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Model Based SCR Controls

Development of a model based, mapless SCR control approach

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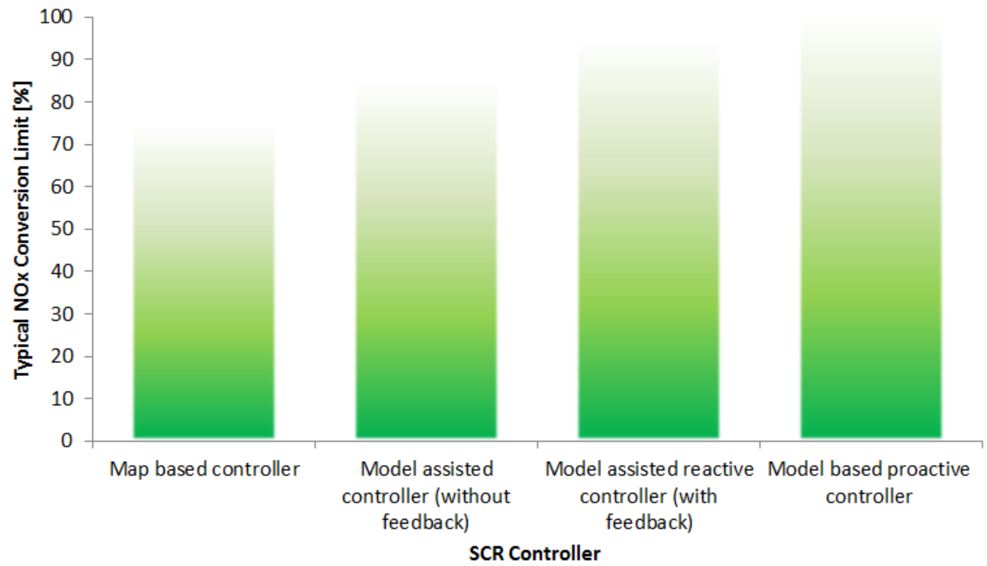
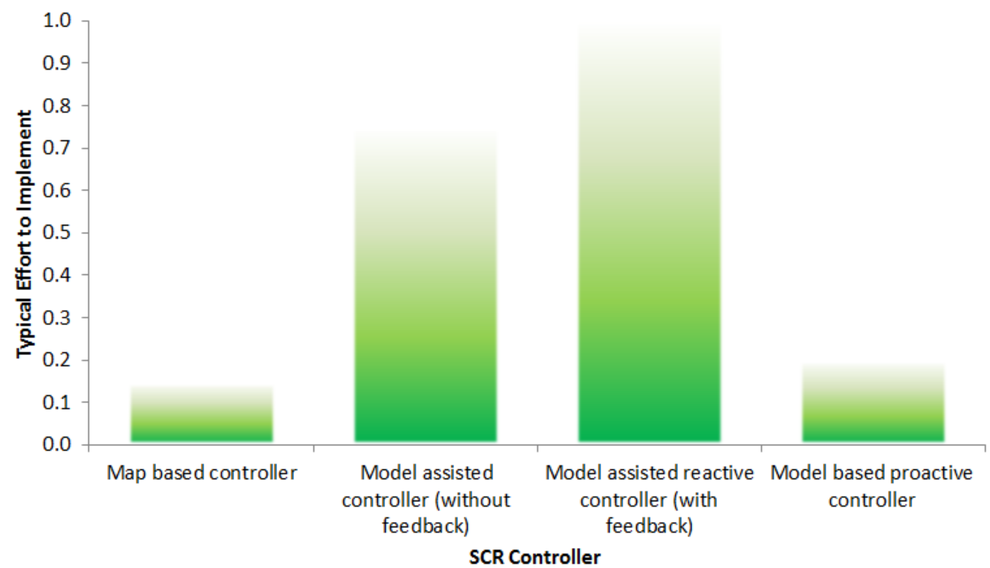
Introduction

- AdBlue/DEF dosing controls for the SCR can be a complex algorithm, relying on various lookup tables and maps to achieve desired NOx conversion while limiting tail pipe NH_3 slip
- Maps and lookup tables require a lot of calibration and validation effort to ensure successful implementation of controls
- Significant rework effort is required to retune dosing algorithm for different applications and different desired conversion efficiencies
- However, it should be possible (in theory) to simplify the controls structure through the use of our knowledge of the SCR physics and chemistry (already captured in the physics based SCR model in the ECM)
- Does the theoretical expectation hold
  - In a practical situation?
  - Over various different application cycles?
  - At varying levels of desired NOx conversion efficiencies?

SCR Control Landscape

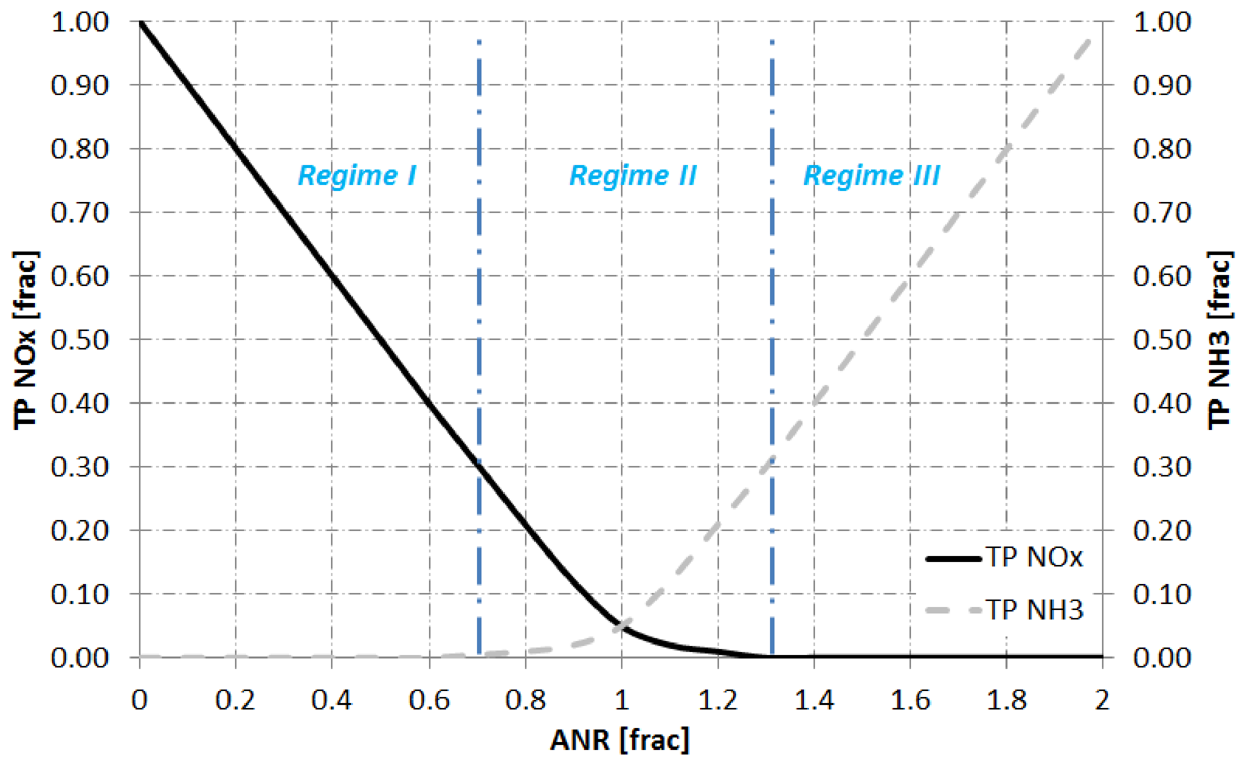
- Traditional SCR control schemes have been a tradeoff between performance and implementation effort
  - Increasingly diminishing performance increments for higher efforts
- Model based proactive controller is a paradigm shift in SCR controls approach
  - Higher performance for lesser effort



