

Development and Implementation of a Mapless, Model Based SCR Control System

Praveen Chavannavar
Caterpillar Inc.

ABSTRACT

Various engine platforms employ Selective Catalytic Reduction (SCR) technology to reduce the tail pipe emissions of oxides of nitrogen (NOx) from diesel engines as part of an overall strategy to comply with the emission regulations in place in various countries. High levels of NOx conversion (greater than 98%) in SCR aftertreatment may provide operating margin to increase overall fuel efficiency. However, to realize the potential fuel efficiency gains, the SCR technology employed should achieve high NOx conversion with limited reductant slip over transient application cycles in addition to steady state operation.

A new approach to SCR controls was developed and implemented. This approach does not rely on any maps to determine the amount of urea solution to be dosed, thus significantly reducing calibration and development time and effort when implementing the SCR technology on multiple engine platforms and applications.

In addition, the controls technique is completely model based and was able to achieve high NOx conversion efficiencies through the SCR system, while ensuring limited ammonia slip due to sharp transient events in the application cycle. This ability allows the system to extract the maximum performance from the SCR catalyst, enabling the catalyst size to be optimized for space and cost constraints.

The successful implementation of this control technique requires an SCR model with prediction accuracies greater than that typically achieved in practical implementation. Therefore, a real time correction technique was used to enhance the model accuracy to the desired levels for use in the controls algorithm.

CITATION: Chavannavar, P., "Development and Implementation of a Mapless, Model Based SCR Control System," *SAE Int. J. Engines* 7(2):2014, doi:10.4271/2014-01-9050.

INTRODUCTION

Most modern large diesel engines in the United States of America, Europe, Japan and other highly regulated countries now employ exhaust aftertreatment as part of a strategy to reduce particular constituents in tail pipe emissions to comply with the local emission regulations. The majority of engines larger than 3 liters displacement tend to favor the use of SCR technology to reduce the NOx in the SCR system through the selective reduction of the NOx by injecting measured quantities of urea water solution (referred to as the Diesel Exhaust Fluid (DEF) in the United States of America and AdBlue in Europe and elsewhere in the world) into the exhaust pipes, upstream of the SCR catalyst. Smaller sized engines use a variety of other NOx reduction technologies such as the Lean NOx trap, either independently or in conjunction with an SCR catalyst [1].

Once injected into the exhaust stream, the urea water solution decomposes to produce ammonia that then reduces the NOx selectively over the SCR catalyst, thus reducing the emissions

of NOx from the engine. While different SCR catalyst formulations have differences in performance and the way they behave on the engine system, they all have a favored temperature region in which they perform at their optimum [2, 3, 4, 5, 6], typically 300 C to 400 C. However, for successful implementation on actual engines, the controls should be capable of enabling the SCR operation in a wider temperature range, usually 200 C to 500 C or higher. To further confound the non-linear change in reaction rates due to the involved chemical kinetics, the ammonia storage capacity of the catalyst itself changes as a function of temperature [4, 7, 8]. This variable ammonia storage capacity can cause the catalyst to abruptly release ammonia into the exhaust pipe leading to ammonia slip, or if starved of adequate surface ammonia, underperform with regard to NOx reduction. Further complicating the issue is the fact that the ammonia storage dynamics occur over a different time scale (of the order of minutes) as compared to the SCR reactions themselves on the

typical engine transient events (which occur over timescales on the order of seconds or lesser). This adds to the challenge of developing a suitable control algorithm for urea dosing.

CONFIGURATION OF SCR SYSTEM

In addition to the SCR catalyst itself, the SCR system consists of the PETU (Pump, Electronics and Tank Unit). The tank is responsible for storing and acting as the source of the urea solution during operation. It typically also includes heating elements, quality and level sensors and heated pipelines to deliver the urea solution to the pump, which then provides the pressure differential that allows the urea solution to be injected into the exhaust pipe as a fine spray through an injector. The fine atomization of the urea solution is critical in preventing the build-up of unwanted urea and urea decomposition by-products within the exhaust system, particularly at low temperatures. Once introduced into the exhaust stream at a suitable location that is conducive to proper mixing, the urea solution proceeds to decompose into iso-cyanic acid and ammonia (thermolysis) followed by further breakdown of the isocyanic acid into ammonia (hydrolysis) [9].

