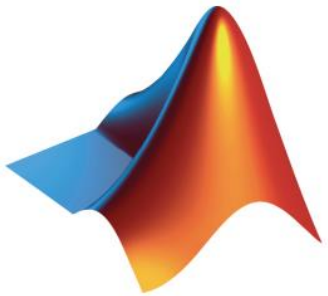
# Applying AI Technologies to Vehicle Sensor Modeling

Authors: Rafael Átila Silva, PhD candidate (Speaker)
Gustavo Duarte
Marcelo Lanza
Ming Yu, PhD.
Evandro Queiroz



MathWorks®
Automotive Conference
2022

Betim, BR

2022/04/07

# Table of contents


## 1 – Understanding the problem

- Vehicle NOx sensor application
  - Physics modeling issue/concerns
  - Getting AI help

## 2 – AI Technology applied

- Machine Learning method
  - Non-Parametric Regression (Tree model)

## 3 – Designing the NOx sensor model

- Data source
- Data processing
- Sensor model training
- Model results

## 4 – NOx sensor model application

- NOx sensor embedded into vehicle model
  - GT-Suite with Simulink (Co-Simulation setup)
- Simulation cases:
  - Case 1 - Standardized driving cycle (LA92)
  - Case 2 - Real World driving cycle (Presidente Antônio Carlos Avenue – Belo Horizonte, BR)

## 5 – Conclusions

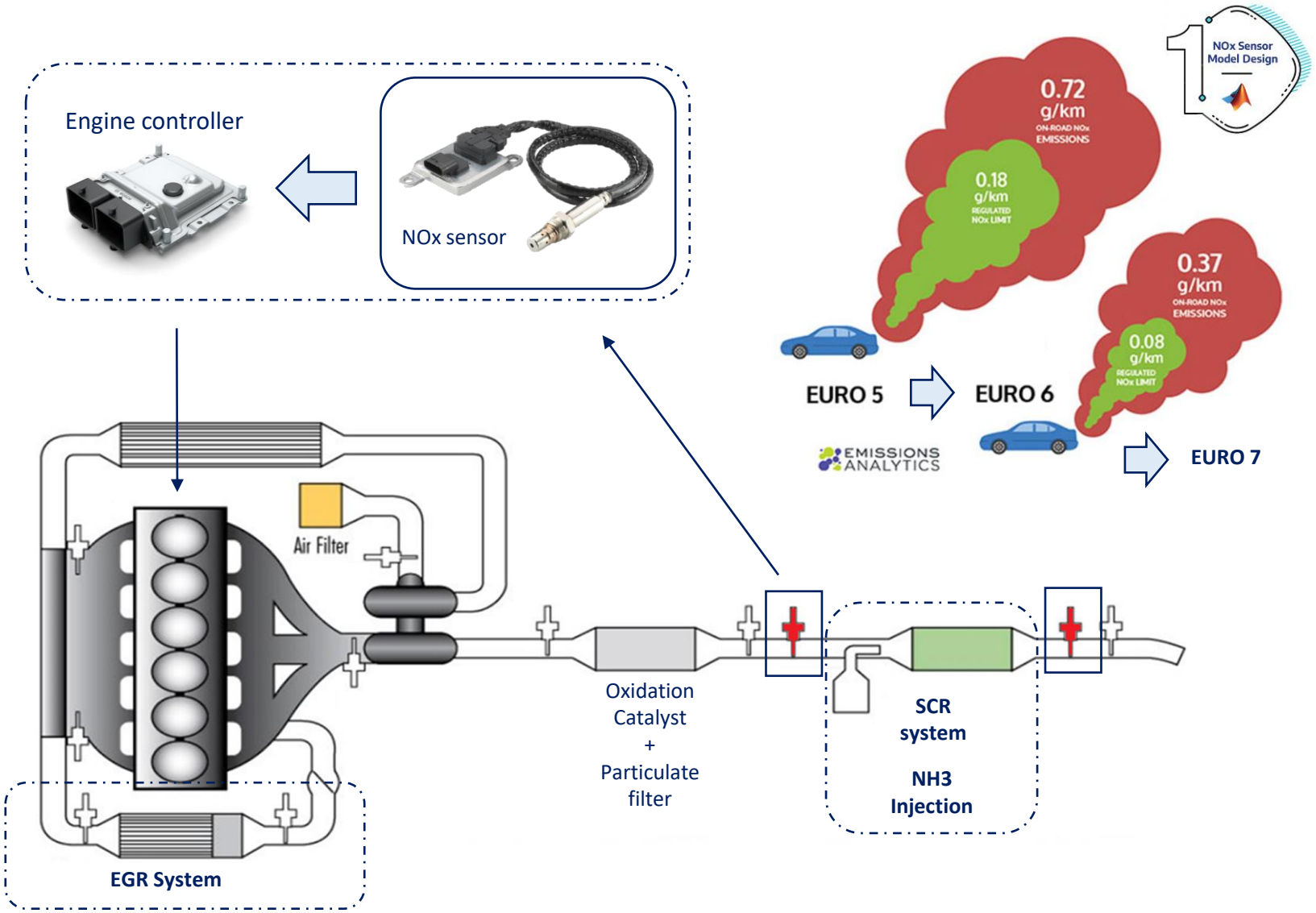
# Vehicle NOx Emission

**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:**

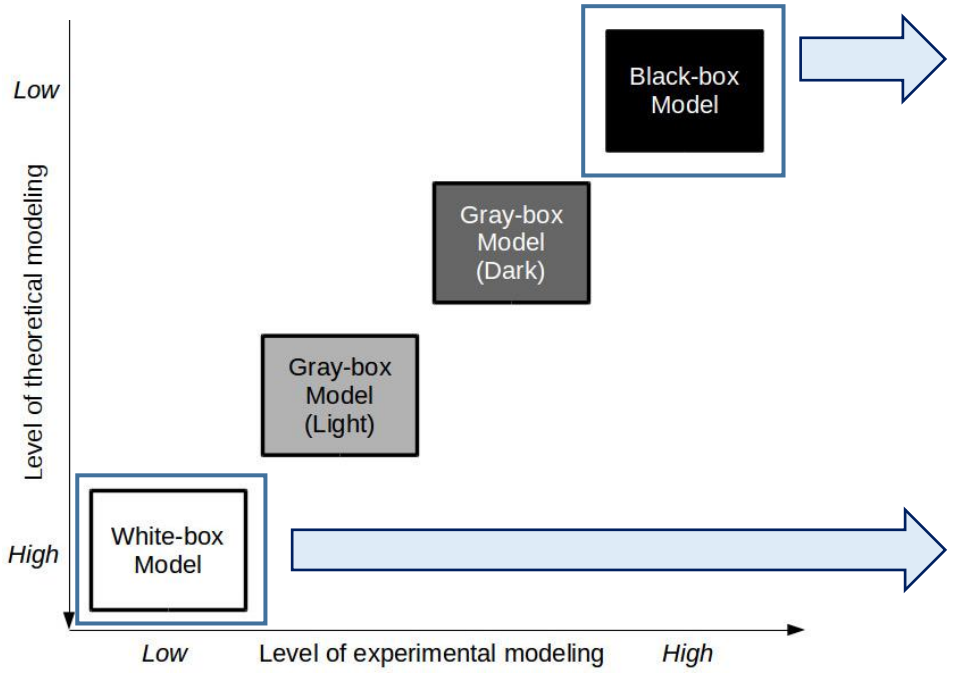
- Redundancy and Reliability
- Optimization of the number of physical sensors
- Diagnoses



