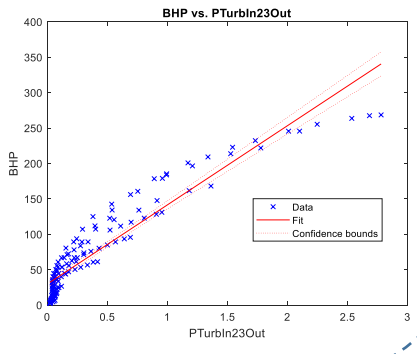
Virtual Data Exported from GT-Suite

1st step - data correlation

- Data analysis (correlation)
- Select the most relevant predictors from database

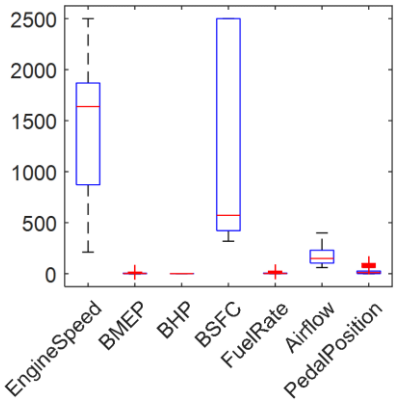






2nd step – Defining Model Input and Outputs

- Predictors (Input)
- NOx concentration (output)



Model input:

- Engine speed
- Brake Specific Fuel Consumption (BSFC)
- Brake Horsepower (BHP)
- Fuel rate
- Air flow
- Pedal position

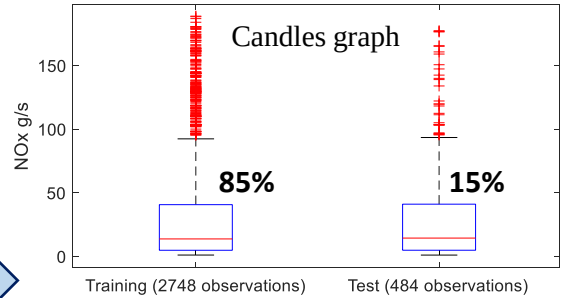
Model output:

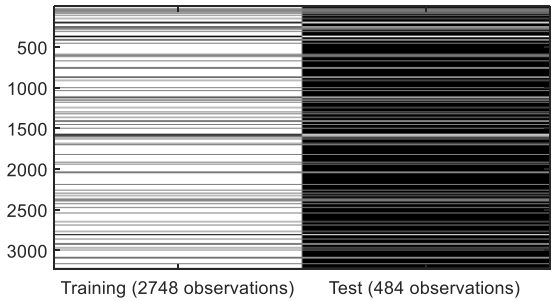
- NOx concentration

3 - Model training

(Decision Tree - Non-Parametric Regression)