This ammonia is then free to react with the NO_x over the SCR catalyst to form N₂ and H₂O that are then released through the tail pipe into the atmosphere. In addition to the SCR catalyst itself, an SCR system may include an upstream Diesel Oxidation Catalyst (DOC) and a downstream Ammonia Oxidation Catalyst (AMOX). In addition to oxidizing hydrocarbons and carbon monoxide present in the exhaust stream, the DOC also oxidizes the NO in the exhaust to NO₂, thus raising the NO₂/NO_x ratio. Since the SCR catalysts perform optimally at a NO₂/NO_x ratio of 0.5 [5, 6], this helps improve the NO_x conversion efficiency of the SCR system. The AMOX oxidizes the NH₃ slip out of the SCR catalyst into N₂ and H₂O. This allows the controller to dose higher levels of urea solution, in turn boosting the NO_x conversion achieved over the SCR catalyst [2].

Finally, the controller logic is implemented in the ECM (Engine Control Module) to regulate the urea dosing rate in response to the varying conditions as the engine operates at different conditions over its application cycle. With the relative maturation of the SCR hardware technology, further improvements in the overall system NO_x conversion efficiency require a suitably advanced control algorithm capable of exploiting the hardware fully to obtain the desired high NO_x conversion efficiencies in excess of 98%, within the stipulated space, cost and NH₃ slip constraint envelopes [4, 10].

SCR CONTROLLERS

Different approaches can be employed to control the urea dosing in SCR systems. Depending on the system hardware and the desired levels of NO_x conversion, the implemented SCR controls may be feedforward (open loop) or feedback (closed loop) and may be map-based or use an empirical or

physical model. The choice of the control algorithm influences the system performance limits as well as development and implementation costs and efforts [4].

Feedforward Versus Feedback SCR Controllers

An SCR control system that relies upon maps, look-up tables, empirical and/or physical models to determine the required level of dosing to reduce NO_x over the SCR would be considered to be a feedforward SCR controller. Typically, such controllers are simpler to implement and calibrate. However, since such an approach does not incorporate any information from the tail pipe in the control process, it may not be suitable for achieving high NO_x conversion levels on highly transient application cycles.

A feedback SCR controller uses some form of information from the SCR outlet (typically provided by a NO_x sensor) to alter the urea dosing rate transiently based on the demands of the situation. Accordingly, the use of feedback in a closed loop SCR controller may enable higher NO_x conversion on transient cycles without suffering from high NH₃ slip [11, 12, 13, 14, 15, 16, 17, 18, 19, 20].

The use of a feedback SCR controller allows for the system to be robust to system variability, including but not limited to catalyst coating, ambient operating conditions, engine performance variation and aging [11]. The implementation of feedback in the SCR controller is, however, not a trivial task. The SCR system can potentially slip NO_x (a mix of NO and NO₂) or NH₃ or a combination of the two (NO_x and NH₃). The control algorithm needs to be robust to appropriately assess the slip regime and make corresponding changes to the urea dosing rate to compensate. It is well known, however, that the commercially available NO_x sensors used on engine systems are cross sensitive to the presence of NH₃ in the exhaust stream [19, 20]. Dedicated NH₃ sensors are also available [4, 12, 13], and have been used by some engine manufacturers in their systems. Also, the addition of the NH₃ sensor would be an added cost to the engine system and source of potential reliability issues. It is for these reasons that many investigations have been conducted to implement feedback SCR control using the available NO_x sensors [11, 14, 15, 16, 17, 18, 19]. The typical challenge associated with this approach is to consistently and accurately discriminate between NO_x and NH₃ slip. The solutions to this problem include use of signal processing [19], use of mid-brick sensors [18], or use of models to estimate (and limit) stored NH₃ on the catalyst to limit NH₃ slip [11].

Map Based Versus Model Based SCR Controllers

The use of pure map/look-up table based SCR controller implies that the system is not able to consistently operate at the threshold of impending NH₃ slip (which would result in higher NO_x conversion efficiencies) because the system's performance variation is not accounted for in the system.

However, for applications that need a lower level of NOx conversion (of the order of 80%) or are not very transient, a map based SCR controller is a simpler and less complex means to successfully implementing SCR.

SCR controllers may employ a physical model [8, 11, 12, 15, 18, 21, 22, 23], or use empirical models [10, 24, 25] to estimate the performance and state of the SCR catalyst. The use of models to predict the SCR performance helps reduce (but not necessarily eliminate) the reliance on maps and look up tables, making the SCR controller simpler to calibrate and implement for different engine platforms. Models can also be used to help the SCR controller be more predictive and anticipate and mitigate large NH₃ slip events since ultimately, the SCR control problem is one of managing the NH₃ storage on the catalyst to maximize NOx conversion while minimizing NH₃ slip [17].

It may also be noted that while model based controllers are better able to predict the onset of NH₃ slip, the controller typically cannot respond quickly enough to prevent NH₃ slip during rapid increases in temperature. As a result, most model based SCR control implementations still contain a maximum NH₃ storage map that limits the amount of NH₃ that is allowed on the SCR catalyst at a given time, particularly at the lower temperatures. While this helps limit the potential for large NH₃ slip during the temperature changes, it may come at the price of reduced NOx conversion efficiency [4, 11, 17].

