Development of Numerical Simulink Model to Predict Tail Pipe NOx Emissions of a BSVI Vehicle with Lean NO_x Trap

Prepared by:

M V Harish Babu
Senior Engineer
Mahindra & Mahindra - AFS

R Padmavathi
Lead Engineer
Mahindra & Mahindra - AFS

Dr. Saravanan Muthiah
Sr. Principal Engineer
Mahindra & Mahindra - AFS

Contents

- Objective and Motivation
- Current OEM Challenges for BSVI
- Lean NOx Traps (LNT) vs. Selective Catalytic Reduction (SCR)
- Introduction to LNT
- Approach
- Components of LNT Modeling
  - Efficiency
  - Regeneration
  - Temperature Transient Slip
  - Storage Capacity
- Simulink Model
- Correlation
- Applications

Objective and Motivation

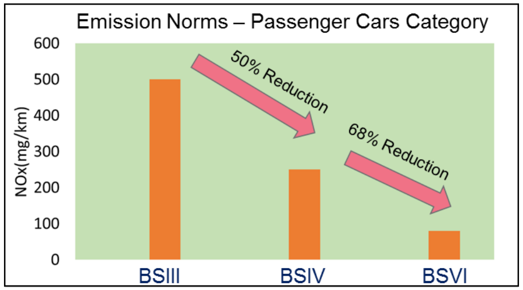
Objective:

The objective of the current modelling is to estimate the Tail Pipe NO_x emissions in order to understand the feasibility of meeting BSVI emissions norms & RDE Compliance factors with LNT as an after treatment system for NO_x reduction.

Motivation:

Effects of NO_x:

- Acid Rain
- Global Warming
- Ground level Ozone (SMOG)
- Visibility
- Respiratory Diseases



BS VI - April, 2020
RDE compliance

HC
CO
PM
NO_x
+ other gases

Less time available for the OEMs to be BSVI ready

Current OEM challenges for BSVI

- Less development time to be ready with BSVI
- Complexity of RDE
- Cost increase due to after treatment systems
- Durability of after treatment components
- Customer acceptance (Not to compromise on FE, driveability due to addition of after treatment systems)

Importance of Real driving Emissions :

- Real Driving Emissions(RDE) is critical in BSVI
- RDE will have a mixture of driving conditions of:

City

Critical factors:

- Critical bumper to bumper traffic
- Very less exhaust temperature
- Critical for after treatment systems light off

Rural

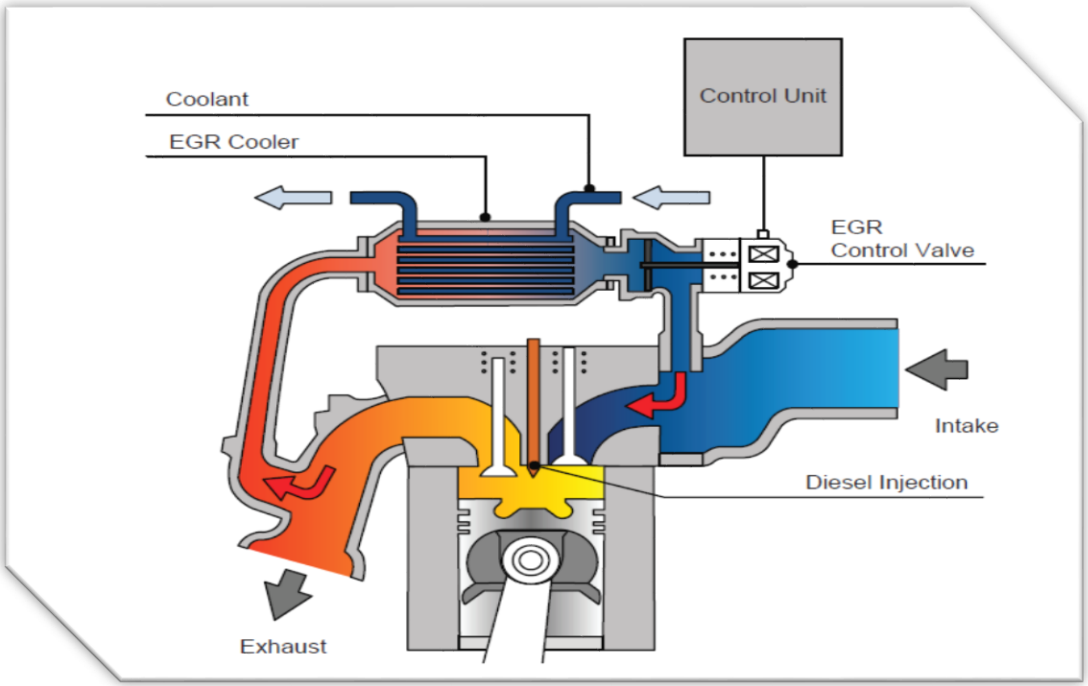
- High Engine out NO_x
- High accelerations

Highway

- Very high exhaust temperatures
- Very high Engine out NO_x
- High exhaust flow rate

Diesel Engine NO_x control:

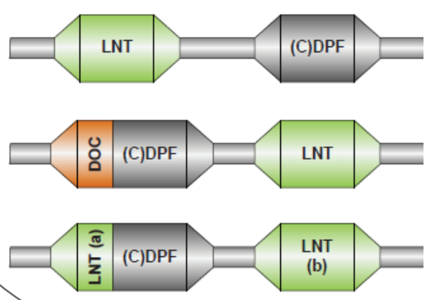
Typical Engine configuration till BSIV



Addition of After treatment devices is the way forward to meet BSVI norms

BSVI Engines

After treatment devices

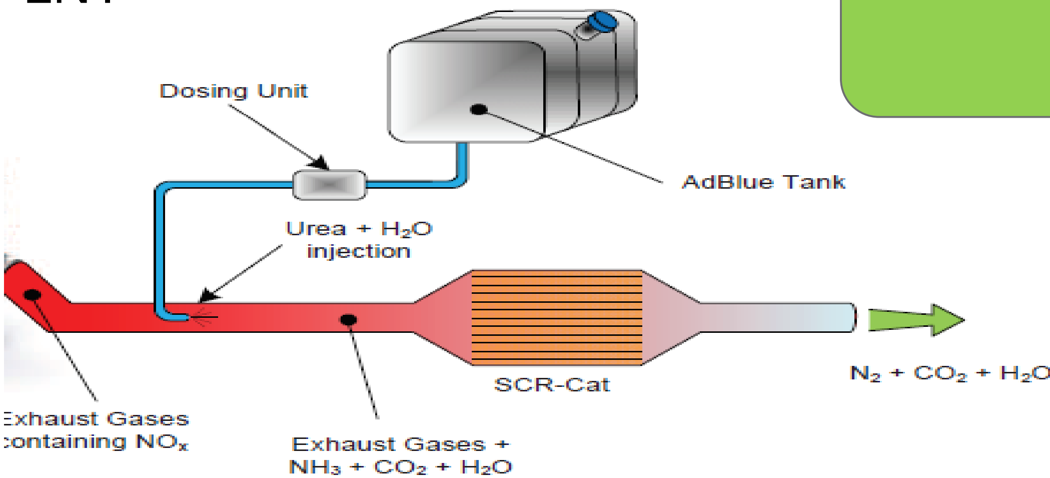


Reference: Modeling and Control of After treatment Systems for Diesel Combustion Engines, Vladimir Dvorak, *Diploma Thesis*.