3rd step - Training and test data distribution

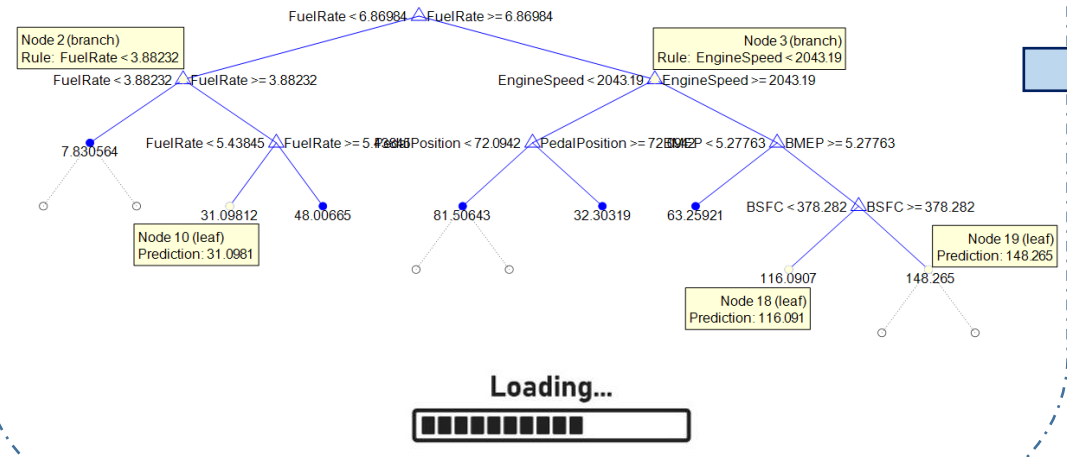




Randomly sampling distribution

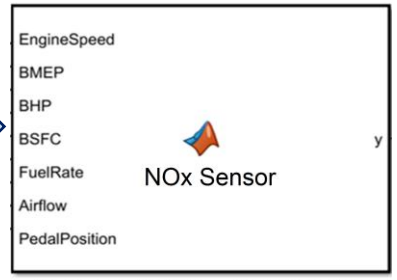
4th step - Model Training (Non-Parametric Regression)

- It was generated a tree model with 621 nodes
- Figure shown an overview of 19 nodes



Loading...