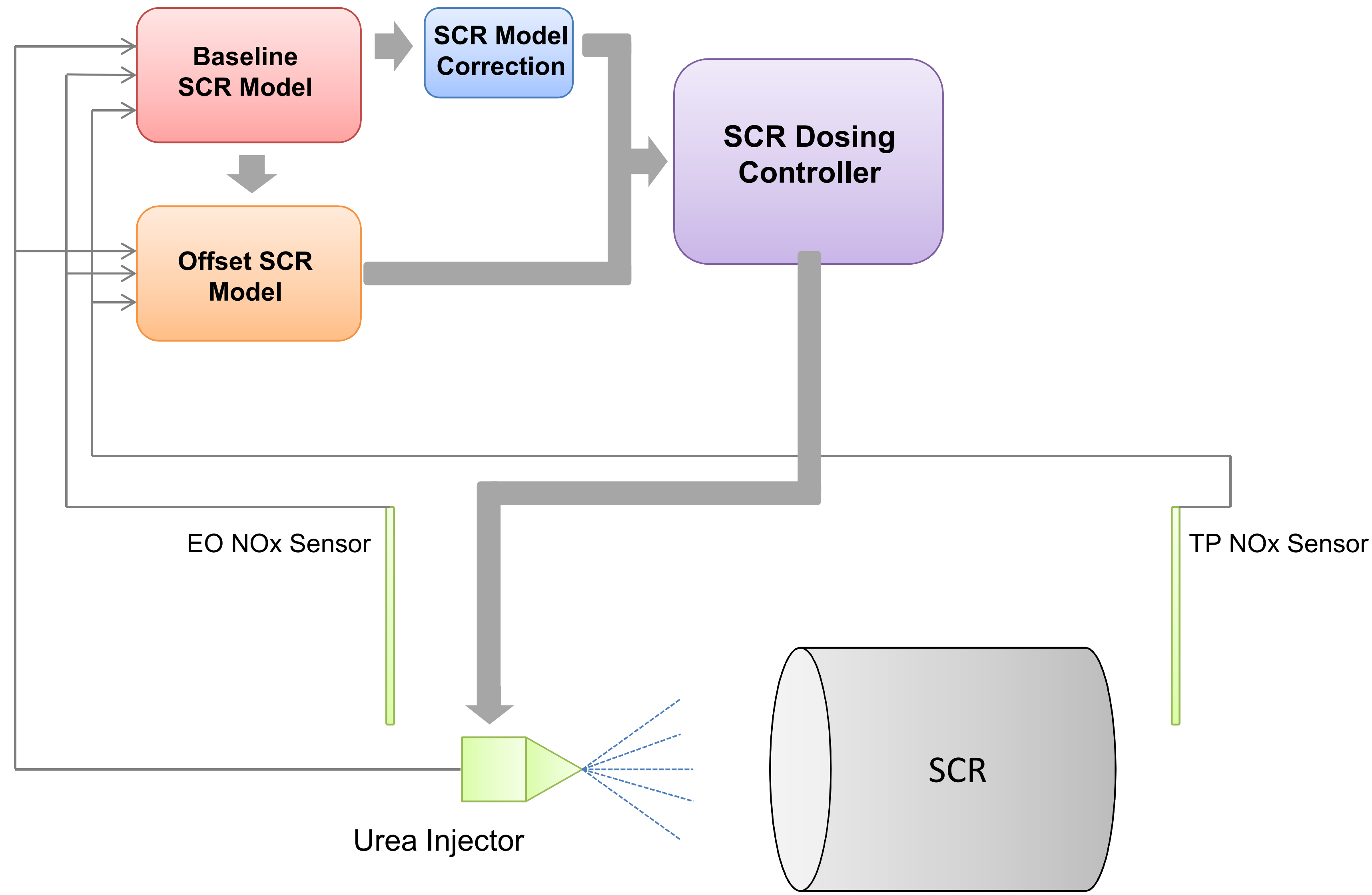


Fundamentals of SCR Chemistry

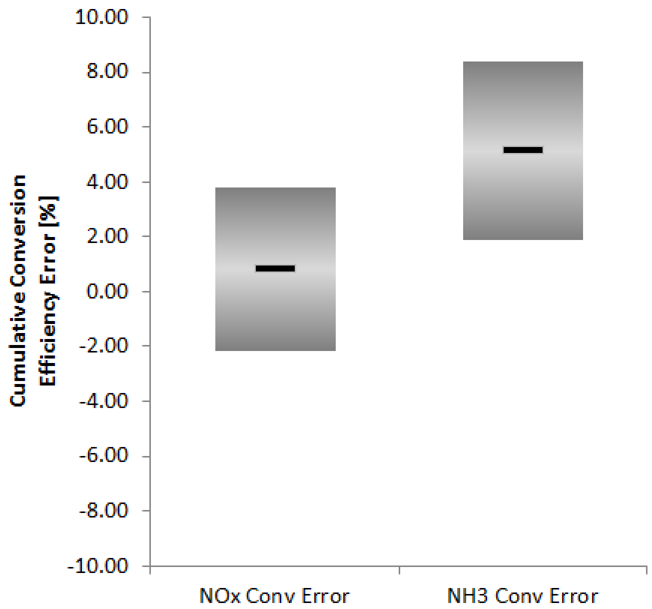
- **Regime I: Low NOx**
  - NOx slope wrt dosing ~ -1
  - NH_3 slope wrt dosing ~ 0
- **Regime II: ~ 100% NOx conversion**
  - NOx slope wrt dosing ~ - NH_3 slope wrt dosing
- **Regime III: High NH_3 slip**
  - NOx slope wrt dosing ~ 0
  - NH_3 slope wrt dosing ~ 1



Schematic of SCR Control System



Typical SCR Model Performance



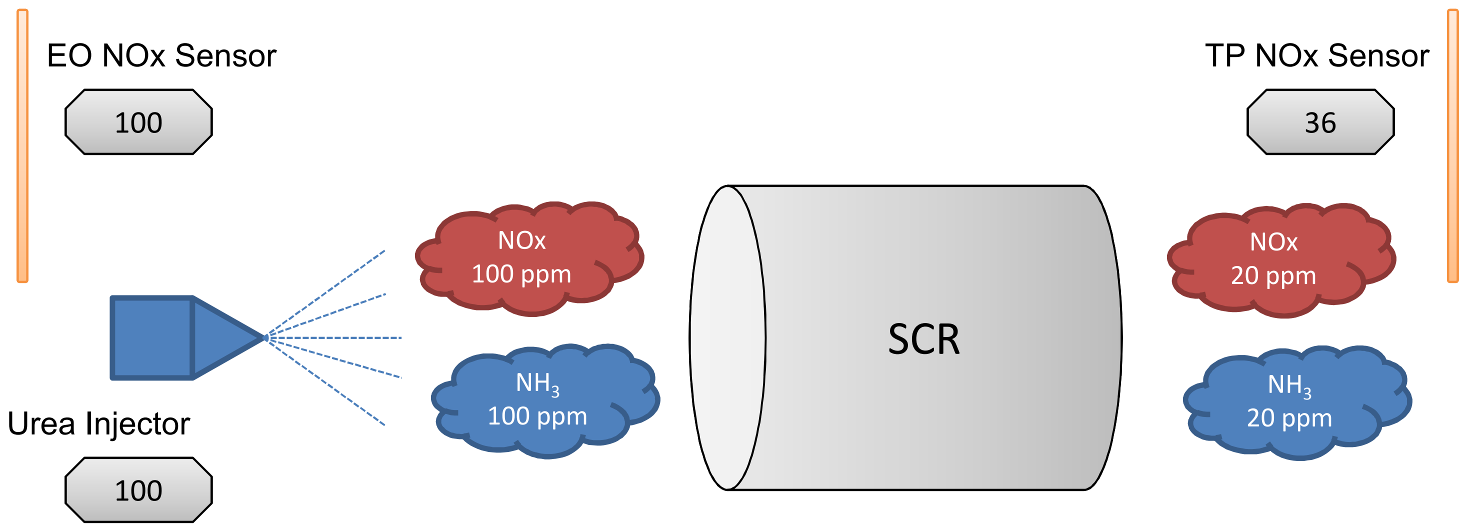
$$Prediction\ Error\ (\%) = 1 - \frac{(Measured - Predicted)}{SCR\ inlet\ concentrations}$$

- The model errors for NOx and NH_3 predictions are well within 10% for typical transient cycles lasting 1 hour or longer
- Errors are due to various reasons:
  - In field factors (temporary deactivation of catalyst)
  - Irreversible long term aging effects
  - Errors in dosing system etc.
- This level of accuracy is not sufficient for a SCR control strategy that relies completely on the model
- Eg: 10% error with 1000 ppm EO NOx results in 100 ppm error in predictions