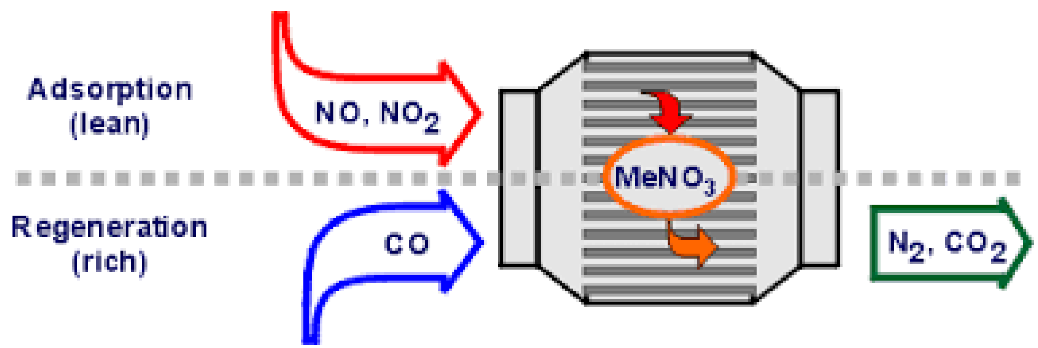
BSVI and Beyond: NO_X reduction Technologies

- SCR
- LNT

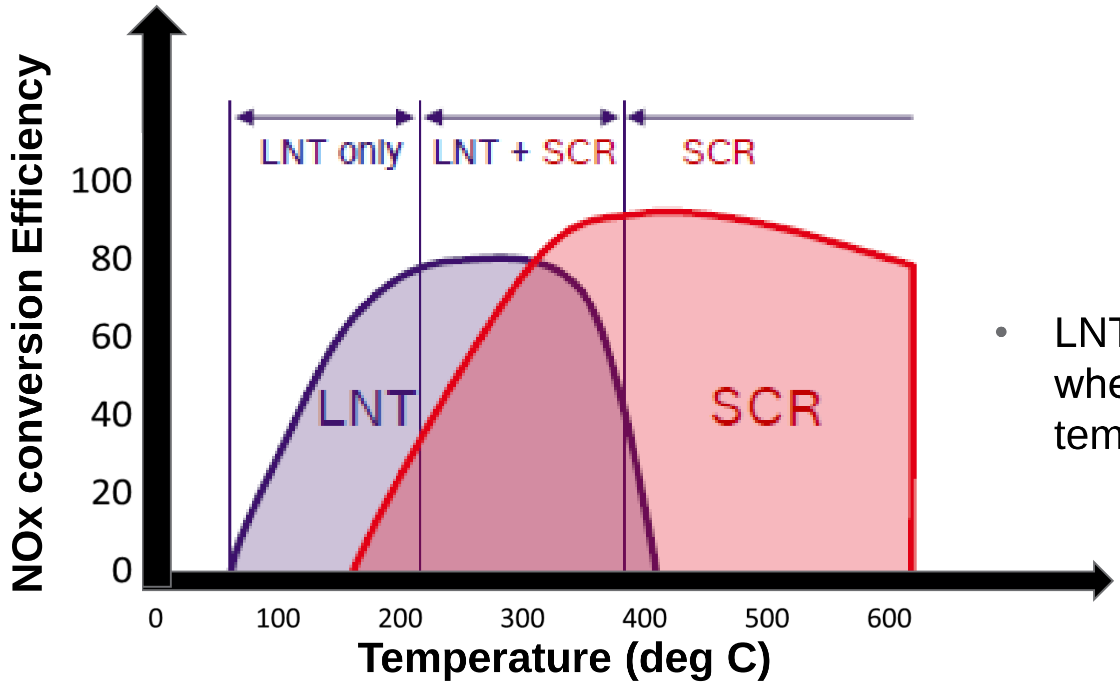
SCR



LNT



LNT vs. SCR



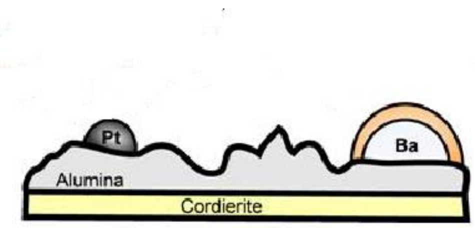
- LNT is efficient at low temperatures where as SCR's best operating temperatures tend to be higher.

Features comparison:

Parameter	Packaging Constraints	Reductant Fluid	Fuel Penalty	NO_X Conversion Efficiency	Desulphation
LNT	-	0	-	+	-
SCR	--	-	0	++	0

Introduction to Lean NO_x Traps(LNT)

- NO_x is adsorbed onto a catalyst during lean engine operation. When the catalyst is saturated, the system is regenerated in short periods of fuel-rich operation during which NO_x is catalytically reduced.



Formulation of LNT

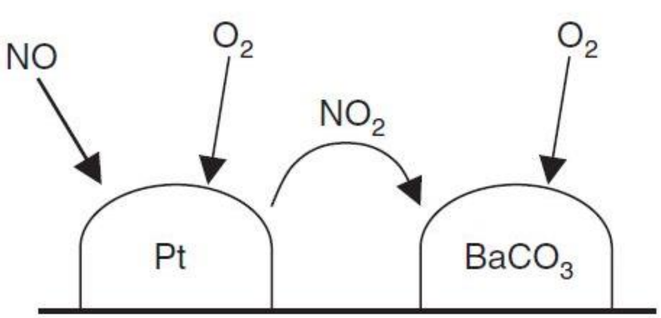
- The two phases of operation of LNT are:

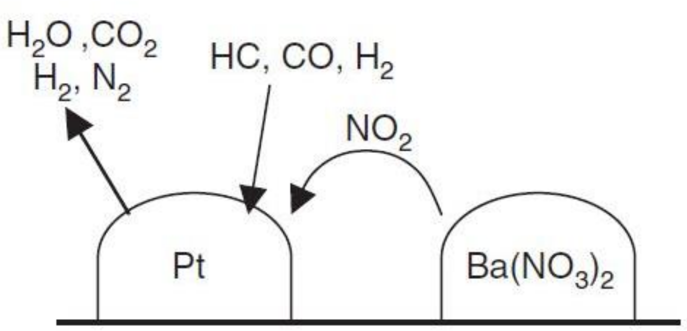
Storage

$$NO + 0.5\ O_2 \leftrightarrow NO_2$$
$$\tfrac{1}{2}\ BaCO_3 + NO_2 + \tfrac{1}{4}\ O_2 \leftrightarrow \tfrac{1}{2}\ Ba(NO_3)_2 + \tfrac{1}{2}\ CO_2.$$

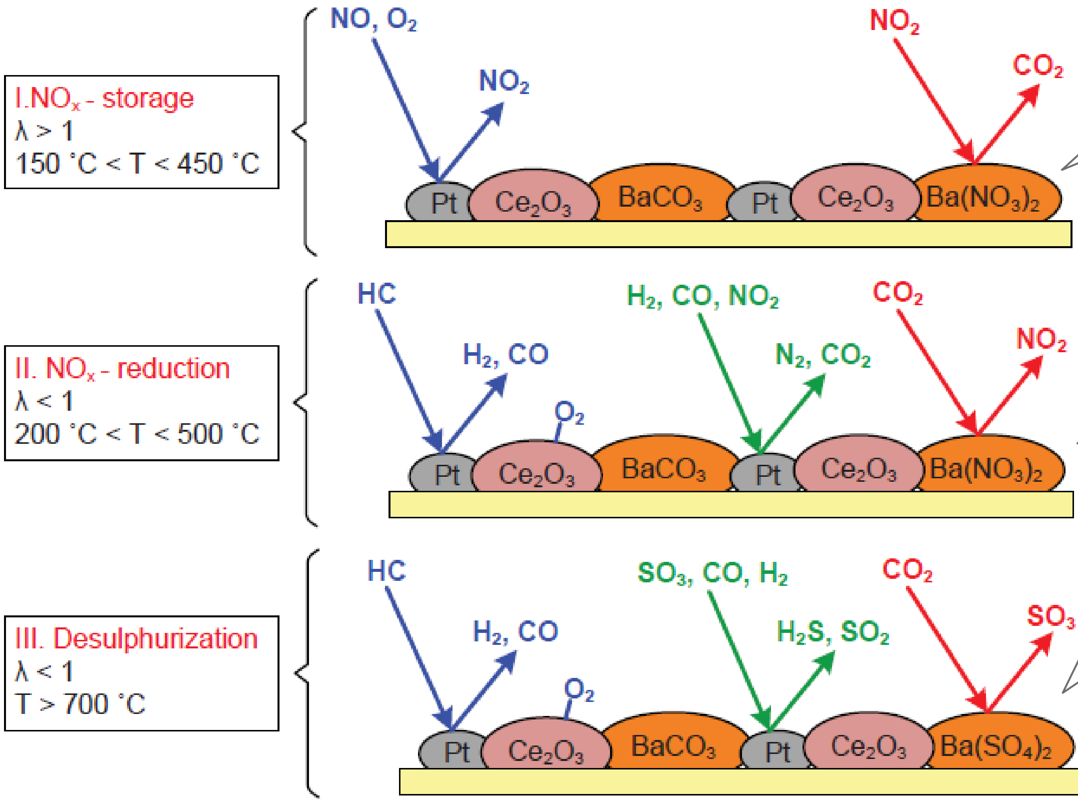
Purge/Regeneration

$$Ba(NO_3)_2 \leftrightarrow BaO + 2NO_2 + \tfrac{1}{2}\ O_2.$$
$$BaO + CO_2 \rightarrow BaCO_3$$