# Vehicle NOx Sensor Modeling

Physics modeling issue/concerns

Getting AI help




**Artificial Intelligence (AI) modeling**

- Machine Learning
- Deep learning
- Artificial Neural Network

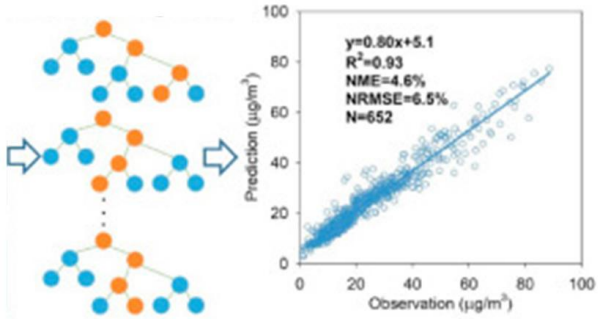
**Training based technology**

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

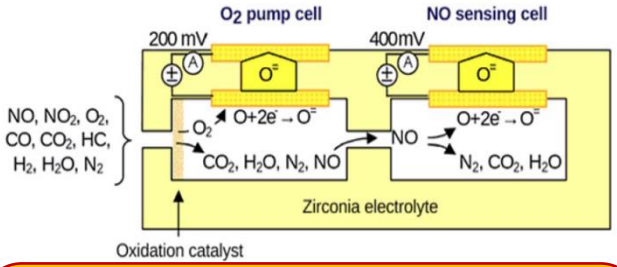
**Theoretical modeling – Eq. derived from physics**

- 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.

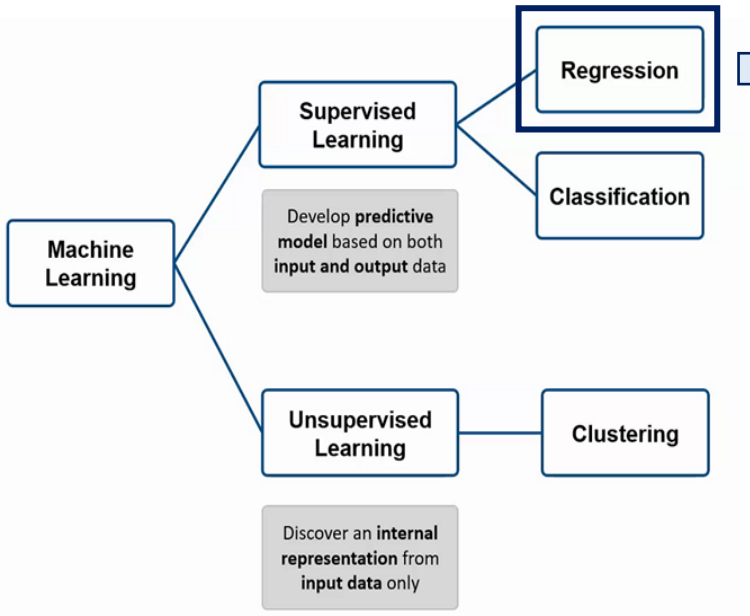



Figure 1 - Machine Learning methods. (MathWorks, 2021)