5th step - NOx Sensor Model embedded with Simulink

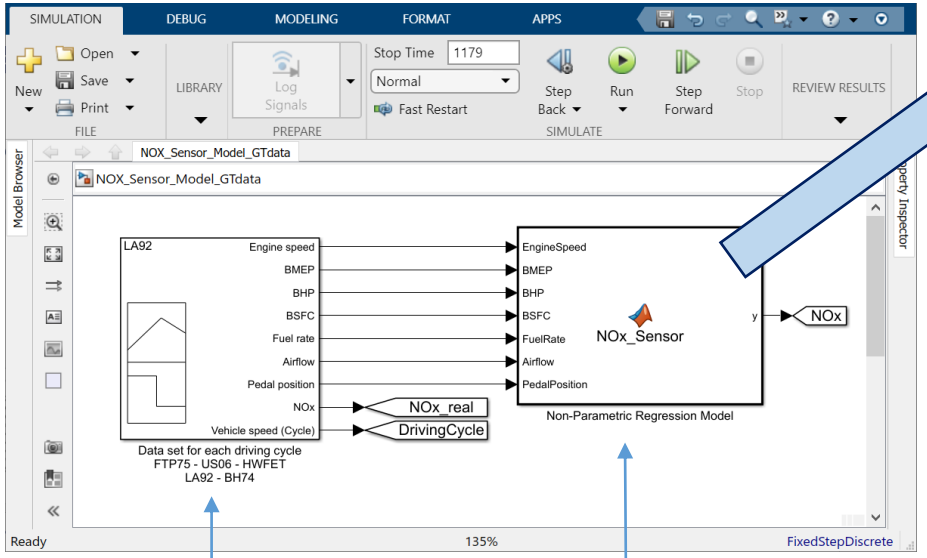


Non-Parametric Model - Regression Tree

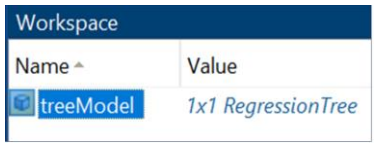
MATLAB SIMULINK

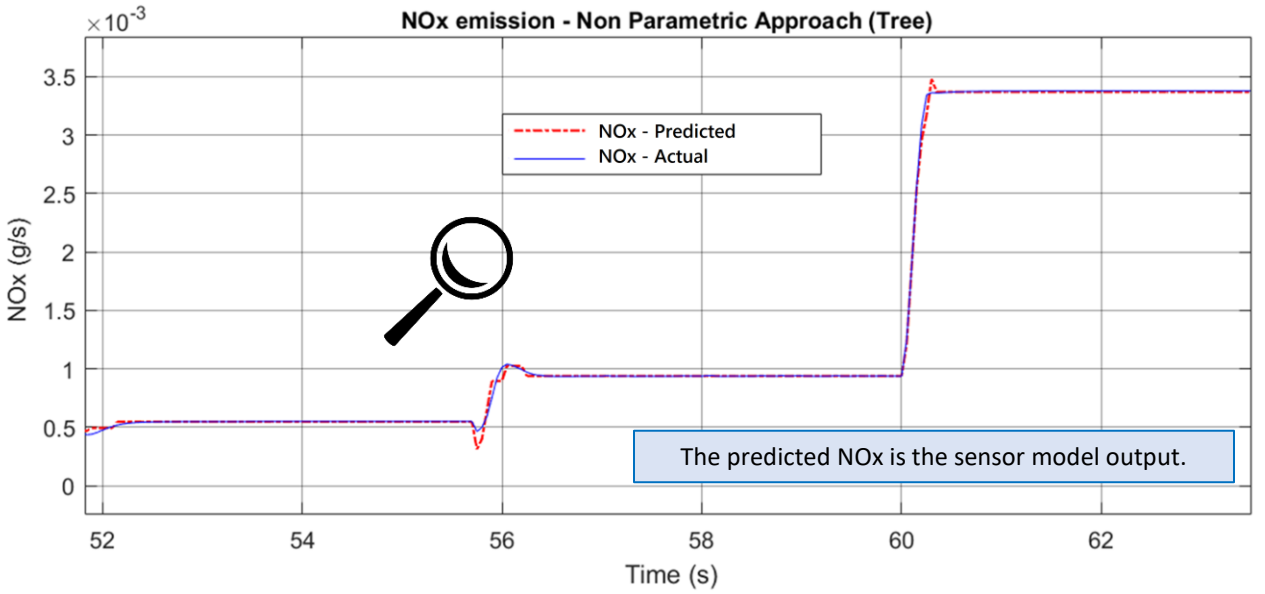
4 - Models Results

NOx sensor model embedded with Simulink



Virtual vehicle data imported

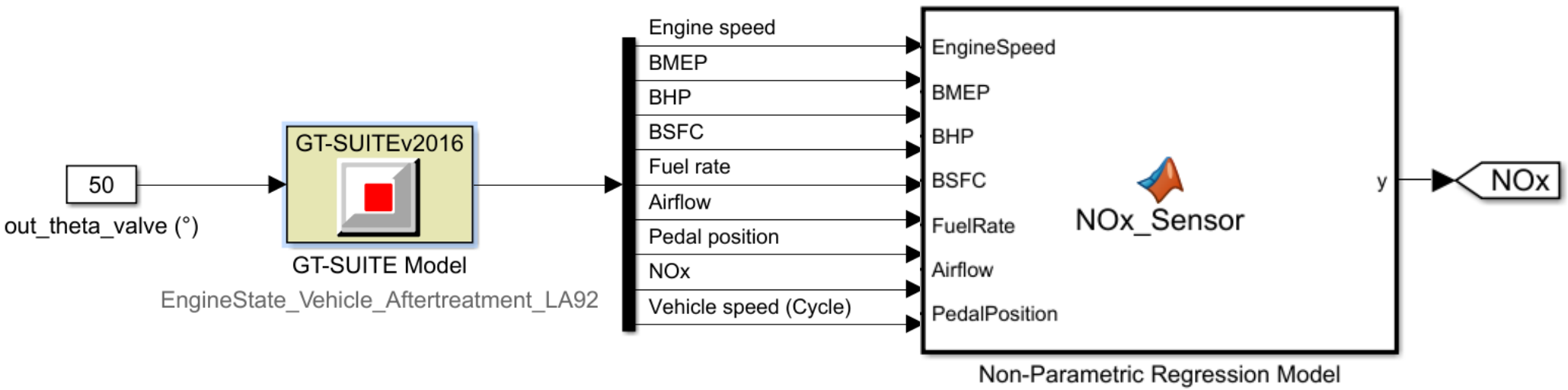


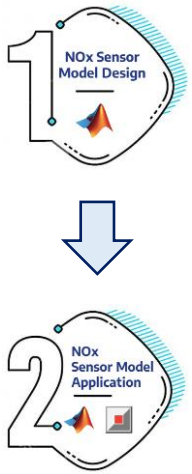


Takeaway:

- The NOx sensor model can quite represent both the steady and transient behavior.
- The NOx sensor model is capable of running in real-time applications.

NOx sensor model





NOx Sensor model is ready for integration

* Method has been validated
** Test data is required to model / train the NOx sensors.