Another approach to SCR controls is Model Predictive Controls (MPC). Model Predictive Control is computationally intensive and not easily amenable to implementation on the ECM [8, 22]. However, as on-board computational capabilities continue to increase, MPC should gain greater relevance.

Model based implementations of SCR controls can also more readily account for degradation of the SCR catalyst performance due to aging through a second set of kinetic constants representative of an aged catalyst or through other methods to change the kinetics as a function of time.

A more extensive review of the various SCR controllers implemented may be found in [4].

IMPLEMENTATION OF A MODEL BASED SCR CONTROLLER

The following section describes the implementation of a map-less, model based SCR controller that is easy to implement and validate on a range of platforms and can be easily set to achieve different levels of NOx conversion efficiency.

Physics Based SCR Model

The implementation of a model based SCR controller requires a SCR model that can be executed in real time or faster on the Engine Control Module (ECM), while being capable of accurately predicting the transient performance of the SCR catalyst.

SCR chemistry, particularly on the zeolite SCR catalysts, is a complex phenomenon with multiple active sites playing a role in the reduction of NOx [3, 5, 6, 26]. Models incorporating these features play an important role in the investigation of the underlying SCR reaction mechanisms and catalyst capabilities but are not suited for implementation in the ECM due to the greater computation demands of these models. For the purposes of SCR control, a generic (applicable to iron zeolite, copper zeolite and V SCR formulations) 1D SCR model is appropriate.

This work makes use of a 1D SCR model with 6 global reactions to predict the transient performance of the SCR catalyst [27]. The calibration process and accuracy of this model has been previously documented [27]. However, for this study, the model was recalibrated to predict the performance of a vanadia based SCR formulation. This model does not explicitly include mass transfer limitations, i.e. the reactions involved are entirely kinetically limited, with the 6 included reactions accounting for NH₃ adsorption-desorption, NH₃ oxidation, standard SCR NOx reduction, fast SCR NOx reduction, NO₂ NOx reduction as outlined in the literature [27, 28, 29, 30].

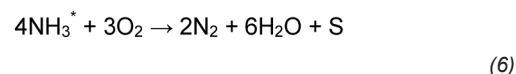
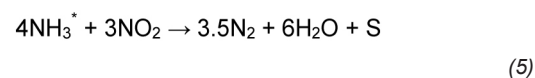
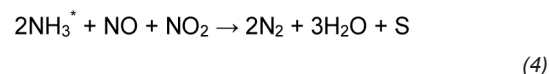
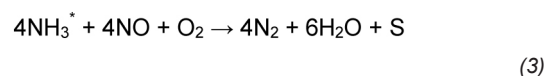
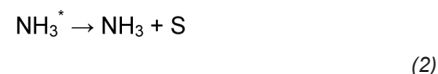


Figure 1 shows the comparison of the model predictions for NOx and NH₃ versus actual experimental data over a Ramped Modal Cycle (RMC). As can be seen from the plots, there is good agreement between the model predictions and the experimental data.

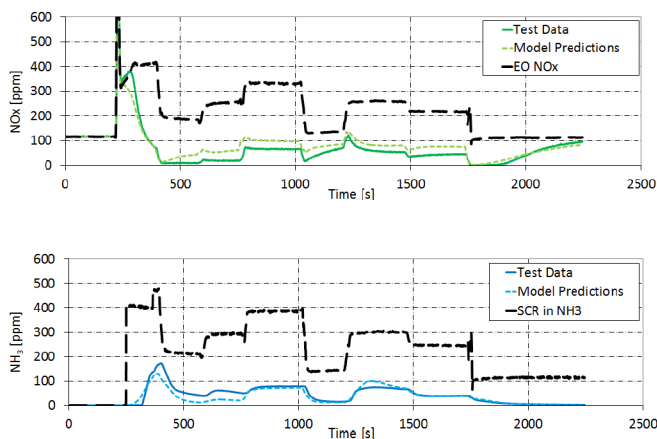


Figure 1. SCR Model predictions over a Ramped Modal Cycle (RMC)

The model predictions show similar levels of accuracy over a wide range of application cycles. Based on the results of numerous runs, totaling approximately 20 hours of run time, statistical analysis was conducted on the model prediction errors to quantify the model accuracy. The model predictions for NO_x were found to have a mean error of 0.82% with a 95% confidence interval for the error being [-2.16% +3.81%]. Similarly, the model predictions for NH₃ were found to have a mean error of 5.14% with the 95% confidence interval for the error being [+1.88% +8.39%].