Phases of LNT

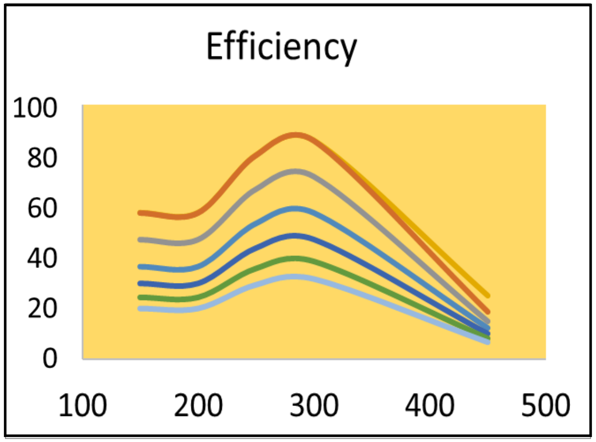


In lean mode, NO is converted to NO_2 on PGM and is further stored by Barium as Barium Nitrate

In rich mode, NO_2 is released by Barium and it is converted into N_2 on PGM

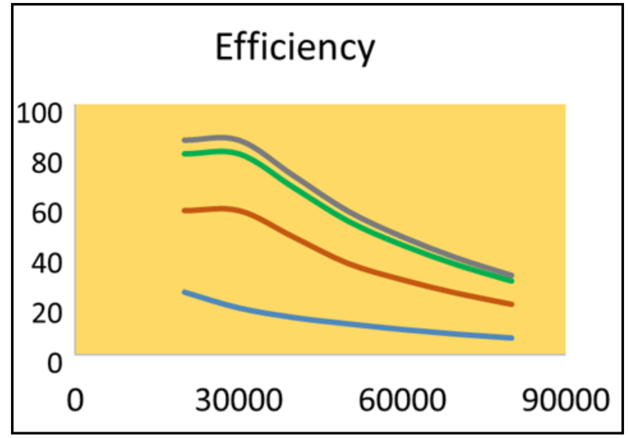
Sulphur, owing to high affinity, requires very high temperatures to be removed. Hence, a desulphation is conducted periodically.

LNT Characteristics



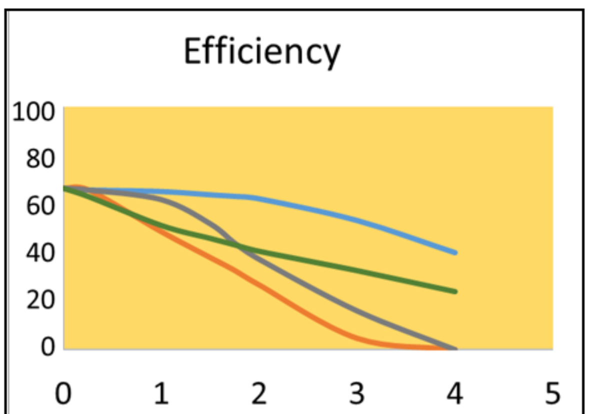
Temp (deg C)

At different Space Velocities and at constant filling and NO_x ppm



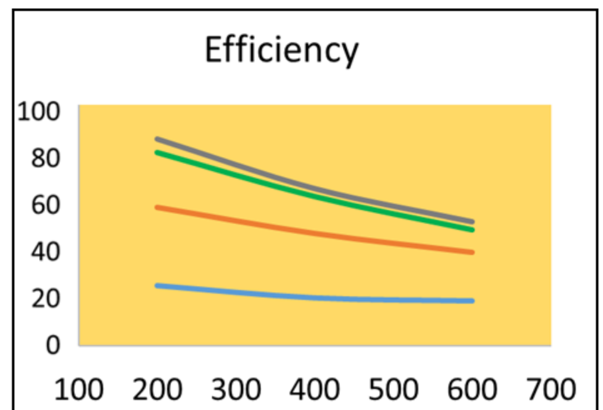
SV(1/hr)

At different Temperatures and at constant filling and NO_x ppm



Stored NO_x (g/l)

For different Temperatures and at constant Space Velocity and NO_x ppm



NO_x ppm

For different Temperatures and at constant Space Velocity and Stored NO_x

Traditional Procedure

Obtain LNT prototypes from suppliers

Calibrate the Engine to reduce Engine out NO_x

LNT rich mode calibration

LNT Desulphation calibration

LNT Vehicle level calibration

Employ vehicles with LNT and obtain the Tail Pipe Emissions

Decide if LNT will satisfy BSVI norms

Select the right technology

- The traditional procedure would take approximately 1.5-2 years.

- By simulating LNT behavior, we are able to take a call on the suitable after treatment technology in a short span of time (2 months)

Approach

Tests conducted:
- Obtain engine operating conditions
- Obtain engine out emissions data using condensed cycle run on Chassis Dynamometer
- Obtain temperatures of exhaust at various locations

On road testing
RDE data collection

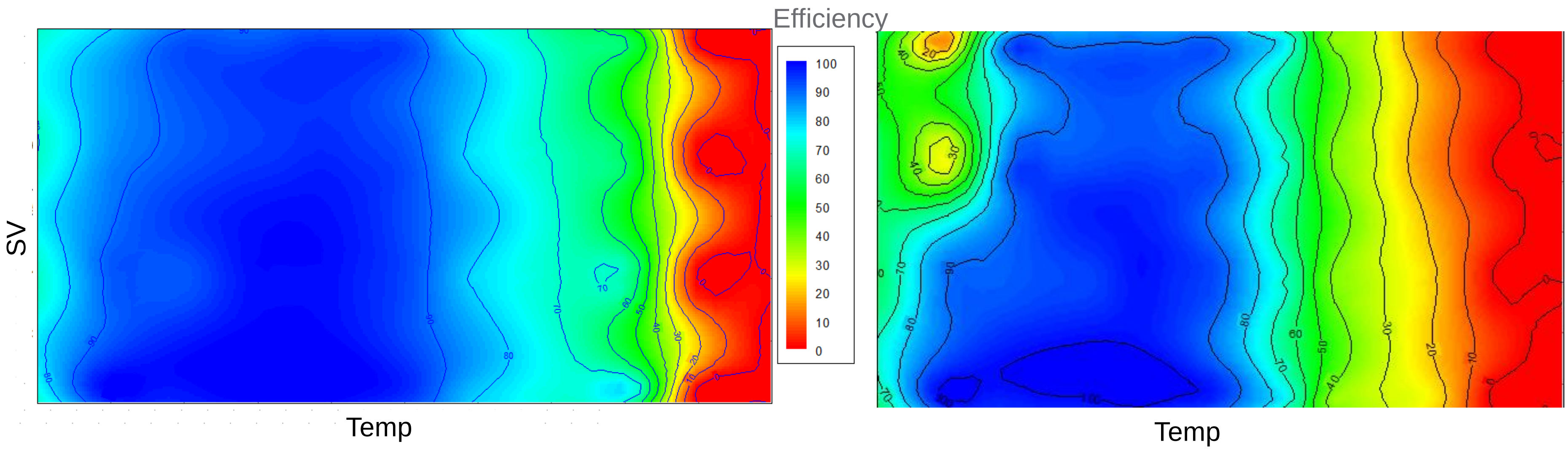
To desktop –
Simulink Model

Lab testing for LNT characterization

Tests conducted:
- NO_x conversion efficiency wrt temperate & Space velocity
- Maximum NOx storage limit at different temperatures
- NO_x conversion efficiency with different filling levels of the cat
- Efficiency of regeneration at different temperatures & filling level
- Temperature transient slip