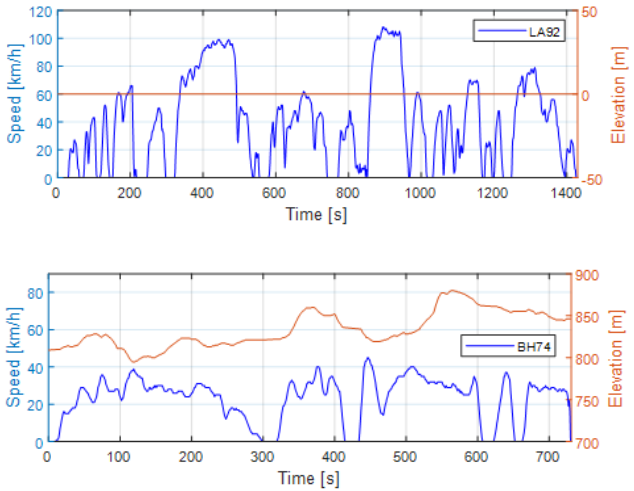
NOx sensor model application (Co-Simulation)

Case 1 - Standardized driving cycle

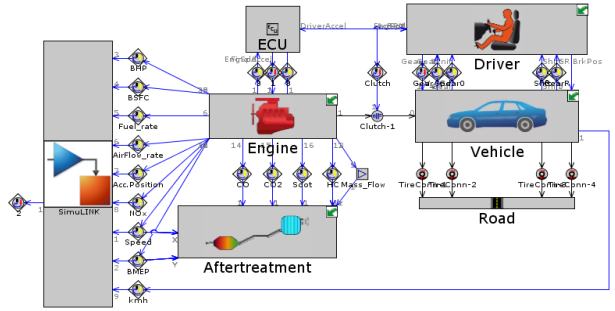
- LA92 – Los Angeles

Case 2 – Brazilian driving cycle

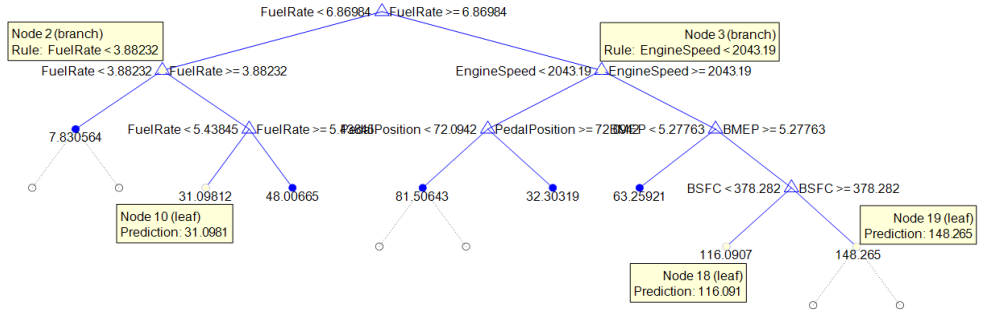
- BH74 – Presidente Antônio Carlos Avenue – Belo Horizonte, BR.