SCR Model Accuracy

- What can be done to improve the model accuracy?
  - **Recalibration:** will not help since model is currently matching nominal catalyst performance well
  - **Detailed (dual site) mechanisms:** not sure if this will help improve accuracy of the predictions. Also, will be very hard to implement this detailed model in ECM
  - **Uncertainty modeling:** can use knowledge of input errors to model SCR performance more probabilistically – providing ‘probable’ TP NOx and TP NH_3 values (note that the nominal value for this range will be the same as current predictions)
  - **Sensor based corrections:** explore using TP sensor to improve prediction accuracy (with or without current model)

Sensor Based Estimation

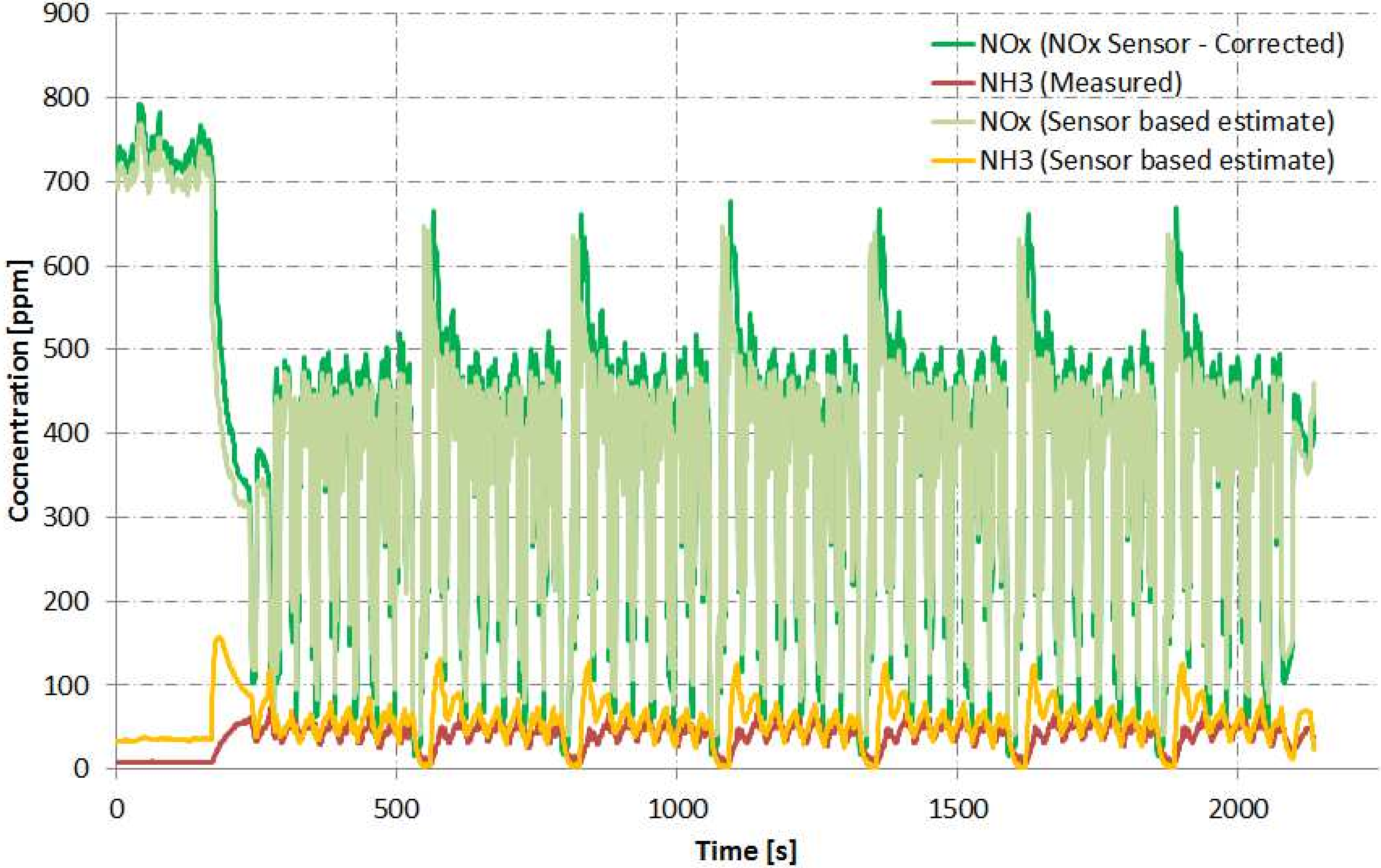


$$\text{TP NH}_3 = \frac{\text{TP NOx Sensor} + \text{Injected NH}_3 - \text{EO NOx Sensor}}{1.8}$$

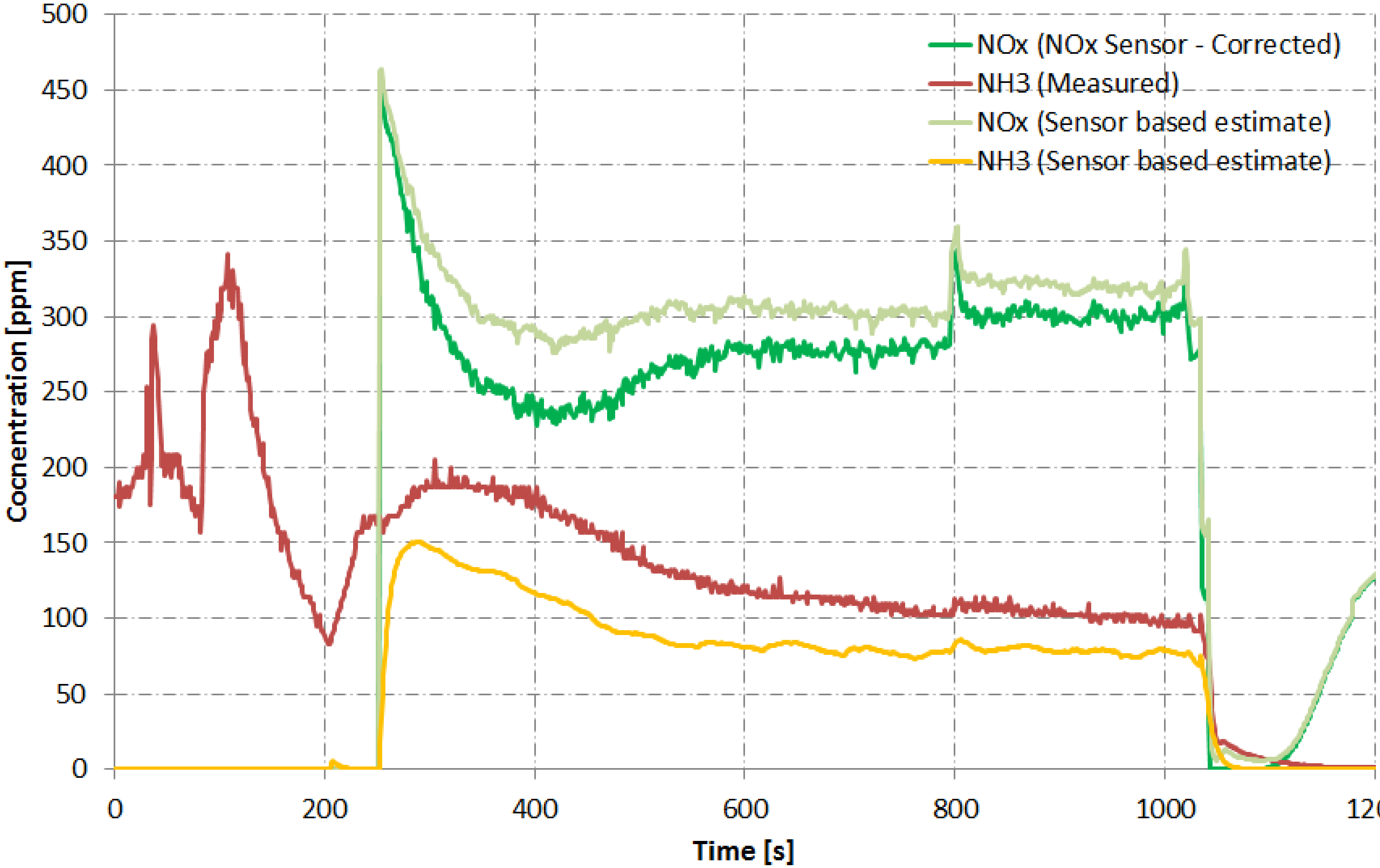
$$\text{TP NOx} = \text{TP NOx Sensor} - 0.8\text{NH}_3$$

Plugging in the known sensor values into the equations above, we obtain a TP NOx estimate of 20 ppm and a TP NH_3 estimate of 20 ppm (relative to the raw sensor reading of 36 ppm)