Components of LNT Modeling

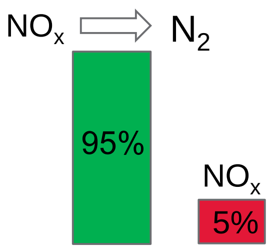
- **Efficiency**
  - Steady State Efficiency maps are obtained from Test Bed.
  - The Efficiency maps provide the dependence of Efficiency on Temperature, Space Velocity and filling.
  - A sample efficiency map is shown below:



The above maps represent the efficiency maps obtained for different fillings; the right picture is for higher filling.

Components of LNT Modeling

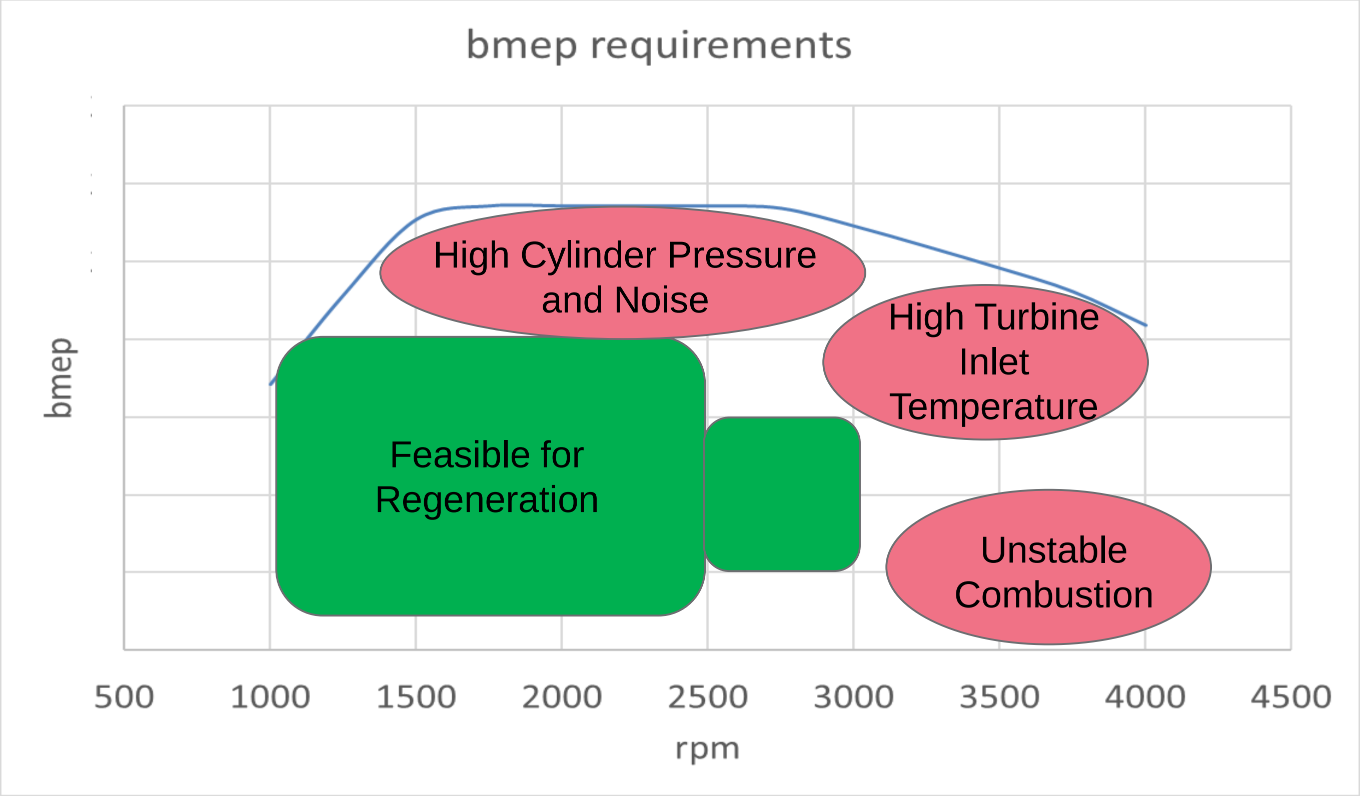
- **Regeneration**
  - Regeneration of LNT requires the engine to switch to rich mode for a small period of time (6-10 sec).
  - Efficiency of Regeneration:



  - Regeneration requires certain operating conditions and if the conditions are not met, regeneration is not performed or will be interrupted. The regeneration conditions are:
    - Minimum exhaust temperature needed: 230ºC

Components of LNT Modeling

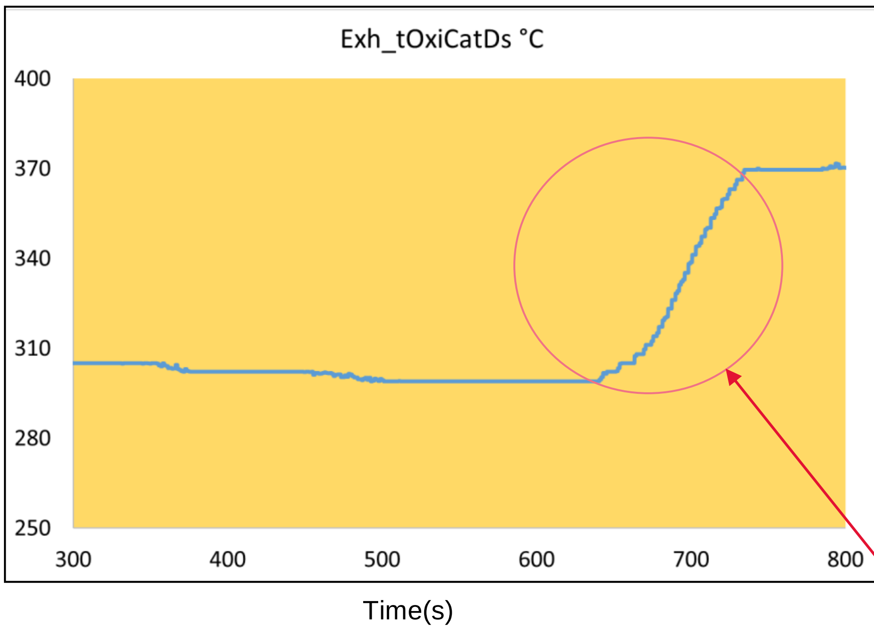
- **Regeneration**
  - brake mean effective pressure(bmep) requirements for regeneration are:

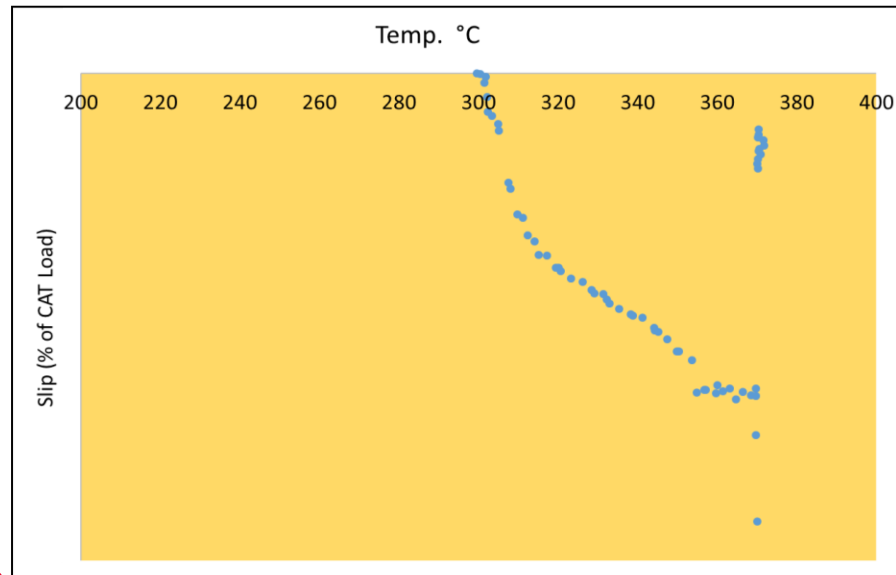


- Regeneration at higher bmep leads to high cylinder pressure and noise of the engine.
- At low bmep and high rpm, the engine would have to risk unstable combustion during regeneration and thus not feasible.
- Regeneration at high bmep and high engine speed can lead to a risk of turbine damage owing to high gas temperatures.