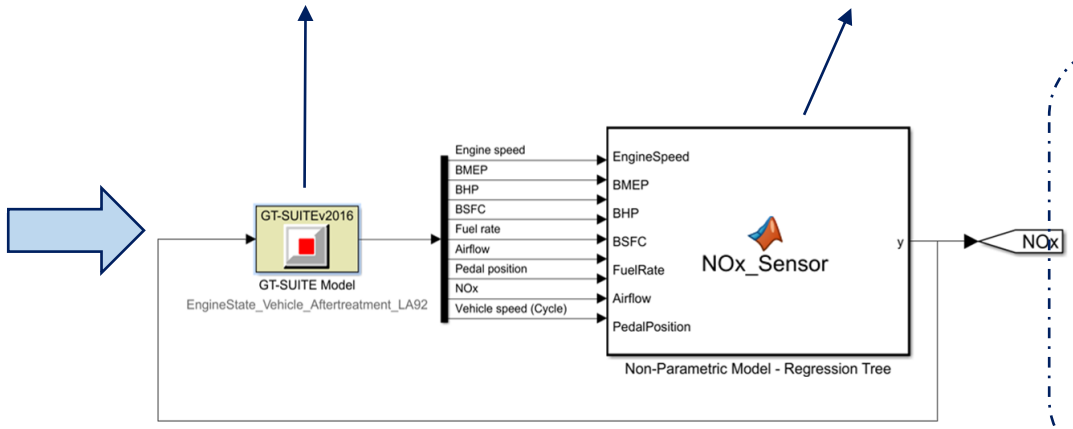


GT-Suite vehicle model

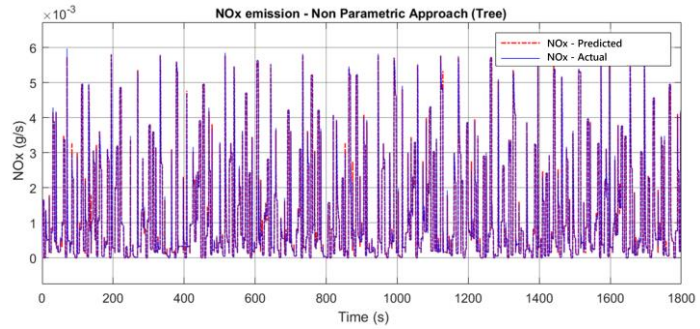


NOx sensor model – Decision tree





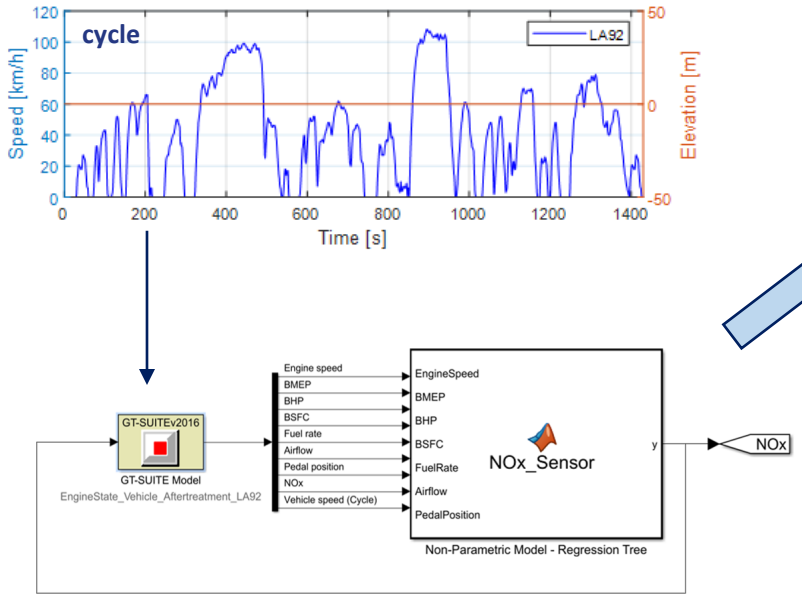
NOx sensed - Sensor model output



NOx sensor model results

Case 1 - Standardized driving cycle