**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?**

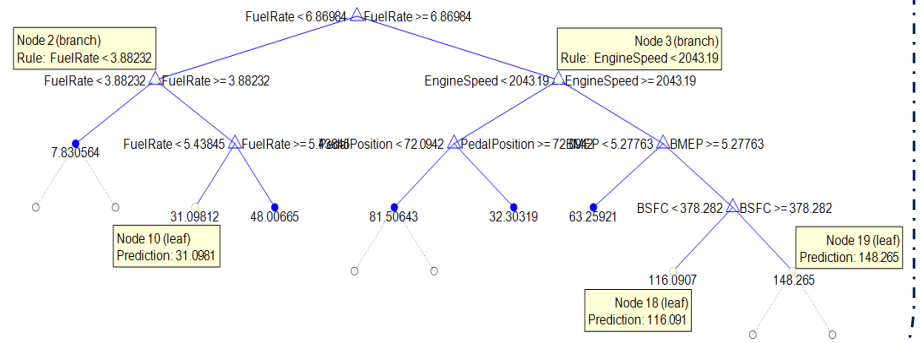



Figure 2 - Decision tree - Non-Parametric Regression

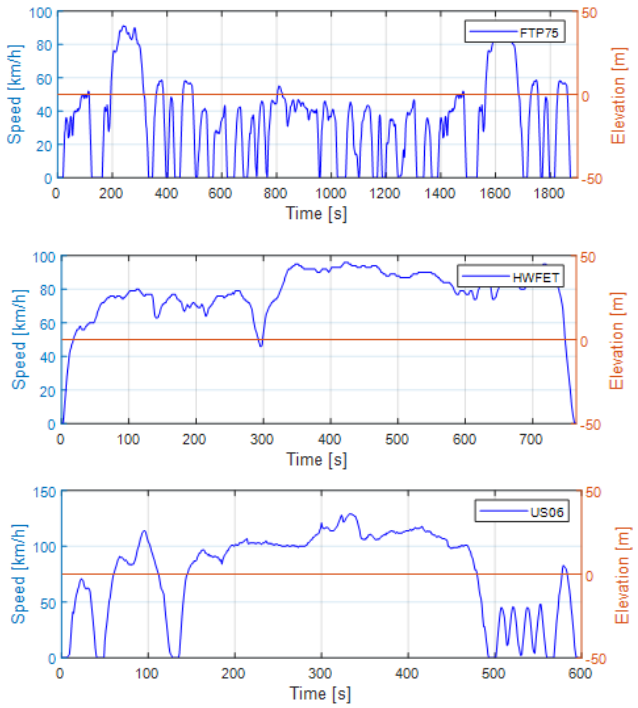
STELLANTIS

NOx Sensor Model Design

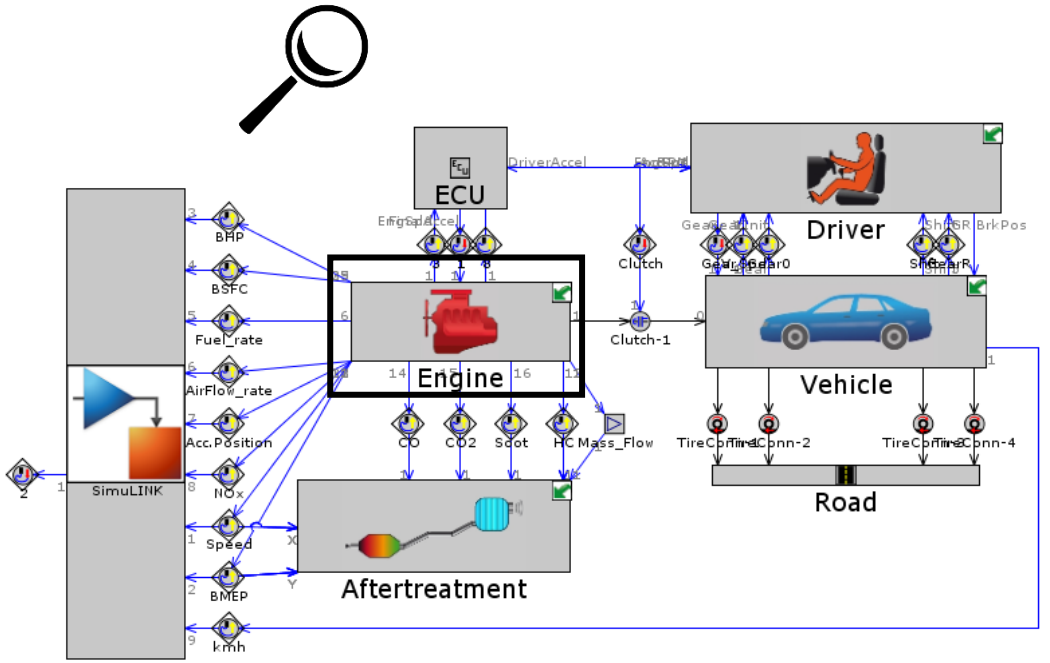
# 1 - Data source

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

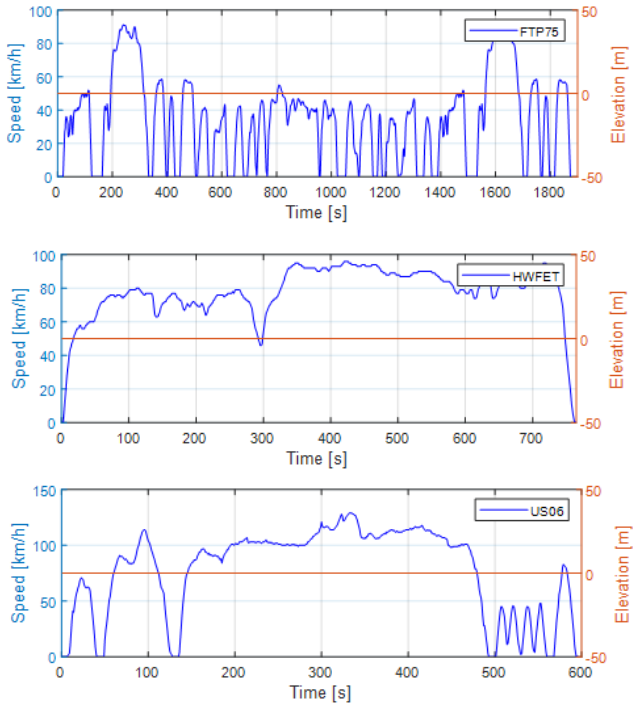


MathWorks

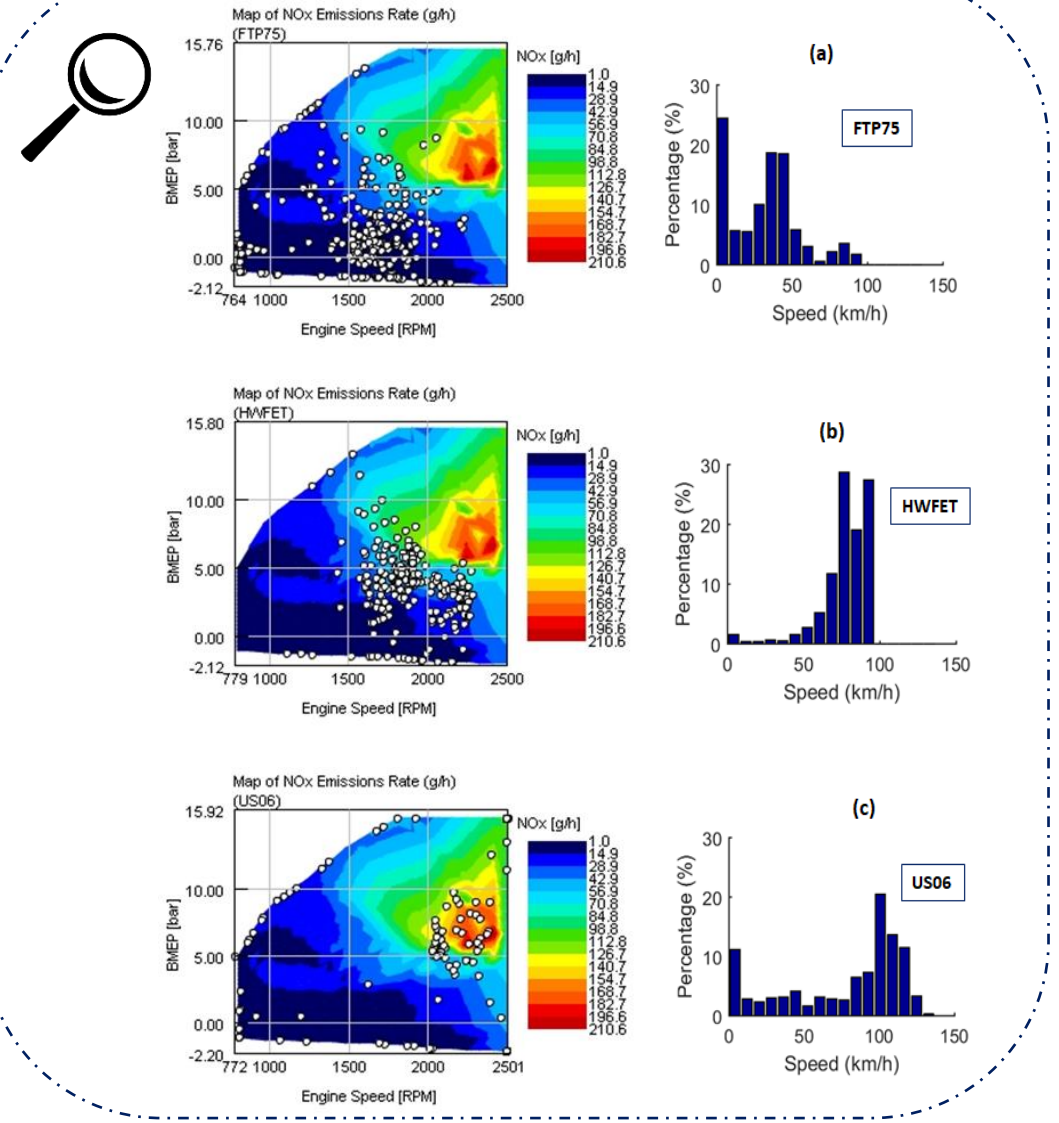
# 1 - Data source

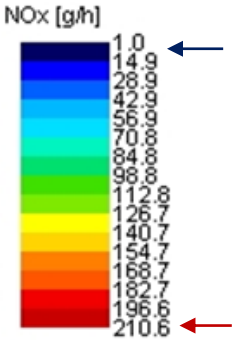
Detailed GT-Suite vehicle model

**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

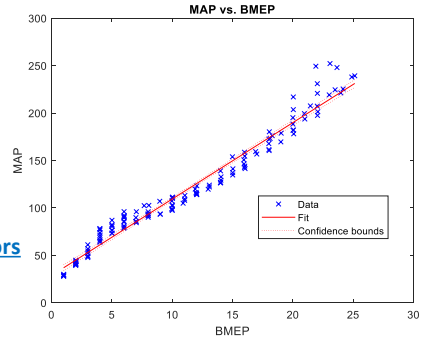
- Data correlation
- Model input and outputs

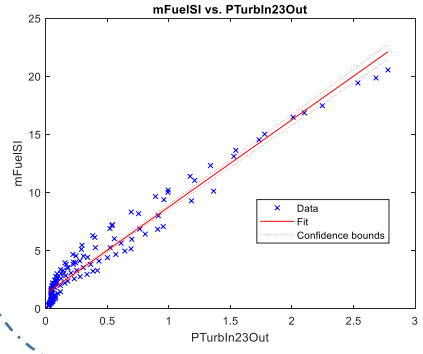
MathWorks tools were used at all steps: from data processing to the model training and validation.