Components of LNT Modeling

- **Temperature Transient Slip**
  - During temperature ramps, Tail Pipe NO_x slip is observed and the corresponding effects are included after analysis.





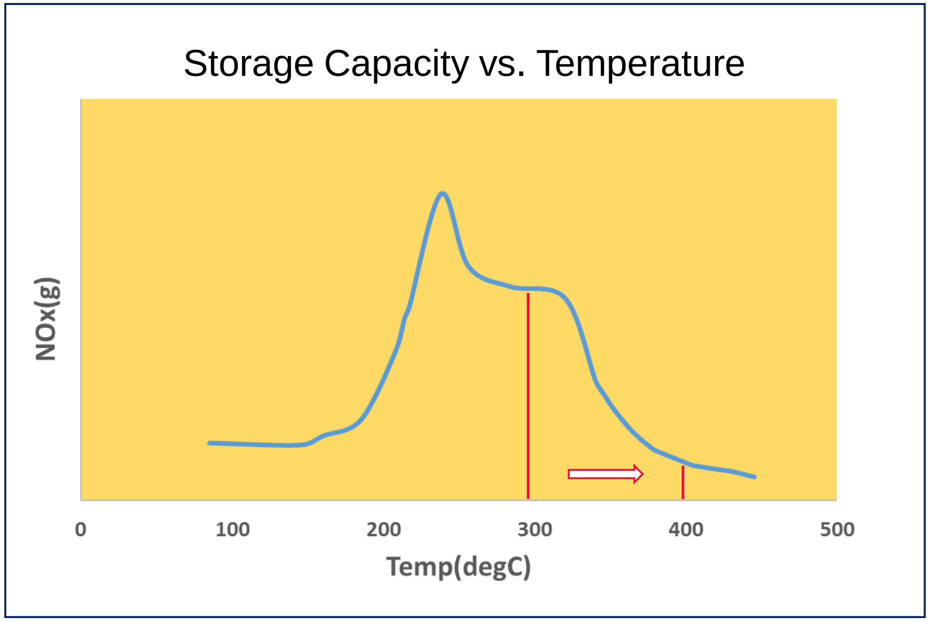
Temperature Ramp

Test Data

Extracted Data

A deviation from Steady State efficiencies, an extra slip of NO_x , is observed during temperature gain ramps. The corresponding differences are extracted by conducting tests at different starting temperatures and extra slip data is extracted.

Components of LNT Modeling



Storage Capacity

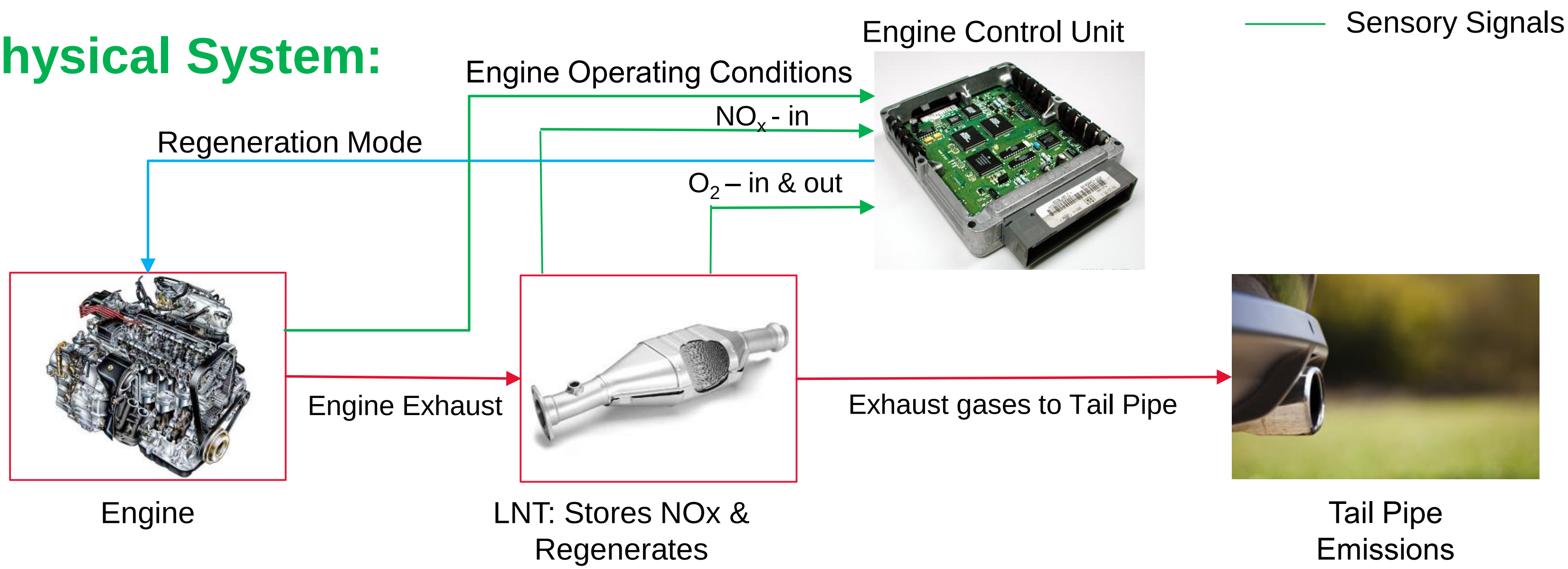
- Storage Capacity = f(T,SV)
- Storage Capacity is high at medium temperatures and drops at either extremities
- Storage Capacity has very less dependency on SV; hence not considered.

Due to transient temperature, a small increase of it can change the storage capacity of CAT drastically

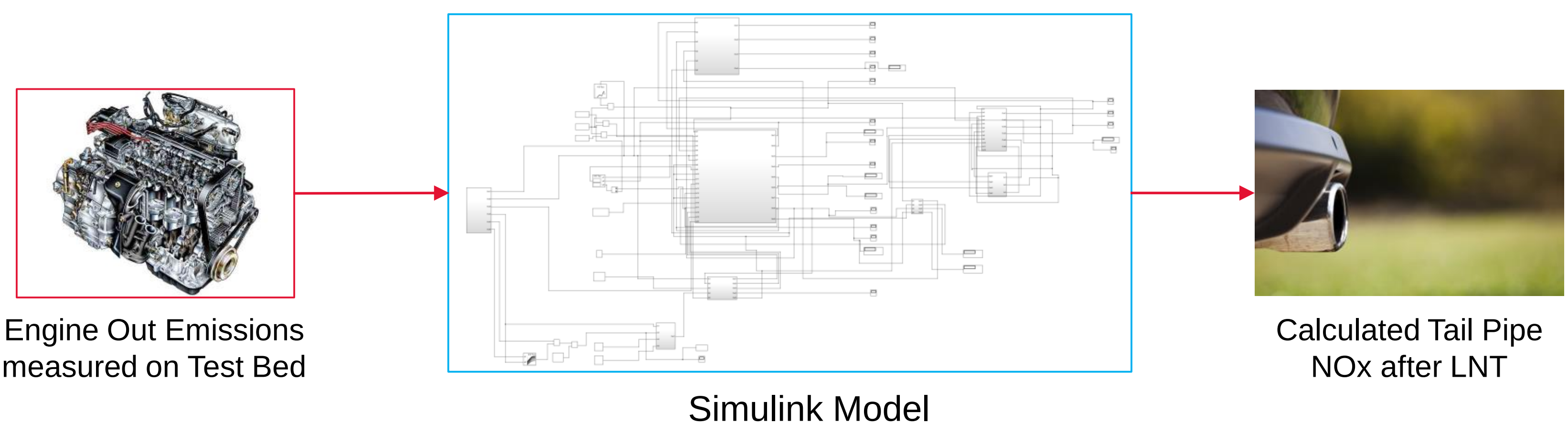
- If the currently stored value of NO_x equals the storage capacity at the current temperature condition, the efficiency reaches 0 and further storage is not possible.
- Similarly, if the current stored NO_x is higher than the storage capacity at the current temperature, LNT desorbs NOx.