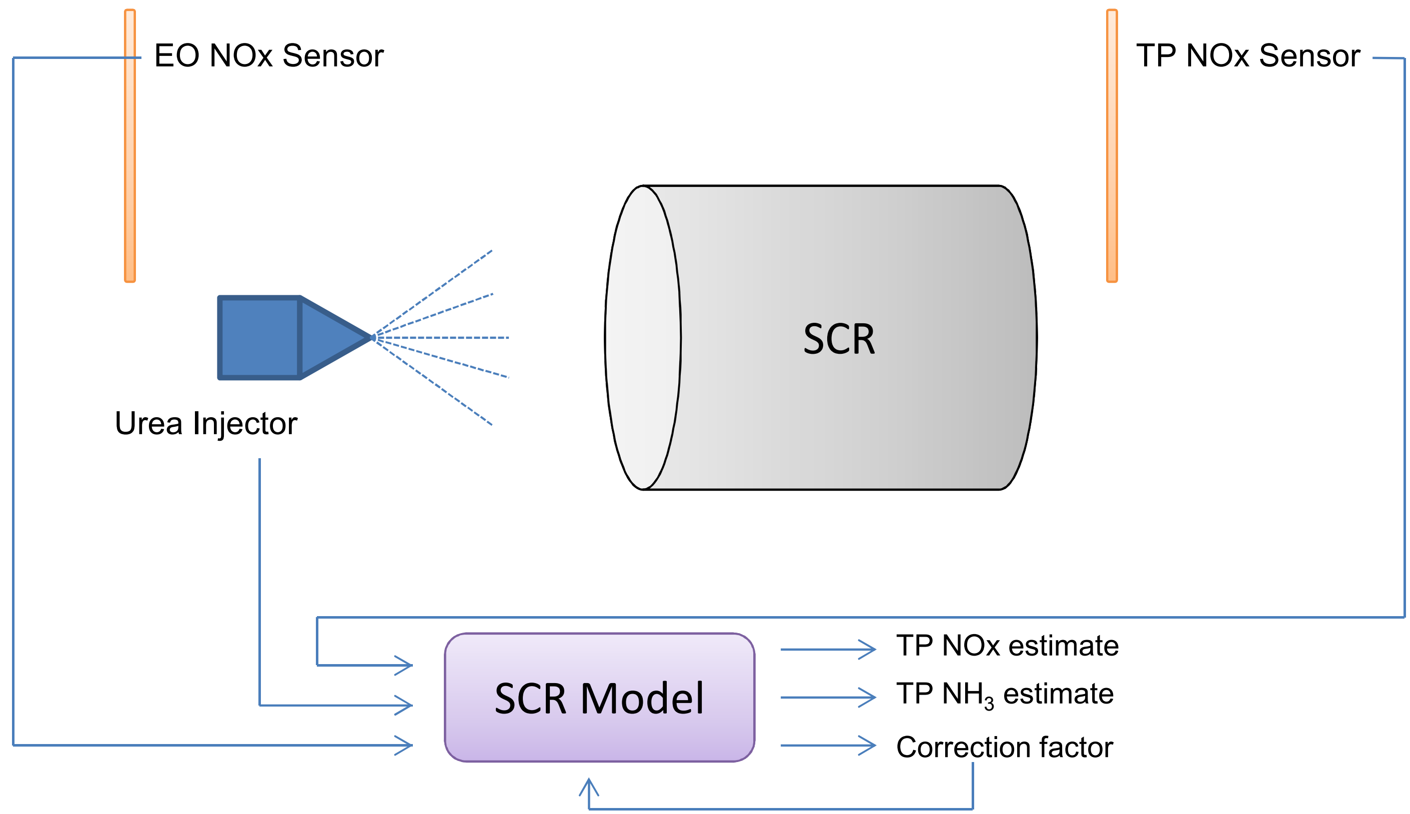
Transient Cycle #1



Transient Cycle #2

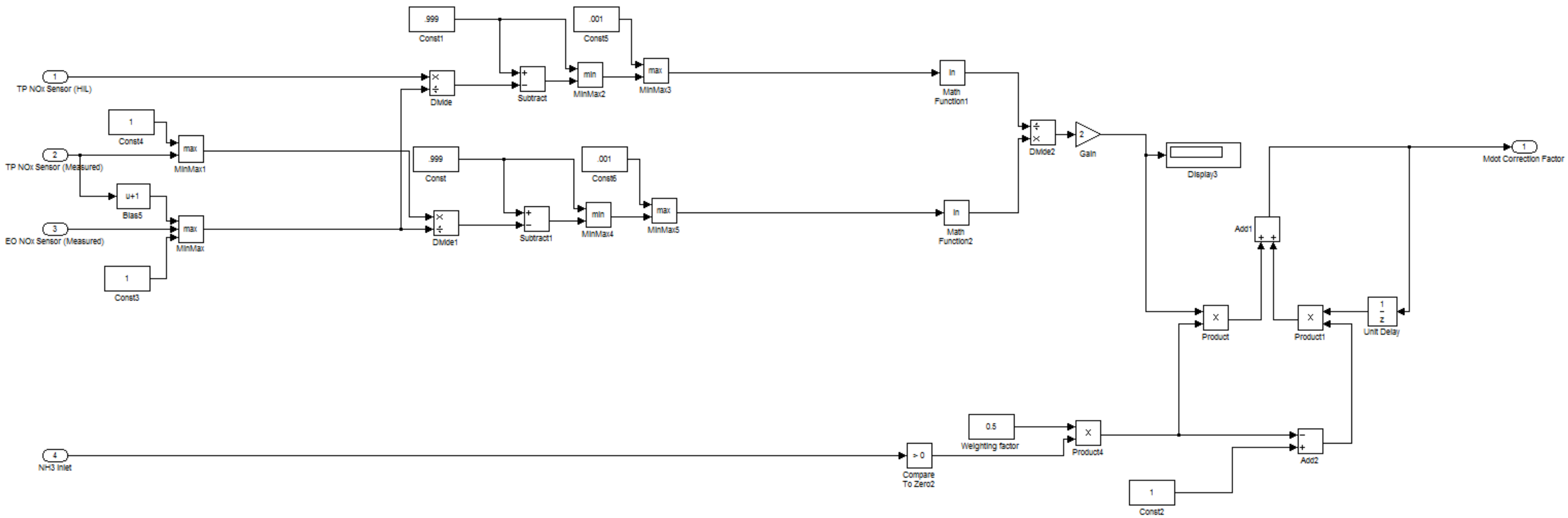


Sensor Based Error Correction for SCR Model



- Kalman filter like approach for correcting SCR predictions using tail pipe NOx sensor measurements
- Approach relies on tail pipe NOx sensor – if sensor drifts/has an error, it will drive the model off course (risk can be mitigated by limiting correction factor magnitude)
- System will scale kinetics up or down on the fly to align model predictions with real time catalyst performance (effects such as HC inhibition etc will be accounted for with this approach)
- Because a physics based model is involved, this approach is robust to transients and high temperatures (will need to verify robustness of high temperatures)

Correction Algorithm



- CASE 0: Model = Sensor
  - If model estimate is equal to sensor estimate, both NOx and NH_3 predictions are correct
  - Not possible to get one correct and the other wrong (assuming sensors are working correctly and model is receiving valid inputs)
  - No correction required (correction factor = 1)
- CASE 1: Model > Sensor
  - If model estimate is higher than sensor estimate, both NOx and NH_3 predictions are higher
  - Not possible to get one higher and one lower (assuming sensors are working correctly and model is receiving valid inputs) under relatively stable operation
  - Need higher reaction rates (correction factor < 1)
- CASE 2: Model < Sensor
  - If model estimate is lower than sensor estimate, both NOx and NH_3 predictions are lower
  - Not possible to get one lower and one higher (assuming sensors are working correctly and model is receiving valid inputs) under relatively stable operation
  - Need lower reaction rates (correction factor > 1)