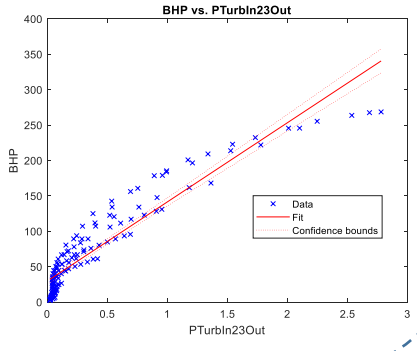
Virtual Data Exported from GT-Suite

## 1st step - data correlation

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

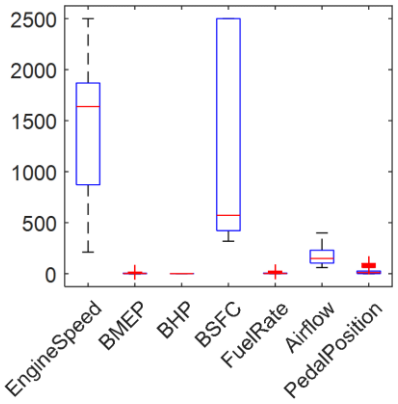



## 2nd step – Defining Model Input and Outputs

- Predictors (Input)
- NOx concentration (output)




**Model input:**

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

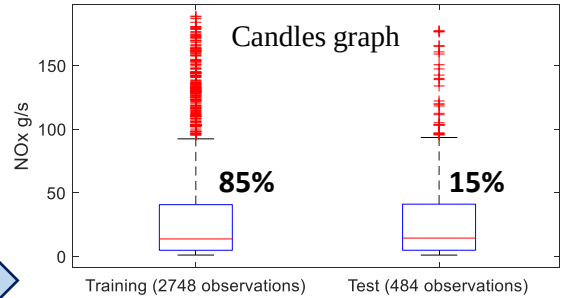
**Model output:**

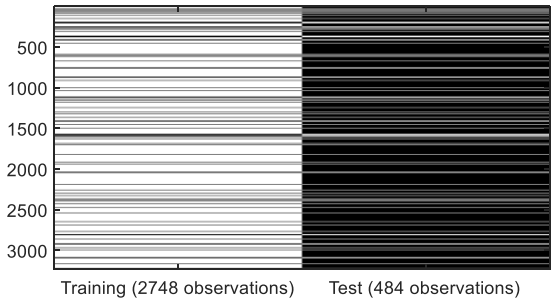
- NOx concentration

# 3 - Model training

(Decision Tree - Non-Parametric Regression)

## 3rd step - Training and test data distribution

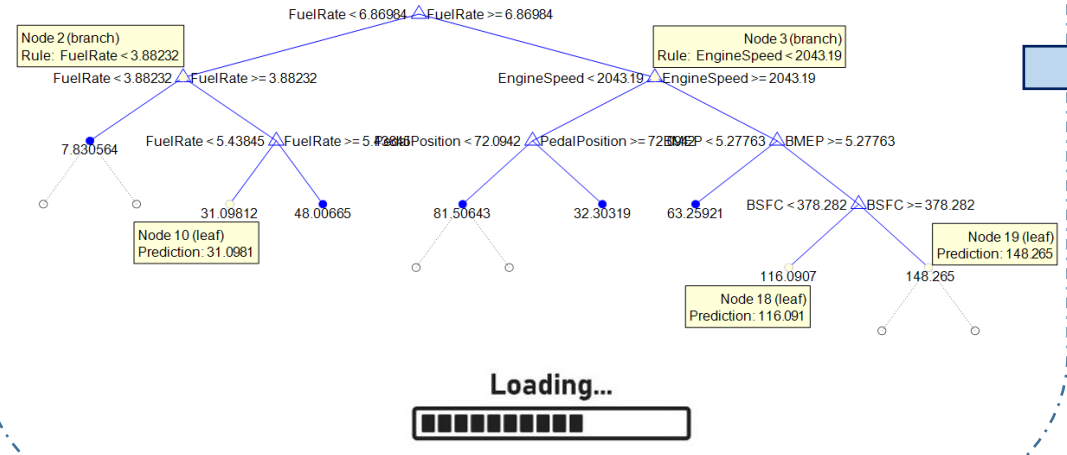



Randomly sampling distribution

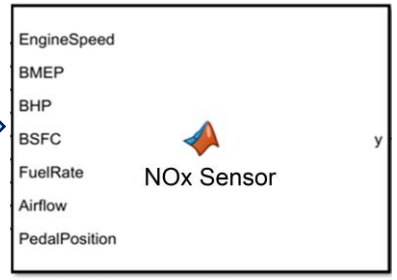
## 4th step - Model Training (Non-Parametric Regression)