Creation of Simulink Model

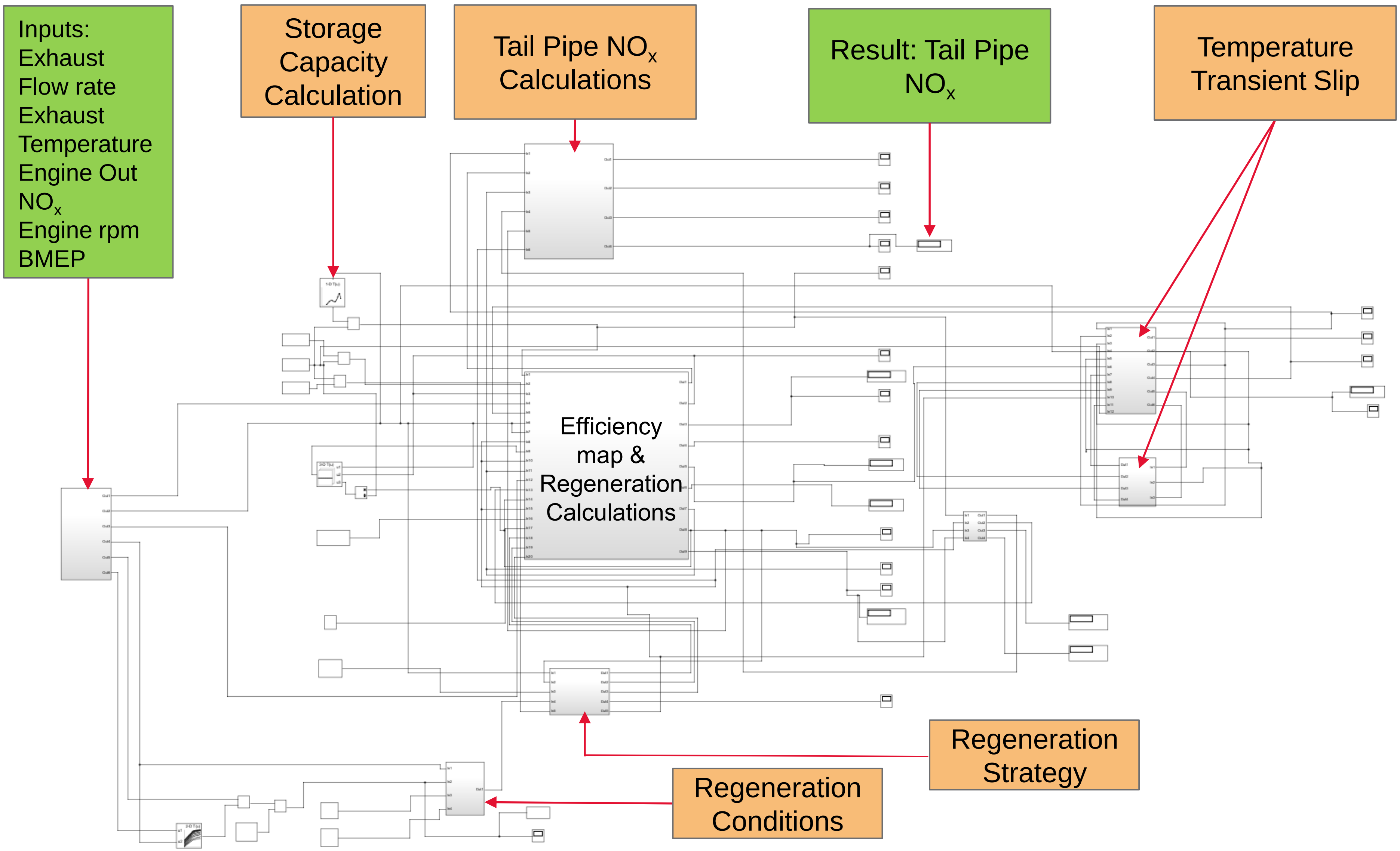
Physical System:



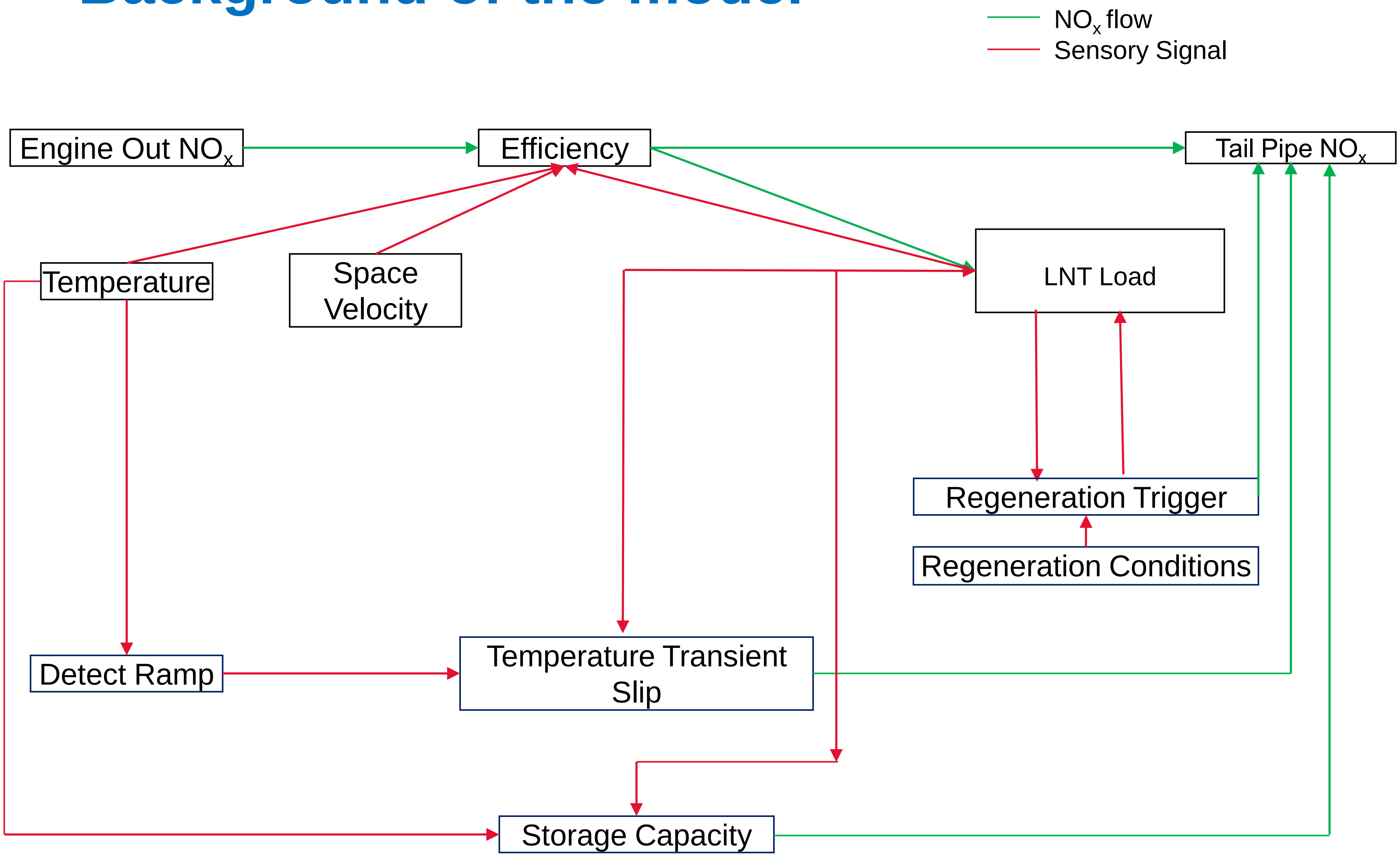
Mathematical Model:



Simulink Model

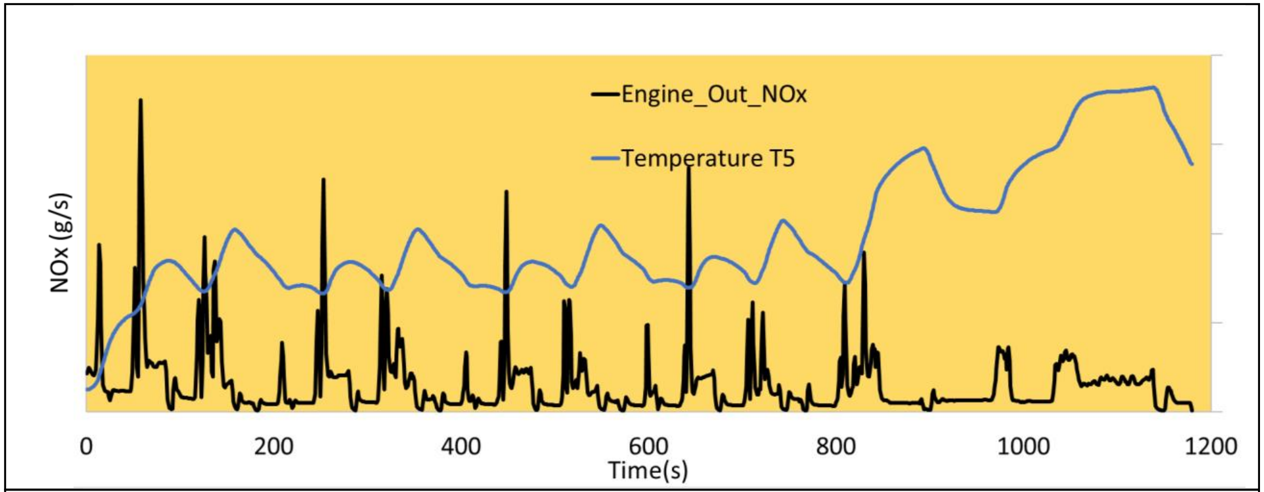


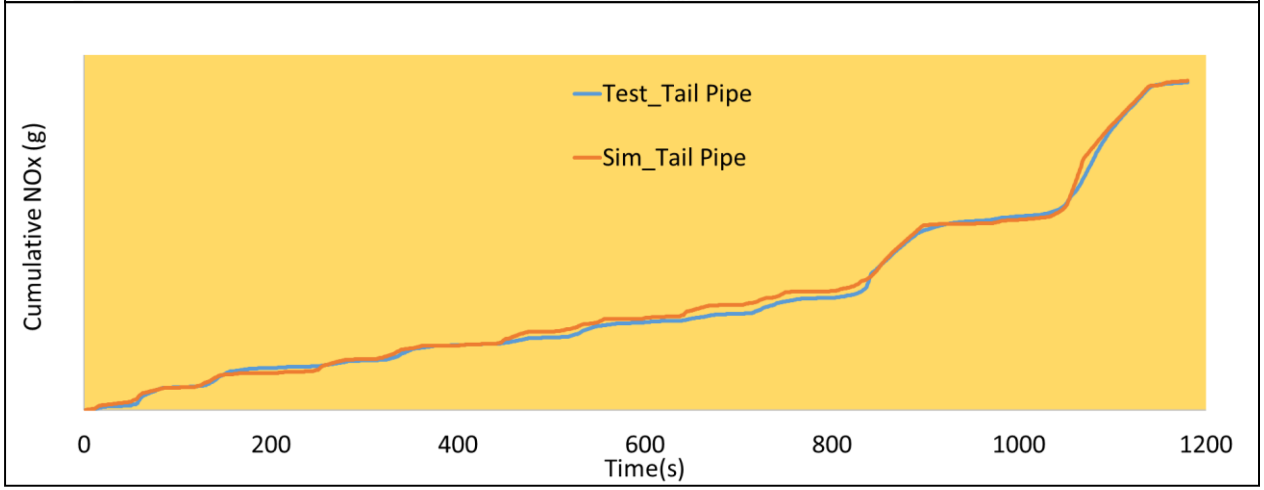
Background of the model



Correlation with New European Driving Cycle (NEDC)

- NEDC Simulation results are compared to Test'

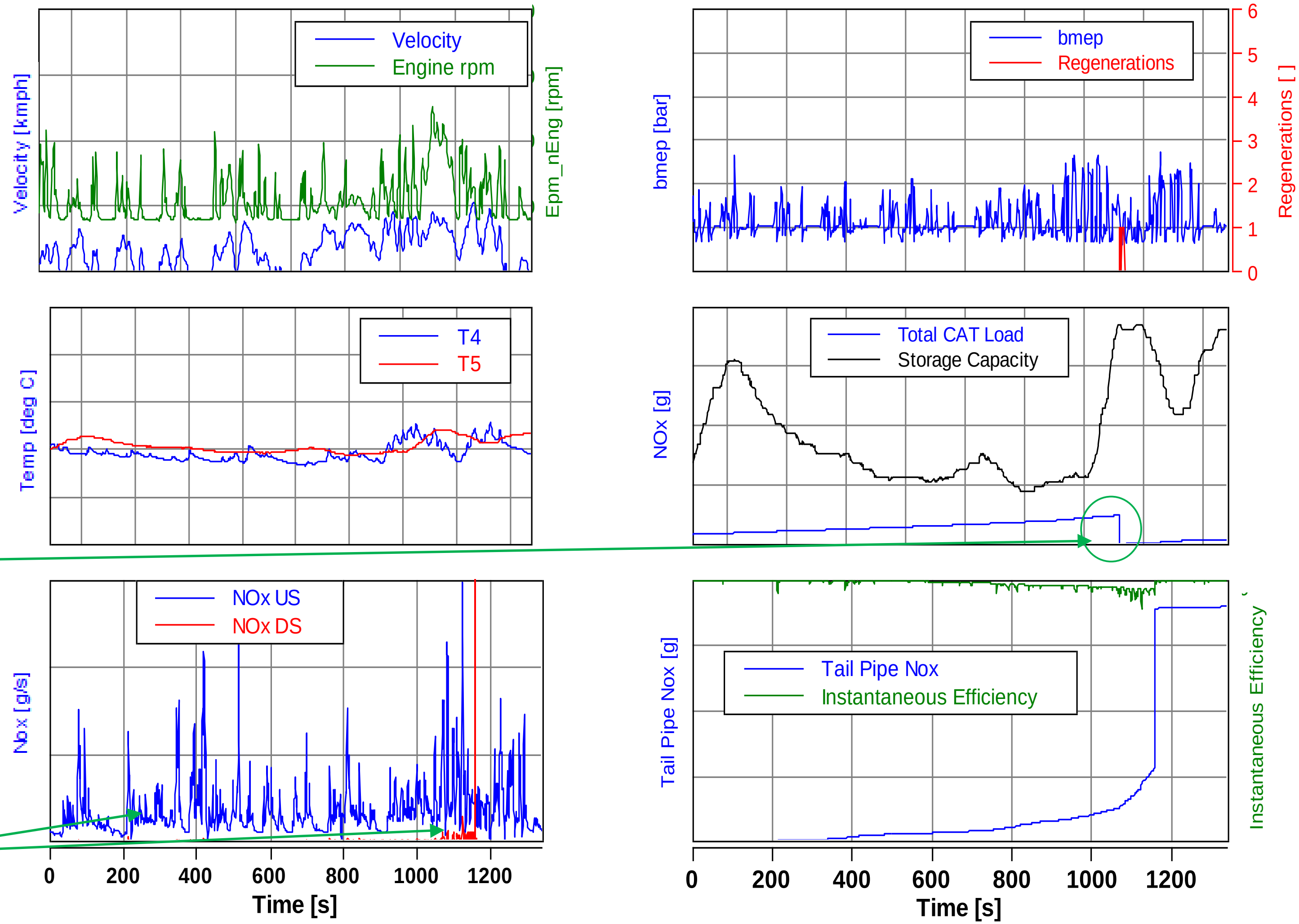




Correlation : 99%

Application to Real Driving Emissions:

Parameter	City Conditions
Time (s)	1341
Distance (km)	4.51
Avg. Speed (kmph)	12.10
CF (-)	0.50



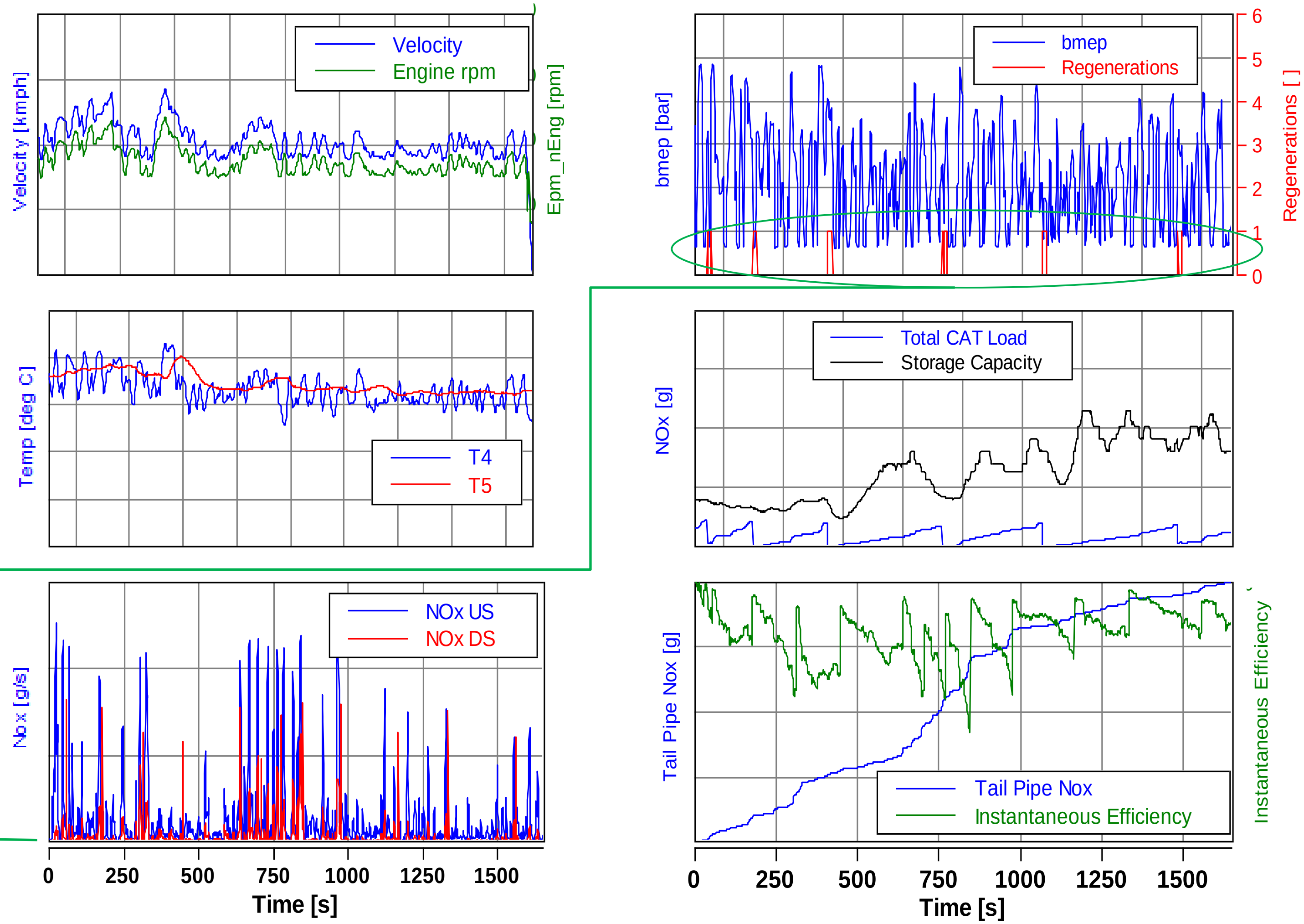
Regeneration

Very less Downstream NO_x compared to upstream NO_x.

CF of 0.5 implies that LNT will satisfy the emission requirements in city conditions.

Application to Real Driving Emissions:

Parameter	Highway Conditions
Time (s)	1651
Distance (km)	38.84
Avg. Speed (kmph)	84.69
CF (-)	2.61



Very high number of regenerations owing to suitable regeneration conditions and high Engine Out NO_x.

High Downstream NO_x because of less efficiency

CF of 2.61 implies that LNT will not satisfy the emission requirements in highway conditions for this vehicle application. But increasing the regeneration frequency can improve the CF.

Change of approach

Traditional approach

Obtain LNT prototypes from suppliers

Calibrate the Engine to reduce Engine out NO_x

LNT rich mode calibration

LNT Desulphation calibration

LNT Vehicle level calibration

Employ vehicles with LNT and obtain the Tail Pipe Emissions

Decide if LNT will satisfy BSVI norms

Select the right technology

- The traditional procedure would take approximately 1.5-2 years.
- By simulating LNT behavior, we are able to take a call on the suitable after treatment technology in a short span of time (2 months)

Requires a lot of time and effort

Simulation based approach

On road testing
RDE data collection

Tests conducted:
Obtain engine operating conditions
Obtain engine out emissions data using condensed cycle run on Chassis Dynamometer
Obtain temperatures of exhaust at various locations

Lab testing for LNT characterization

Tests conducted:
- NO_x conversion efficiency wrt temperate & Space velocity
- Maximum NOx storage limit at different temperatures
- NO_x conversion efficiency with different filling levels of the cat
- Efficiency of regeneration at different temperatures & filling level
- Temperature transient slip

To desktop – Simulink Model

Able to correlate well with tests and requires very less time

Summary

- OEMs have to select the best technology to satisfy BSVI emission norms for all the vehicle variants within the limited time period.
- In this scenario, using a simulation model helps in reducing the precious time and effort.
- In order to study the feasibility of LNT for the given vehicle application, LNT characteristics are obtained along with engine out on-road emissions separately.
- MATLAB Simulink model is created successfully and feasibility study is performed for legislative cycles and RDE conditions.
- The created Simulink model can be used for different vehicle and engine variants and their applications in various RDEs.

Advantages of LNT Simulink model

- The feasibility of LNT meeting the emission requirements in a given cycle even before the vehicle level testing
- An idea of the size required
- An idea of required technology to meet the emission norms
- Comparison between different LNT suppliers
- An estimate of reduction of Engine-out emissions required
- Compliance factor in different RDE cycles can be predicted
- Same model can be used for different vehicle applications
- Time saving of approx. 1.5 years
- Cost saving
- Effort saving

Acknowledgements

- I thank
  - Mr. S Kannan
  - Mr. Siva Subramanian
  - Mr. Krishna Raj

  and the calibration team for their valuable guidance and support.

Thank you for your attention!