Correction Factor

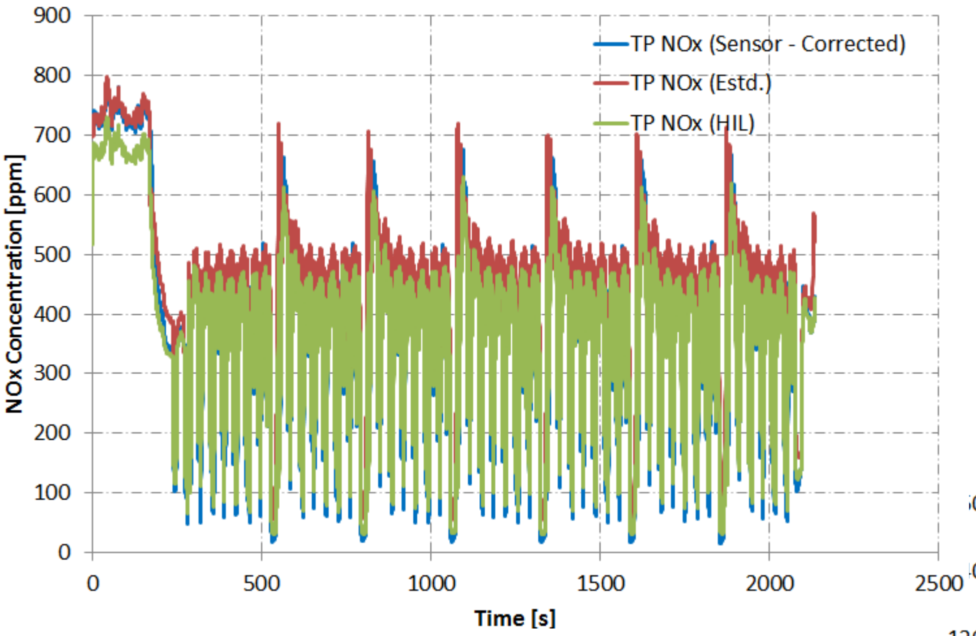
Assuming first order kinetics to correct for the observed error,

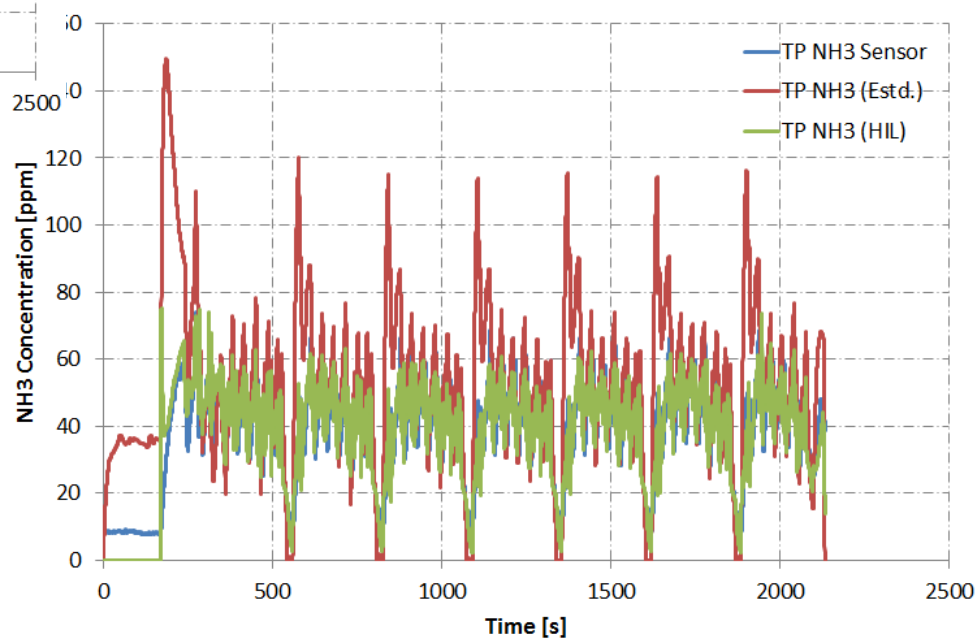
$$Correction\ Factor = \frac{ln(1-\eta_1)}{ln(1-\eta_2)} = \frac{k_1 SV_2}{k_2 SV_1}$$

The Correction factor will be able to compensate for

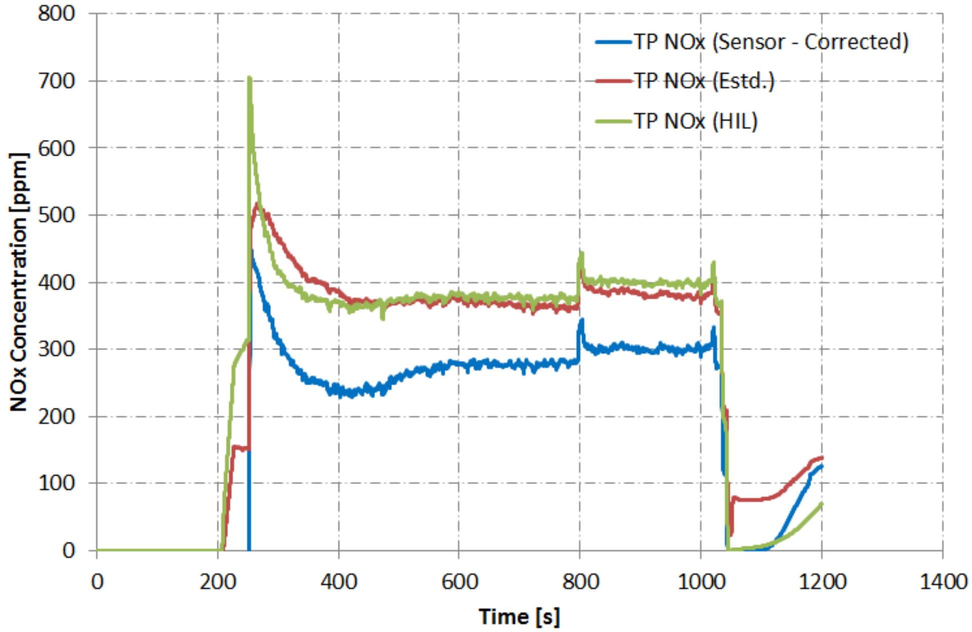
- Temporary changes in catalyst performance (transient inhibiting effects, aging trends etc)
- Incorrect catalyst dimensions (upto a certain limit)