- 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

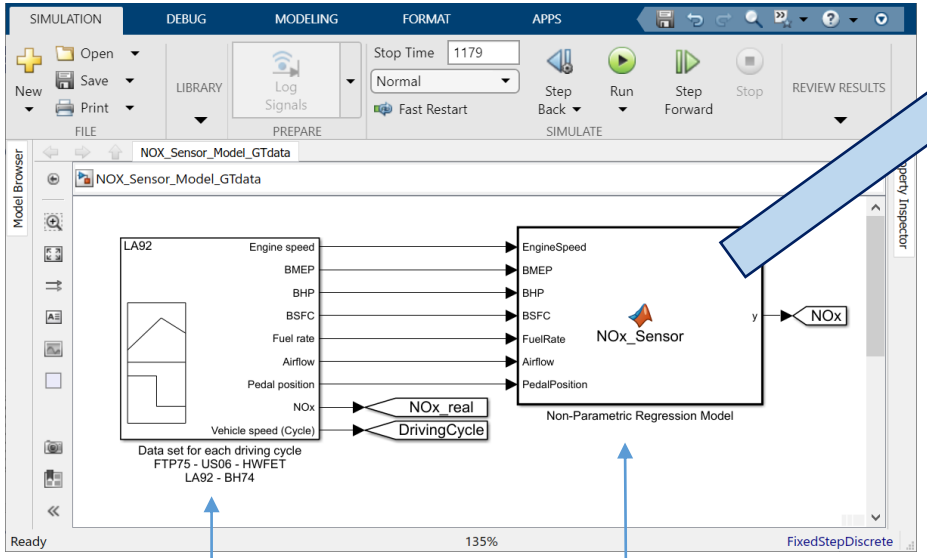



Non-Parametric Model - Regression Tree

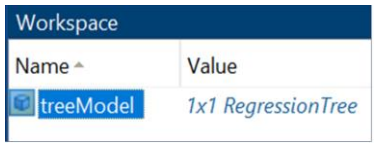
MATLAB SIMULINK

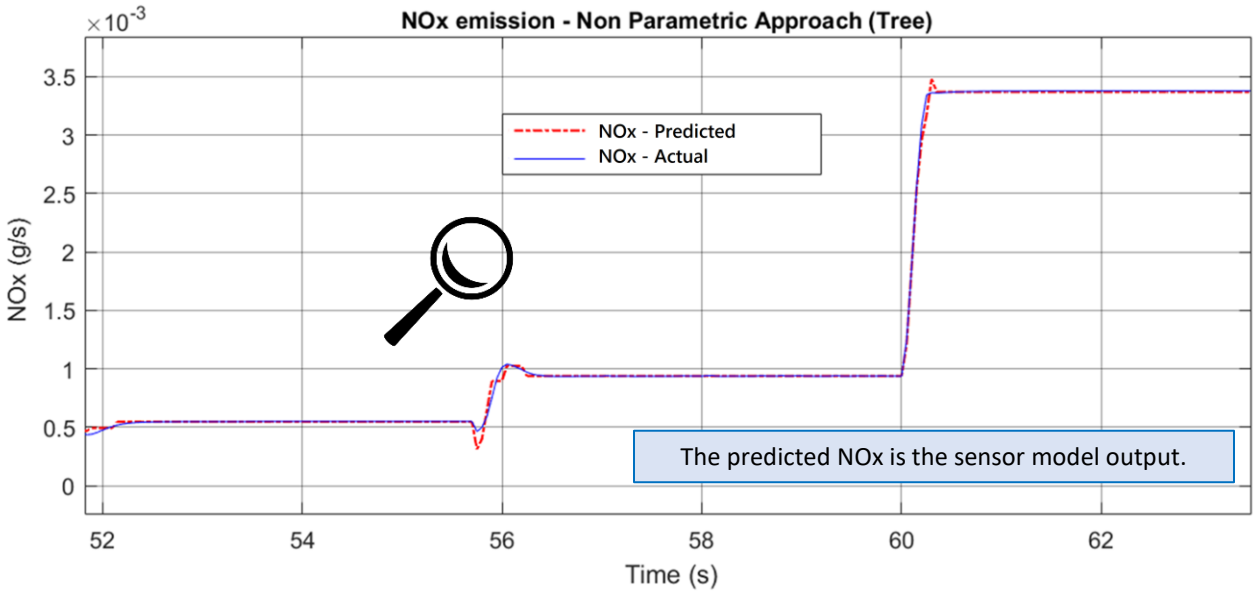
# 4 - Models Results

NOx sensor model embedded with Simulink



Virtual vehicle data imported

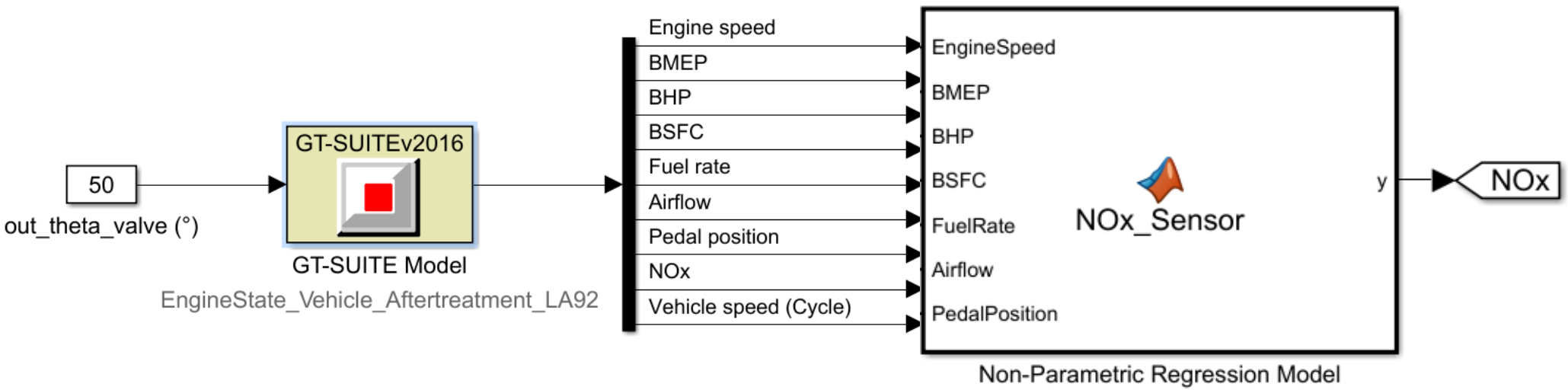


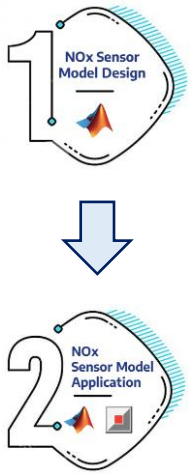




**Takeaway:**

- 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.