- LA92 – Los Angeles



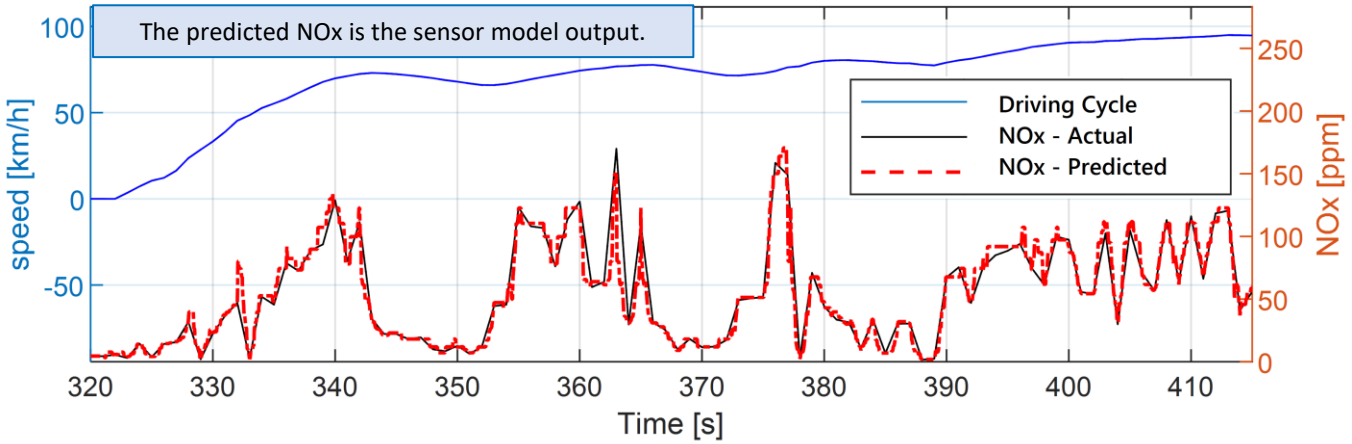


Figure 1 - Driving Cycle and transient NOx concentration

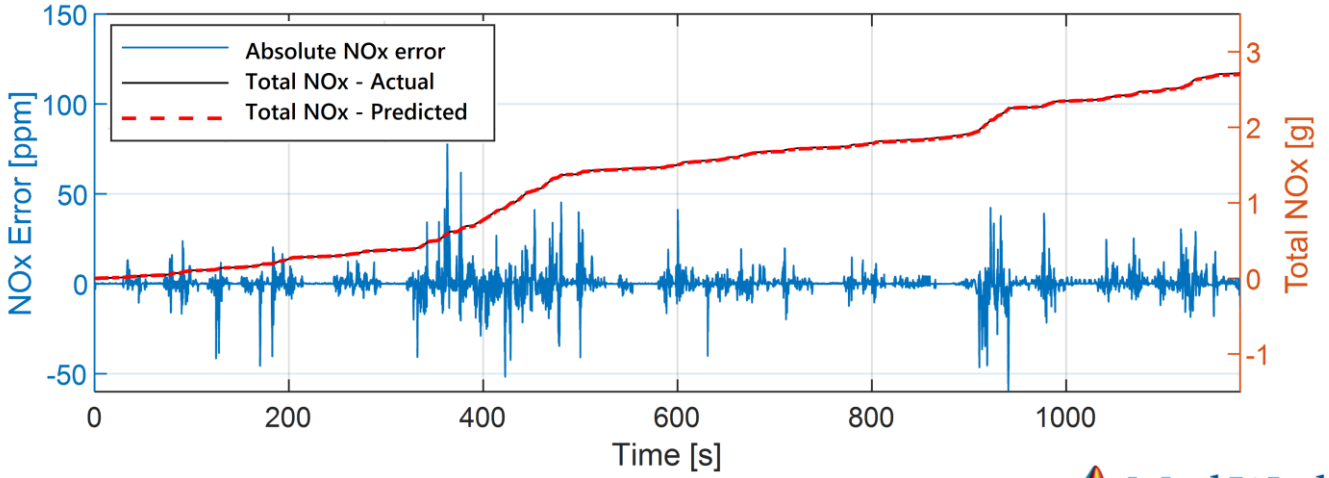
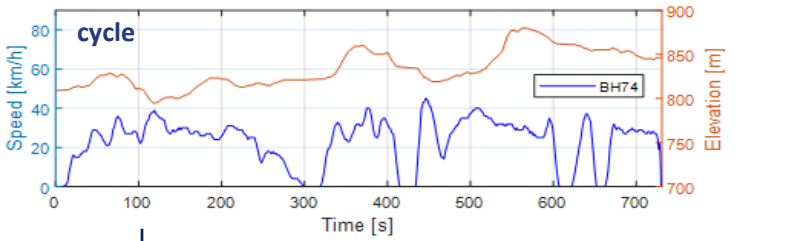


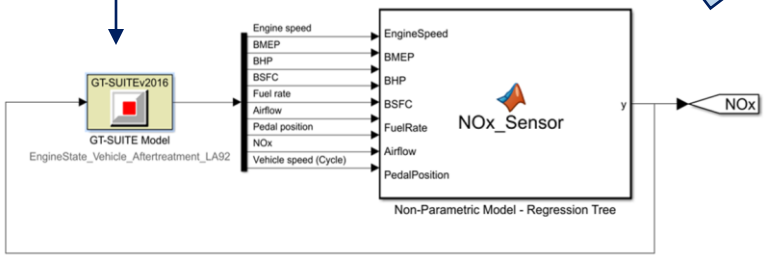
Figure 2 – Abs. instantaneous error and total NOx emission.