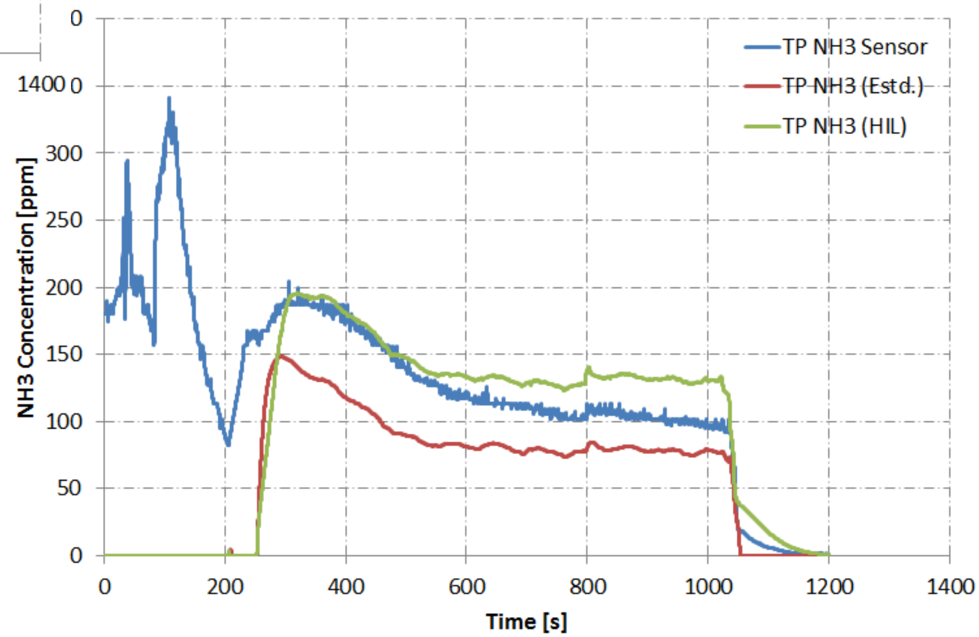
Transient Cycle #1





Transient Cycle #2





Proposed Control Structure

Base SCR Model

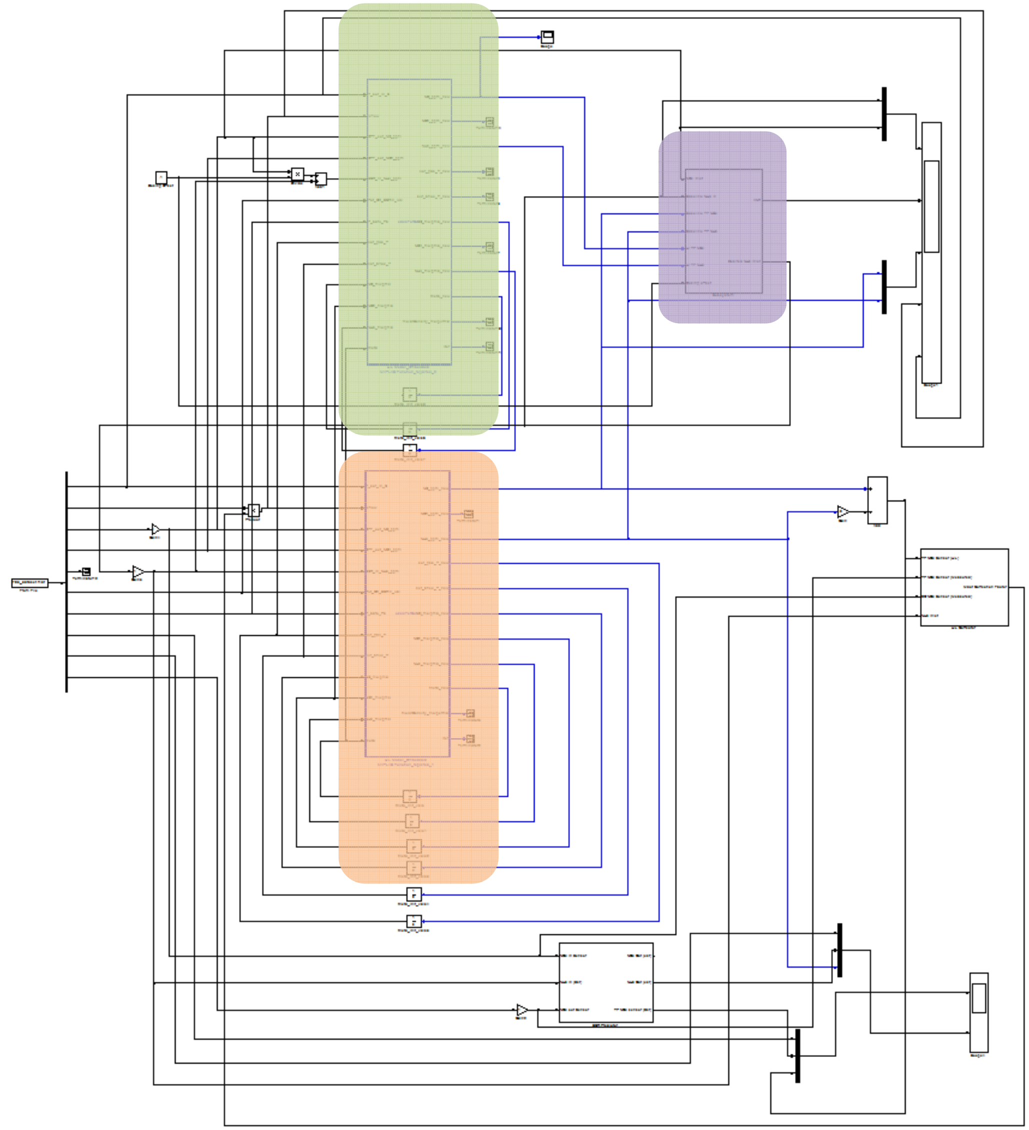
- Calculate TP NOx and NH_3 using nominal inputs for model

Offset SCR Model

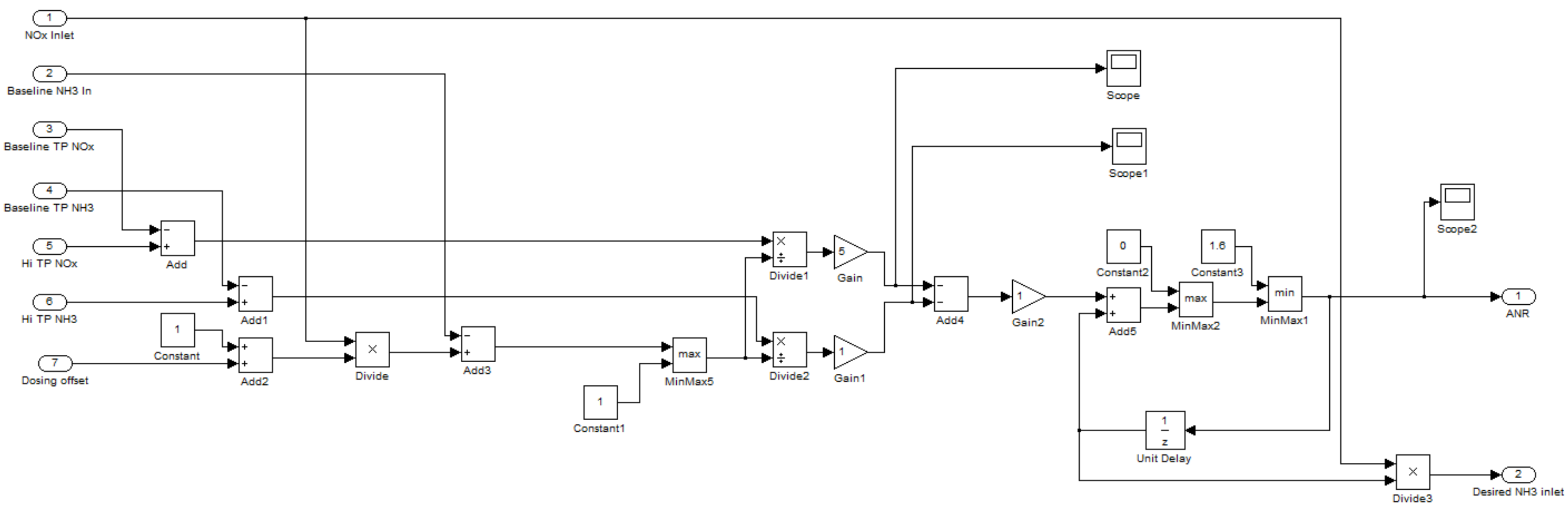
- Calculate TP NOx and NH_3 using +10% offset for DEF dosing

Dosing Controls

- Using TP emission predictions from the base and offset SCR models, determine the derivatives for NOx and NH_3 wrt dosing
- Scale the two derivatives calculated as appropriate using the ‘slip factor’
- Add the scaled derivatives to obtain the net derivative that can be used to scale up or scale down the ANR rate to obtain desired NOx conversion efficiency