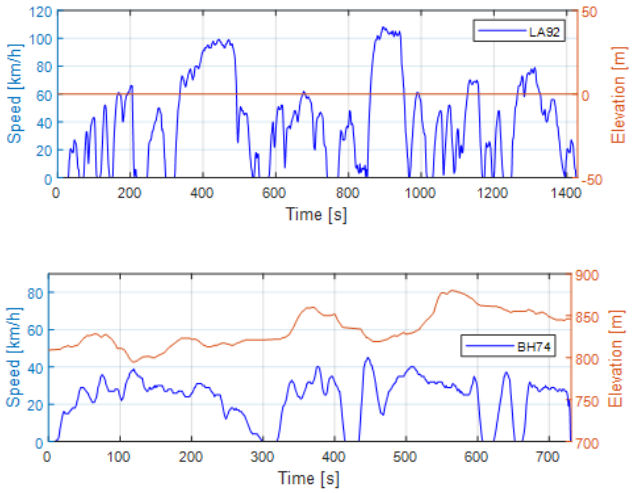
# NOx sensor model application (Co-Simulation)

**Case 1 - Standardized driving cycle**

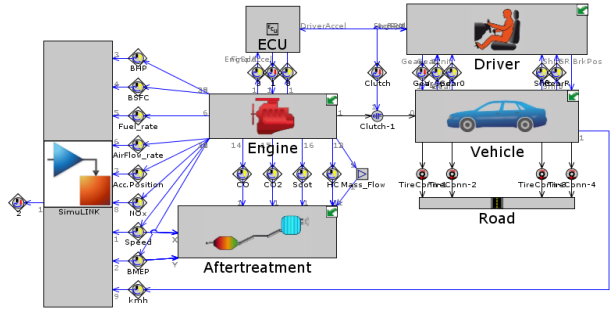
- LA92 – Los Angeles

**Case 2 – Brazilian driving cycle**

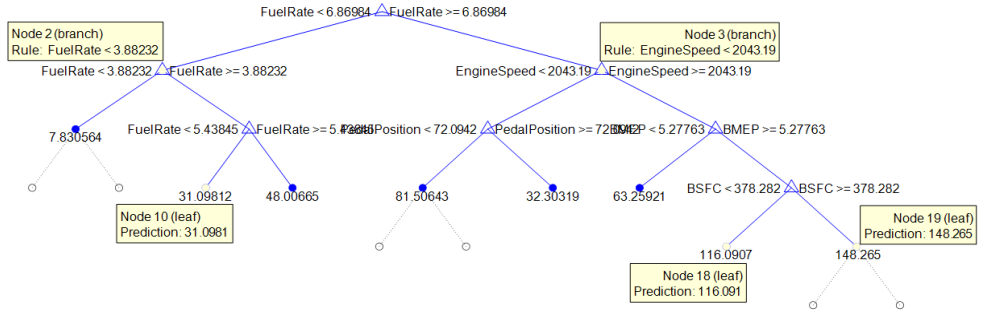
- BH74 – Presidente Antônio Carlos Avenue – Belo Horizonte, BR.