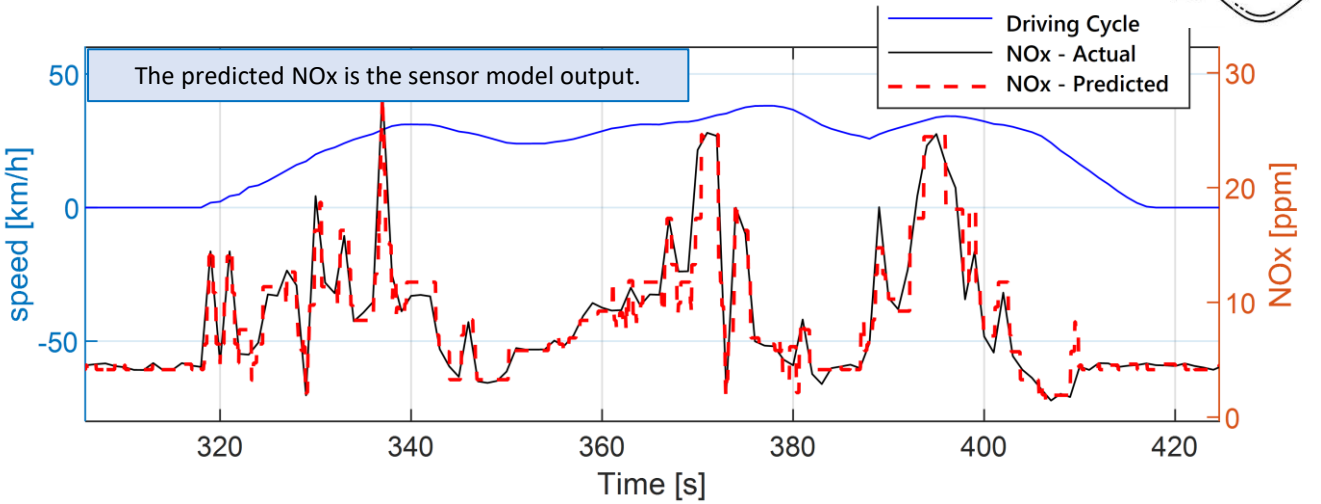
NOx sensor model results

Case 2 – Brazilian driving cycle

- BH74 - Presidente Antônio Carlos Avenue – Belo Horizonte, BR.







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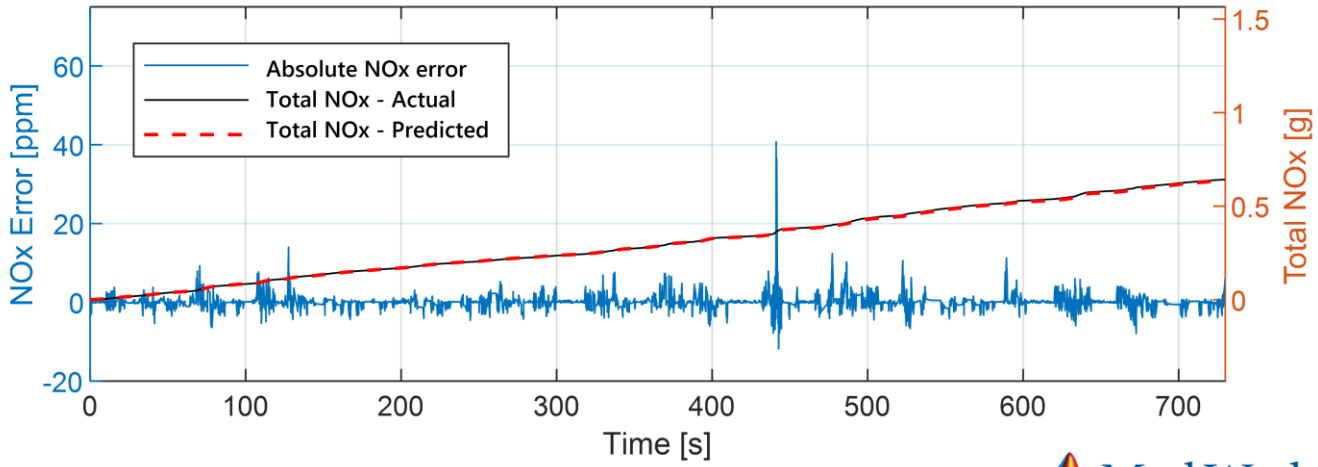


Figure 2 – Abs. instantaneous error and total NOx emission.