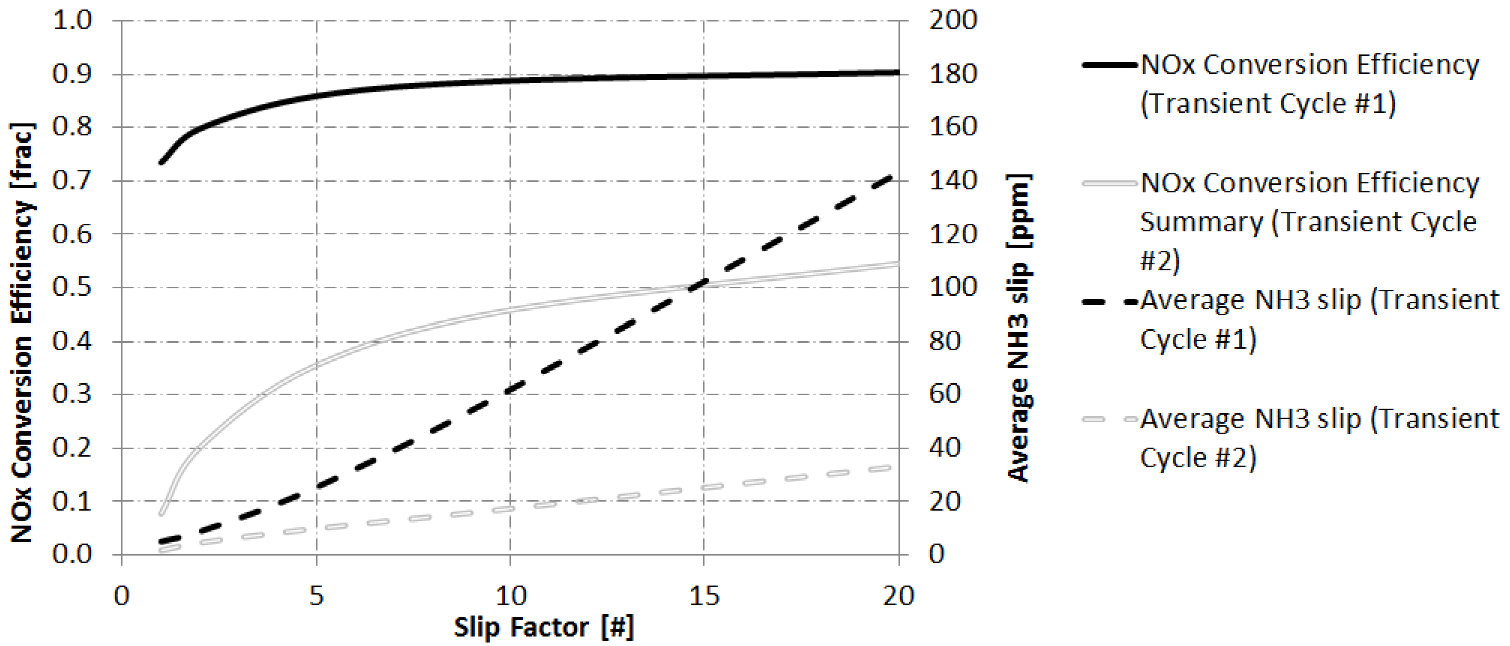


Implementation of Control Logic



- Simplified control structure to determine required DEF dosing rate
- Tail pipe NH_3 slip (and consequently, the tail pipe NOx) emissions are determined by the 'slip factor' value that is used

Controller Performance over transient cycles

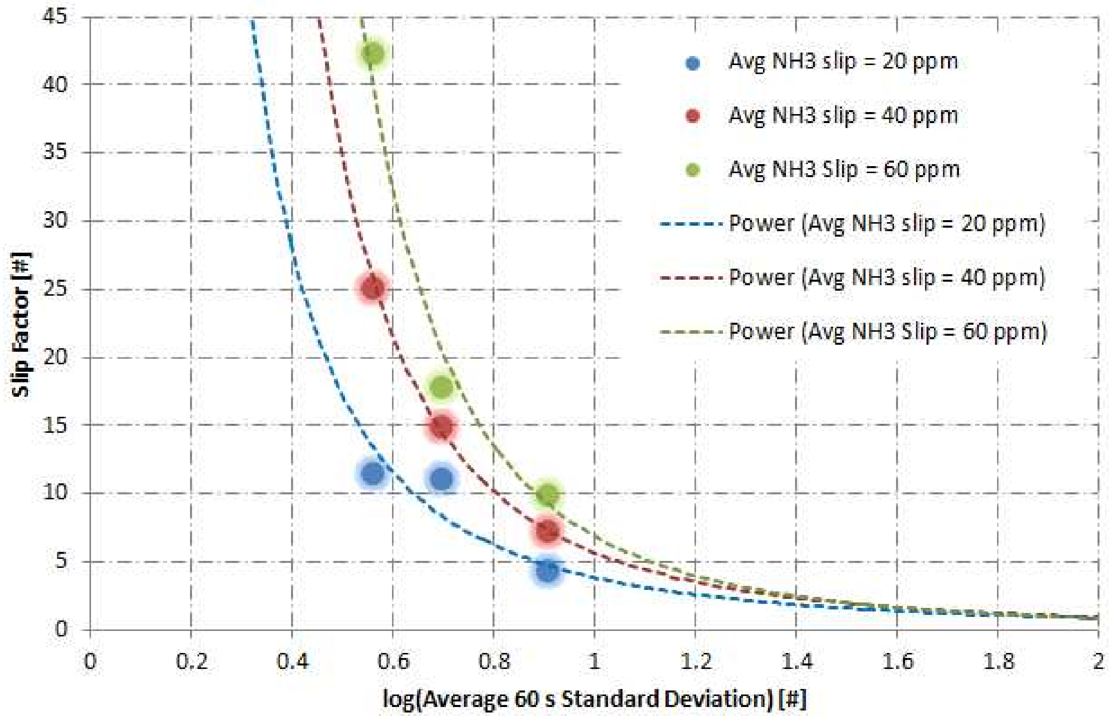


- Offset SCR model based controls is able to control the tail pipe NOx and NH_3 slip as desired
  - Able to operate at or close to desired target NH_3 slip without going unstable or exceeding target NH_3 slip during transients
- Able to characterize fundamental SCR system capability over a transient cycle for given NH_3 slip
  - Note: some of the cycles in the plot above include operation at 150 C, hence the low overall cycle NOx conversion

Calibration 'Slip Factor'

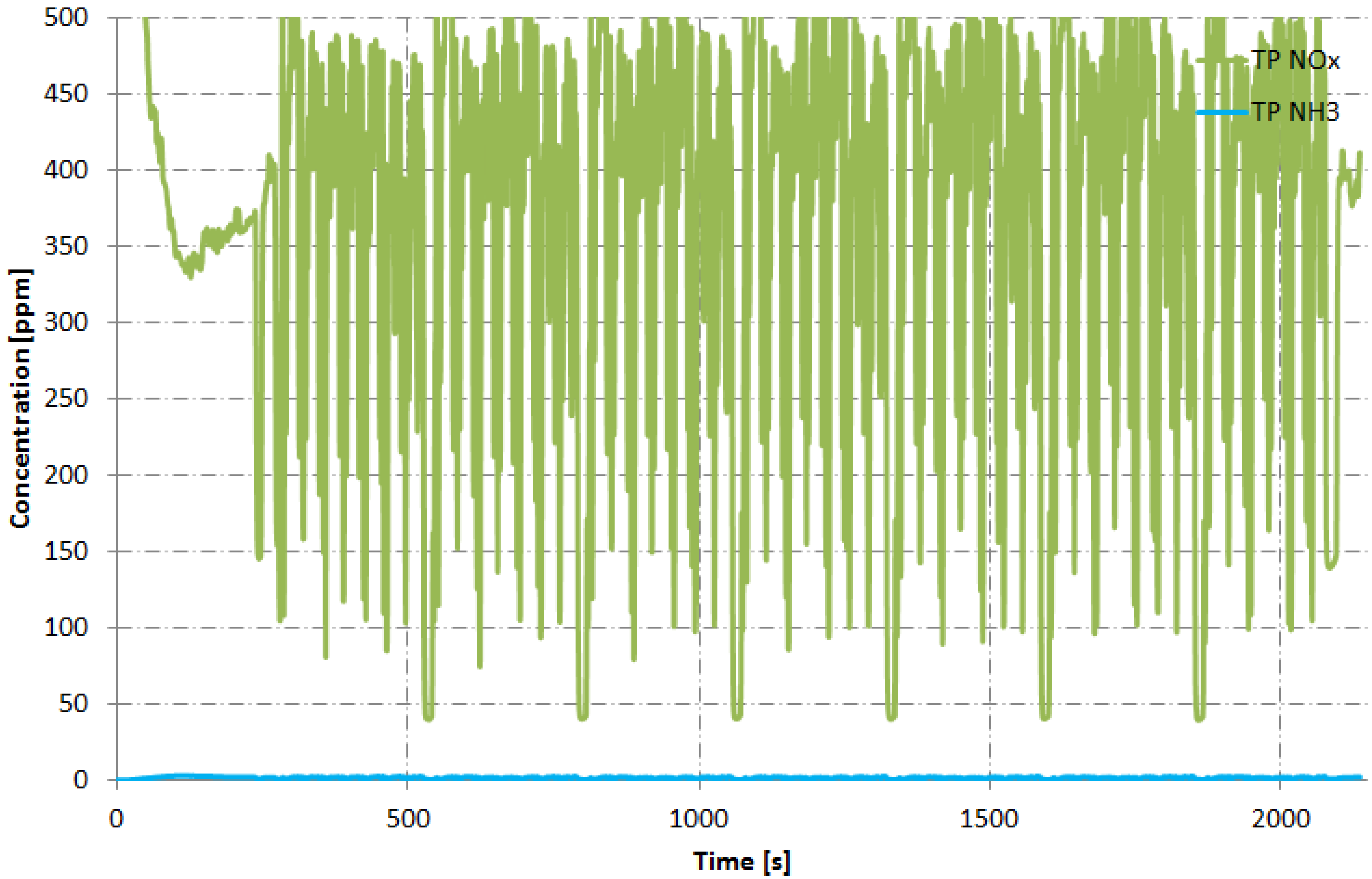
- The slip factor is responsible for determining the tail pipe NH_3 slip over a cycle (and hence, the cycle NOx conversion efficiency)