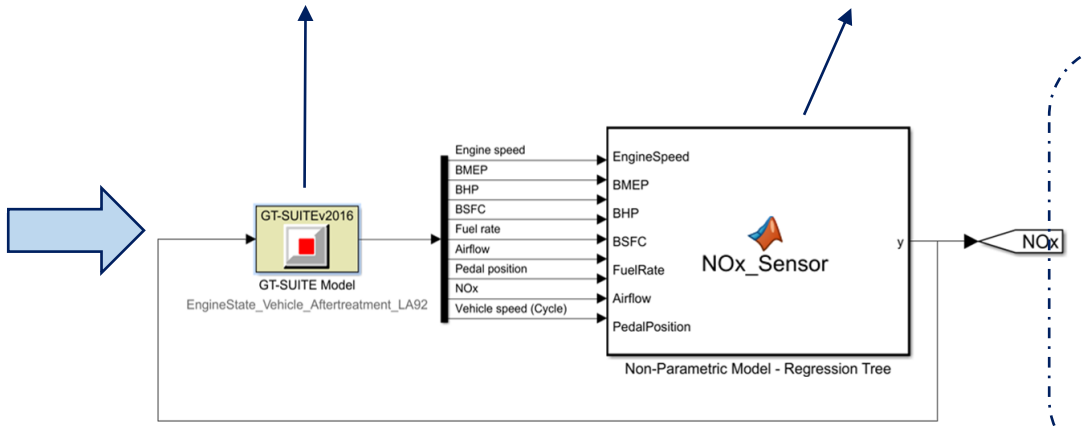



**GT-Suite vehicle model**

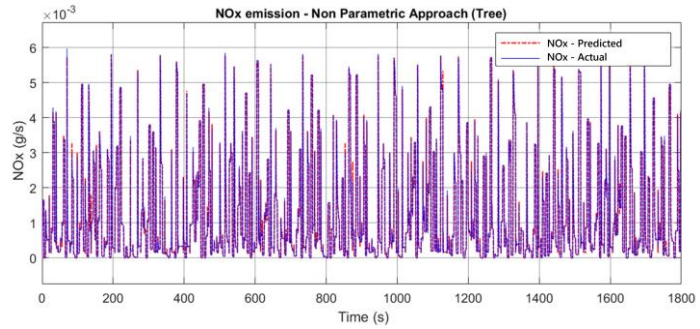



**NOx sensor model – Decision tree**



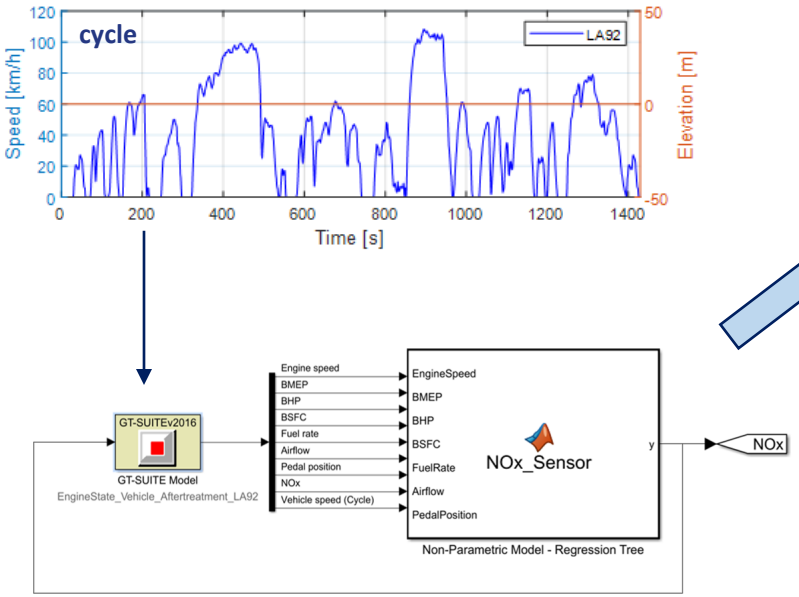

**NOx sensed - Sensor model output**



# NOx sensor model results

## Case 1 - Standardized driving cycle

- LA92 – Los Angeles



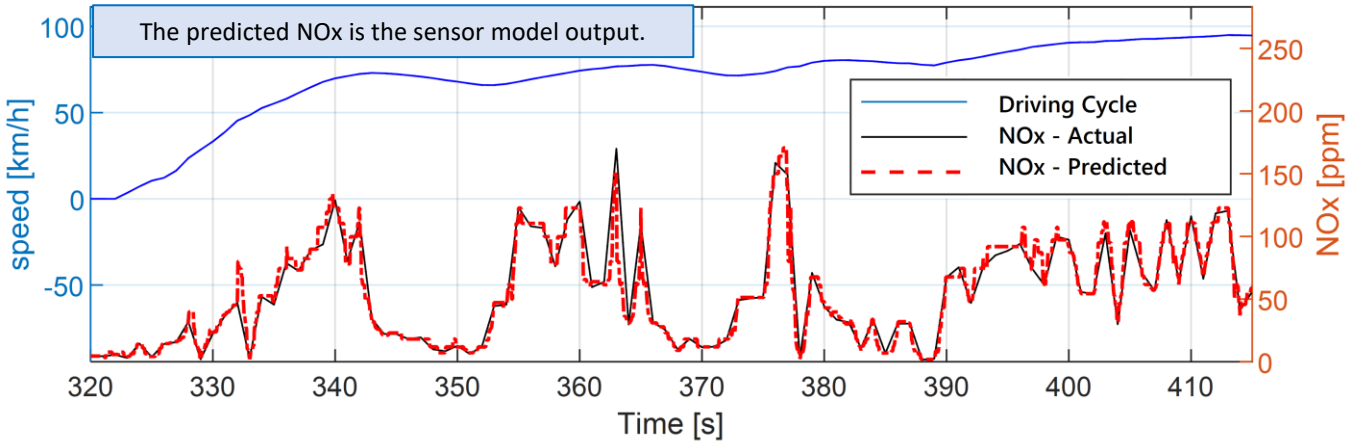




Figure 1 - Driving Cycle and transient NOx concentration

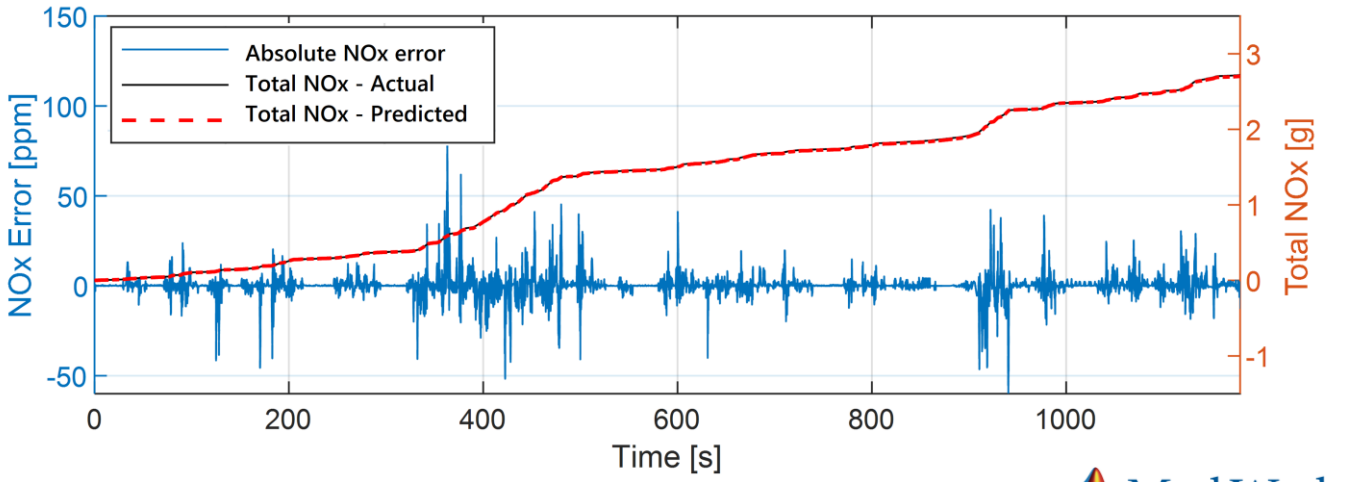
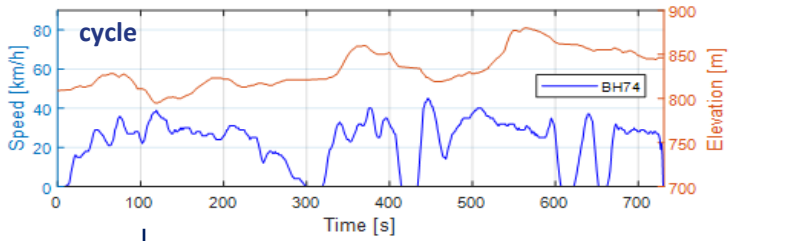


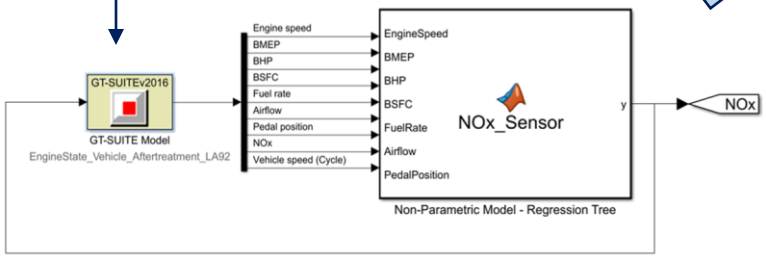

Figure 2 – Abs. instantaneous error and total NOx emission.