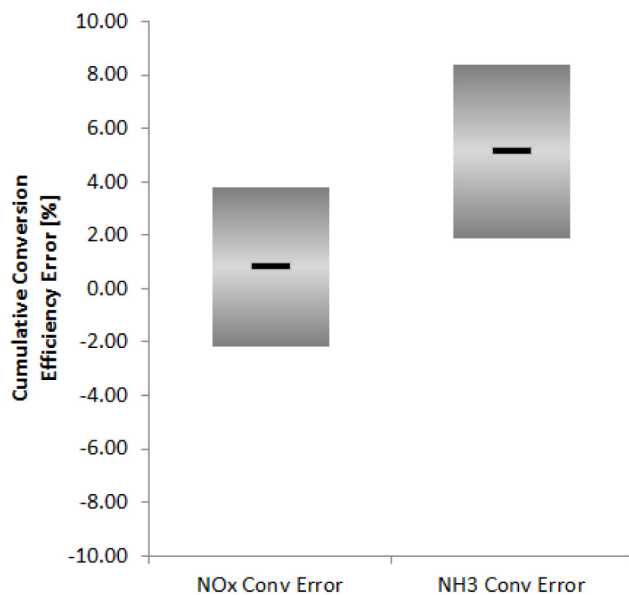


Figure 2. Statistical error estimates for model NO_x and NH₃ predictions

The errors and statistical intervals indicated above in [figure 2](#) are computed for a transient cycle of finite length. The instantaneous errors in NO_x and NH₃ predictions may (and indeed, do) exceed the intervals indicated above. The confidence interval computed is indicative of the model performance over transient cycles with durations approaching orders of 1 hour or longer. For shorter transient events of the order of a few minutes, the errors in NO_x and NH₃ prediction may be higher. This level of accuracy is comparable or better than the best known calibration processes in the field [31].

It may be noted that these error estimates were calculated as:

$$\text{Prediction Error (\%)} = \frac{(\text{Measured} - \text{Predicted})}{\text{SCR inlet concentrations}} \times 100 \quad (7)$$

The prediction error was computed relative to the SCR inlet concentrations to provide a more intuitive estimate of the model accuracy. However, this error estimate could also have been computed using the SCR outlet measurements as the baseline value. In such a case, while the magnitude of the prediction errors would be different (higher), the following analysis and conclusions would still apply.

Error Correction for SCR Model

While the model prediction accuracy as indicated in [Figure 2](#) is in the single digits for cycles of reasonable duration, further improvement in model prediction accuracy is required for the successful implementation of a model based SCR controller that does not include any supporting maps or tunes. This is due to the fact that a 10% error in predicting NH₃ slip can imply an error of 100 ppm in predicting tail pipe concentrations of NH₃ if the urea dosing rate at SCR inlet corresponds to an Ammonia to NO_x Ratio (ANR) of 1.0 with approximately 1000 ppm of NO_x at the SCR inlet.

This is evident in [figure 3](#) where the difference in model prediction for NH₃ slip and measured NH₃ slip is not significant relative to the inlet NO_x or inlet NH₃. However, in absolute terms or with respect to the tail pipe NH₃ measurements, the predicted NH₃ slip can be offset from the measured values by 100% or more at times.

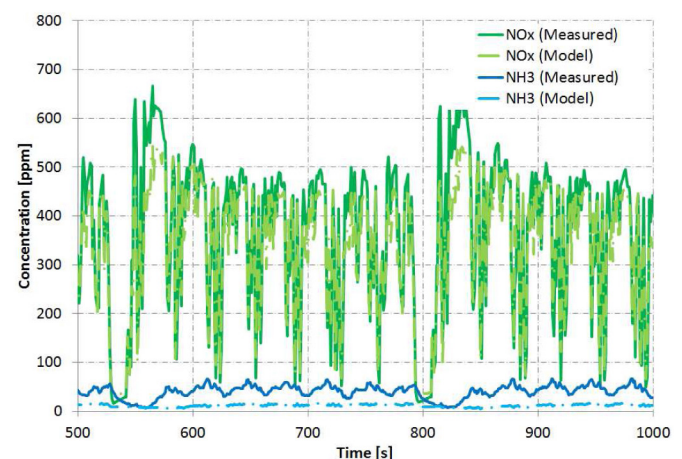


Figure 3. Model predictions versus measurement for tail pipe emissions of NO_x and NH₃ over transient application cycle #1

Additionally, in some situations, the catalyst itself may lose its activity, either temporarily or permanently such as in the case of the inhibition of SCR performance due to the presence of high levels of hydrocarbons in the exhaust stream [32]. An example of the impact of such a temporary inhibition may be seen in [figure 4](#), where the tail pipe predictions for NO_x and