- It is possible to determine the appropriate slip factor value for a given application cycle
  - Can be set on the fly, based on application cycle variability
  - Logarithm of the rolling average of the SCR temperature can function as a measure of how transient the cycle is over a period of time



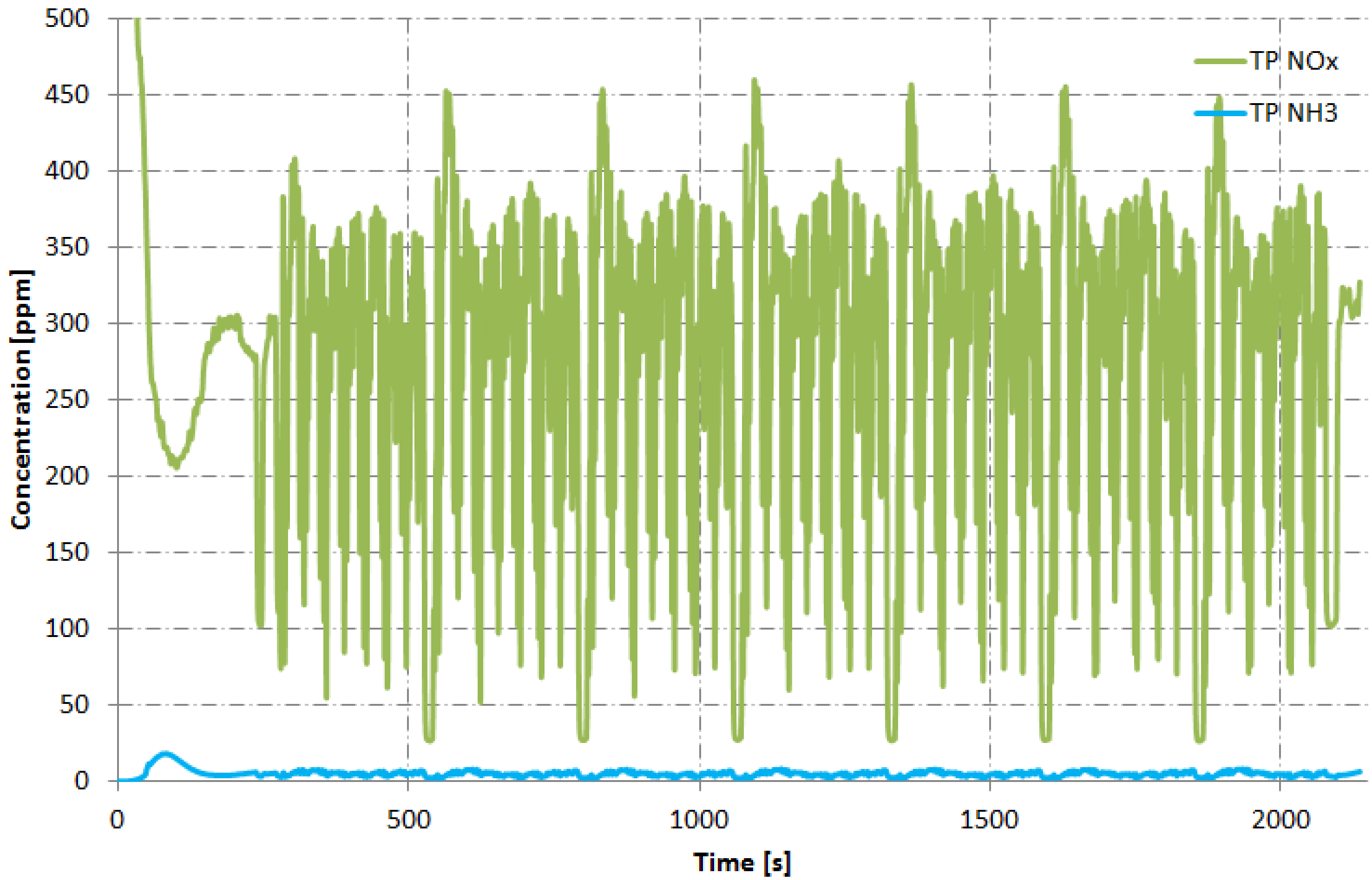
Transient Cycle #1

Slip factor = 2



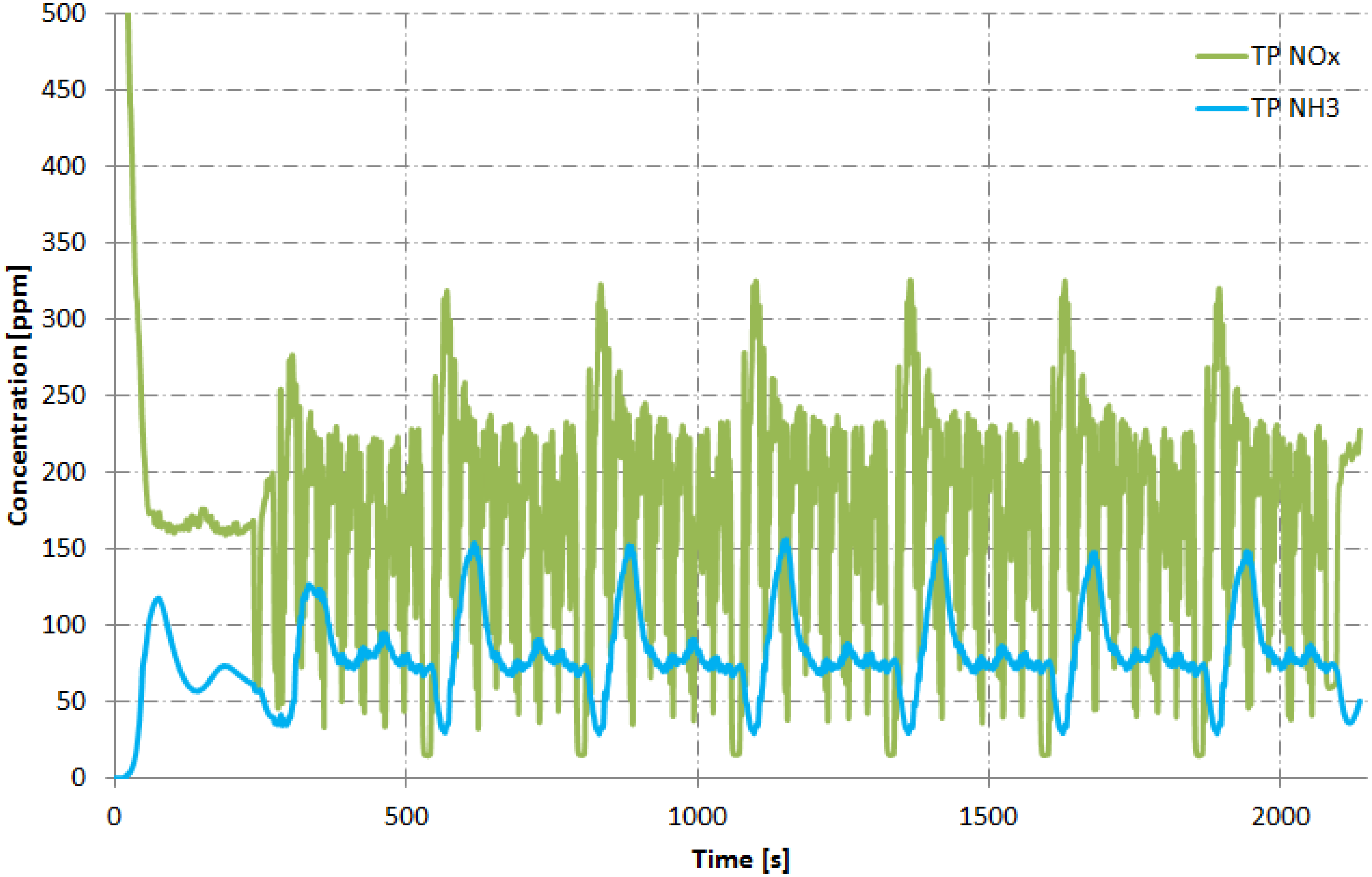
Transient Cycle #1

Slip factor = 5



Transient Cycle #1

Slip factor = 20



Summary

- Demonstrated the feasibility of implementing a model based SCR control without any maps, look up tables or calibration constants
  - Easier (plug and play) implementation on different applications
  - Higher quality/lesser chance of errors
  - Easily implemented for different levels of NOx conversions

- Use of model based SCR controls enables higher NOx conversion values, while limiting NH_3 slip

- Model based SCR controls also fits in well with next gen engine control architecture