NOx sensor model results

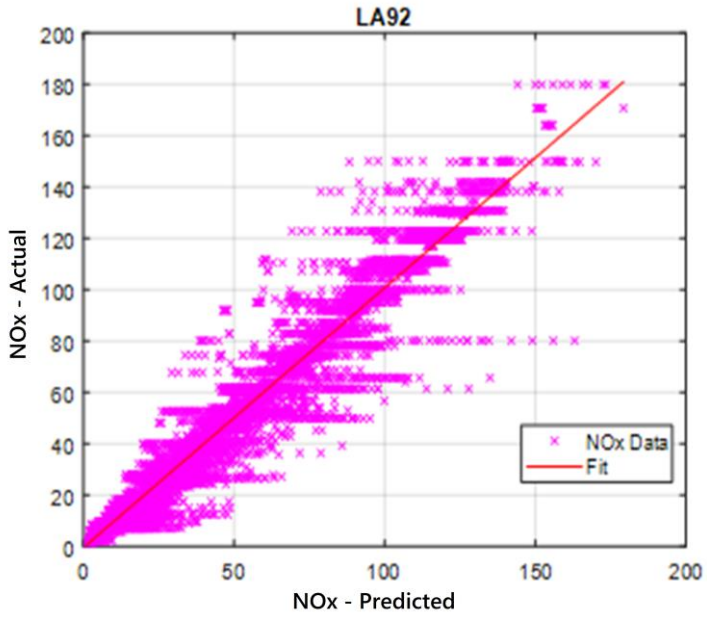
Performance of both cases:

- Loss metric RMSE (Rooted Mean Squared Error)
- Coefficient of determination (R^2)

Takeaway:

- R^2 higher than 92% in both case.
- It shows how well the data sensed fit the actual NOx.

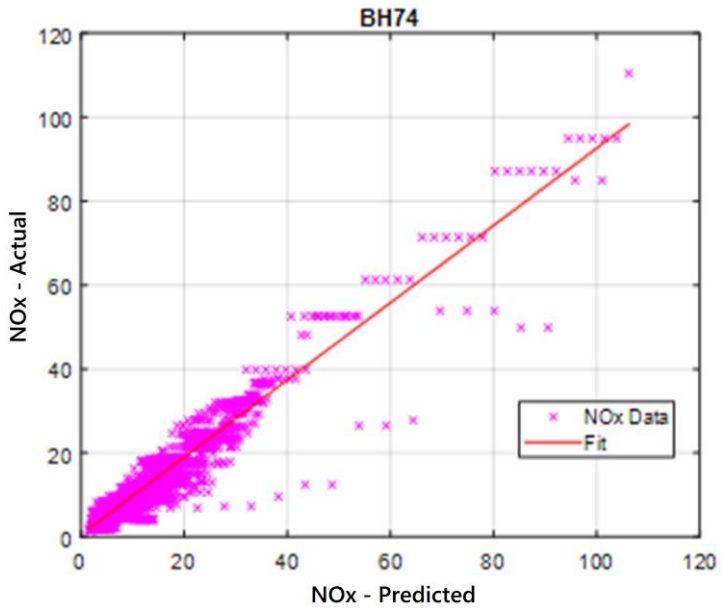
Case 1 - LA92 – Los Angeles cycle



	LA92
RMSE (ppm)	5.53
R^2	0.961

Figure 1 - Actual and Sensed NOx correlation (LA92)

Case 2 – Brazilian driving cycle – BH74



	BH74
RMSE (ppm)	1.76
R^2	0.921

Figure 2 - Actual and Sensed NOx correlation (BH74)

Conclusions

- The AI technology on NOx sensor modeling proves to be successful and it will have wide range applications in automotive industries.
- The Regression Tree can be applied quite well with NOx sensor application.
- The AI modeling method for the NOx sensor has been developed.
- Virtual modeling prove to be great tools for the model development, such as MATLAB/Simulink.
- Training processes is very important for modeling. It requires the data used to be representative of the engine running conditions.

Further developments

- Considering other regression methods and compare results.
- Test data with prototypes can be used to refine the virtual sensor model.
- Embed the NOx sensor algorithm into propulsion systems controller (Redundancy / Reliability / Prognostics).

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Thanks for your time!

Q&A

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