# NOx sensor model results

## Case 2 – Brazilian driving cycle

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



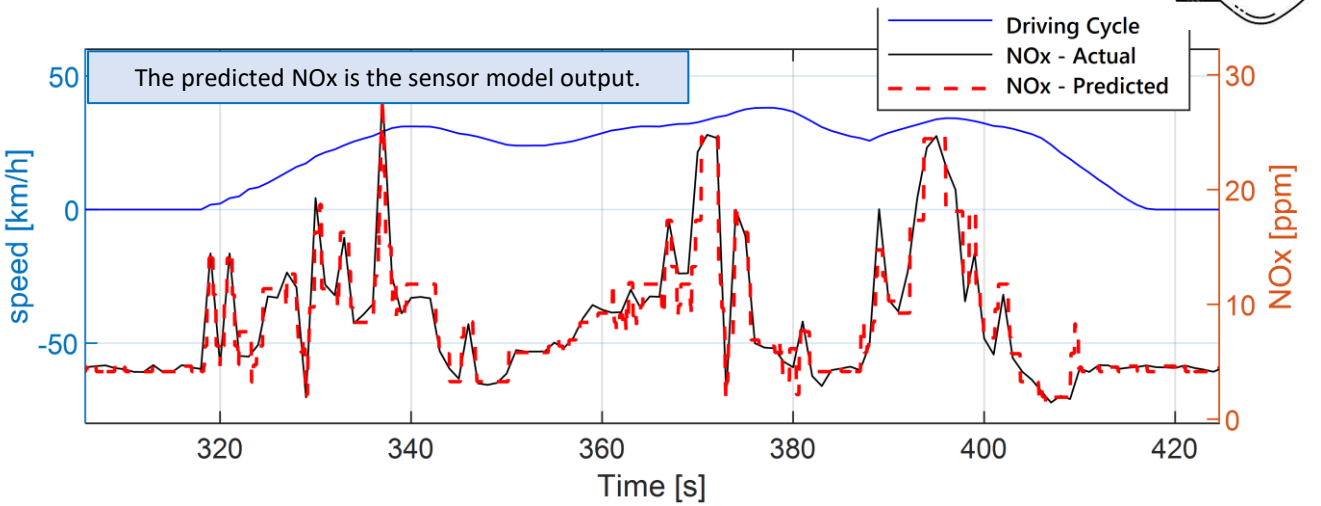




Figure 1 - Driving Cycle and transient NOx concentration

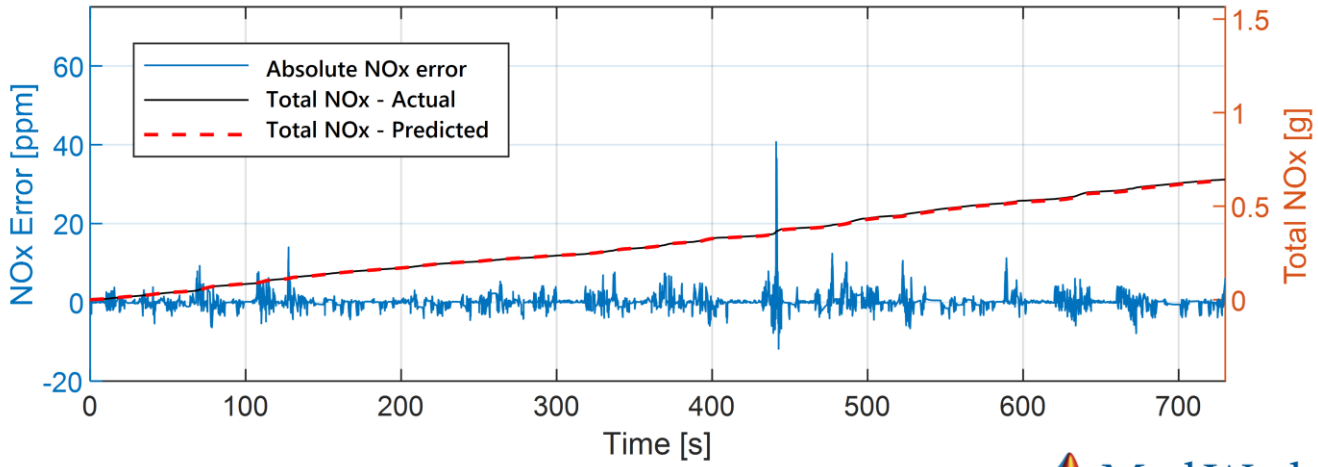



Figure 2 – Abs. instantaneous error and total NOx emission.

# NOx sensor model results

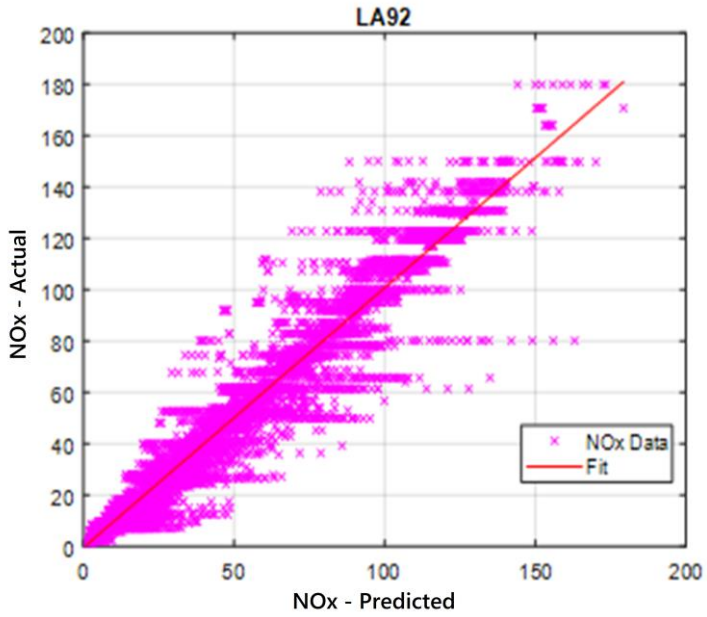
## Performance of both cases:

- 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.

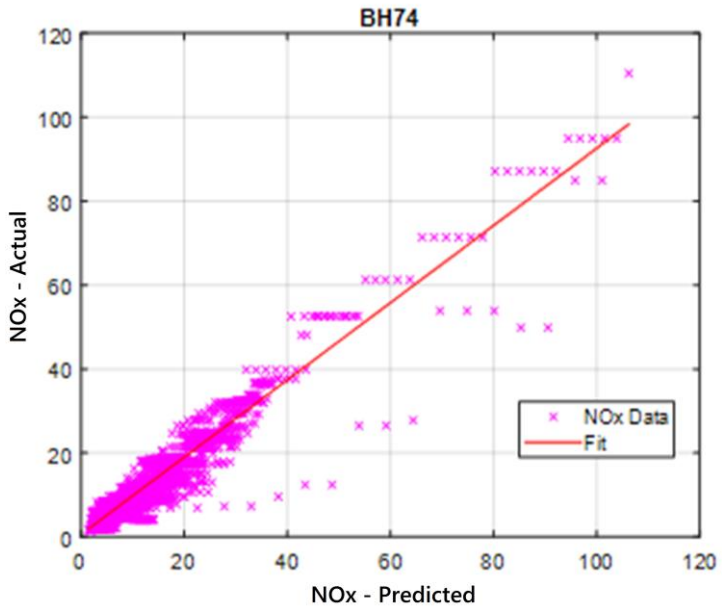
### Case 1 - LA92 – Los Angeles cycle




| | 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).

# Acknowledgment

The authors gratefully acknowledge **MathWorks Company** for providing AI and MATLAB technical support. Special thanks to:

- **Shyam Keshavmurthy**
- **Amit Deshpande**
- **Tom Fuelle**

# Thanks for your time!

# Q&A

**Rafael Átila Silva, PhD candidate.**
rafael.atilasilva@stellantis.com

**Marcelo Lanza**
marcelo.lanza@stellantis.com

**Gustavo Duarte**
gustavo.duarte@stellantis.com

**Mark Yu, PhD.**
mark.yu@stellantis.com