The State of the Art in Selective Catalytic Reduction Control

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INTRODUCTION

Overview of SCR

SCR catalysts remove nitrogen oxides (NO\textsubscript{x}) through a reaction with a reducing agent, which is typically ammonia (NH\textsubscript{3}). A catalyst is required to speed up this reduction reaction, thus reducing the amount of harmful NO\textsubscript{x} emissions significantly. Urea-based SCR catalysts use aqueous urea that is injected into the exhaust stream to produce NH\textsubscript{3} as the active NO\textsubscript{x} reducing agent. Typically, an aqueous solution of diesel emissions fluid (DEF) with 32.5% urea content is carried on board of a vehicle. This concentration has the lowest freezing temperature (eutectic mixing ratio), so even a partially frozen tank maintains the same concentration. An injection system is used to supply it into the exhaust gas stream entering the SCR catalyst, where it decomposes into gaseous NH\textsubscript{3} and can be stored in the catalyst. The NO\textsubscript{x} contained in the engine exhaust gas then reacts with the stored NH\textsubscript{3}, which produces nitrogen and water. The amount of urea injected is controlled to provide a high NO\textsubscript{x} conversion whilst keeping the emissions of excess NH\textsubscript{3} (slip) to low values. Both demands are conflicting targets, because higher concentrations of NH\textsubscript{3} lead to better conversion, but also increased slip. At high conversion, the margin for error is very small, which makes the precise control of NH\textsubscript{3} dosing technically challenging. An Ammonia Oxidation Catalyst (AOC) can be used after the SCR catalyst to reduce NH\textsubscript{3} emissions. While this increases the tolerance to overdosing errors, it only works well at high temperatures, and it may lead to the production of unwanted Nitrous Oxide (N\textsubscript{2}O).

SCR catalysts first appeared on heavy-duty stationary engines where high NO\textsubscript{x} levels are present and where steady state duty cycles can be considered to be the main operating conditions. Under these conditions, reasonable conversion can be achieved using open loop SCR control with fixed NH\textsubscript{3} to NO\textsubscript{x} ratio (ANR). Applying this simple approach to a vehicle, where transient conditions are more frequent, is more challenging, and requires specific transient corrections.

SCR Configurations

A typical Diesel or lean burn engine aftertreatment system consists of a Diesel Oxidation Catalyst (DOC), a Diesel Particulate Filter (DPF), a urea SCR catalyst, and an optional Ammonia Oxidation Catalyst (AOC). The DOC, DPF, and SCR can be combined in a variety of exhaust system configurations [1]. The DOC is usually placed first, to benefit from the hot engine exhaust, [2]. The SCR can be either in front of or behind the DOC catalyst. Both layouts have advantages for different applications. For instance, [3] show a typical set-up where the SCR system is downstream of the DOC/DPF system (Figure 1). This order has the advantage that the DOC can reform NO into NO\textsubscript{2}, which makes the NO\textsubscript{x} conversion in the SCR system more effective.

![Figure 1 – SCR system setup in the exhaust (Harder, Brugger et al. 2011)](image-url)
However, putting the SCR before the DPF helps to avoid fuel economy losses from diesel engines [2], and may help to mitigate deposit formation. Alternative configurations of aftertreatment devices in the exhaust line are possible. In [4-7], the integration of DPF and SCR catalysts in one place is proposed to reduce system size. The inclusion of a NOx trap [5] before the SCR system can significantly improve cold start behavior by capturing the NOx and releasing it when the SCR system is operational. The addition of an Ammonia Oxidation Catalyst (AOC) or Ammonia Slip Catalyst (ASC) after the SCR system is able to reduce the release of NH3 into the environment [6]. This also allows running the SCR catalyst with excess ammonia to increase the conversion [8]. The on-board generation of NH3 is considered to avoid the use of urea [7] mostly for practical reasons.

**Issues in SCR Controls**

Control and control-related tasks in SCR systems have to satisfy a number of concerns. Keeping below the emission limits is essential, but so is the avoidance of damage to the system via deposits or excessive temperatures.

The key challenges of the SCR control system can be summarized as:

- cross sensitivity of NOx sensors to NH3,
- high nonlinearities in the chemical reaction rates, and
- a combination of short, medium and very long time scales in one system.

Most SCR control strategies generally involve a combination of open-loop and closed-loop control. Both output feedback (based on sensors only) and state feedback (using a model based state estimate) are being used.

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**Table 1 – Chemical Reaction Mechanism proposed by [39,48,49]**

| Ser. | Chemical Reaction | Reaction Rate Expression |
|------|-------------------|--------------------------|
| (1)  | S + NH3 → (NH3)_S | \( \dot{r}_1 = k_1 e^{-\frac{-E_1}{R T}} G_{NH3}(1 - \theta) \) |
| (2)  | (NH3)_S → S + NH3 | \( \dot{r}_2 = k_2 e^{-\frac{-E_2(1-a\theta)}{R T}} \theta \) |
| (3)  | 2(NH3)_S + NO + NO2 → 2N2 + 3H2O + 2S | \( \dot{r}_3 = k_3 e^{-\frac{-E_3}{R T}} \theta C_{NO}C_{NO2} \) |
| (4)  | 4(NH3)_S + 4NO + O2 → 4N2 + 6H2O + 4S | \( \dot{r}_4 = k_4 e^{-\frac{-E_2}{R T}} \theta C_{NO}(C_{O2})^{2} \) |
| (5)  | 4(NH3)_S + 3NO2 → 3N2 + 6H2O + 4S | \( \dot{r}_5 = k_5 e^{-\frac{-E_5}{R T}} \theta C_{NO2} \) |
| (6)  | 2(NH3)_S + 1.5O2 → N2 + 3H2O + 2S | \( \dot{r}_6 = k_6 e^{-\frac{-E_6}{R T}} \theta C_{O2} \) |
| (7)  | NO + 0.5O2 ↔ NO2 | \( \dot{r}_7 = k_7 e^{-\frac{-E_7}{R T}} \left[ C_{NO2}(C_{O2})^{0.5} - \frac{C_{NO2}}{K_c} \right] \) |
| (8)  | 2(NH3)_S + 2NO2 → N2 + N2O + 3H2O + 2S | \( \dot{r}_8 = k_8 e^{-\frac{-E_8}{R T}} \theta C_{NO2} \) |

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**MODEL**

In order to facilitate an effective control strategy, a model of an SCR system has to capture the key characteristics of the system, without being too complex to evaluate or to calibrate.

**Reaction Kinetics**

Following the Eley-Rideal mechanism, there are 8 main chemical reactions representing the relevant dynamics in the catalytic converter as detailed in Table 1. The reagents that are rate limiting according to the reaction rate model are set in bold (note that even if several molecules of the same species are converted, typically only the first one is rate limiting).

In these reactions, NH3 refers to gaseous NH3 (in the gas phase). S refers to an unoccupied active catalytic site, and (NH3)_S refers to an NH3 molecule adsorbed at such a site (in the solid phase). Only such an absorbed NH3 molecule (NH3)_S is activated and therefore available for chemical reactions (3-5, 8) with NOx.

The first two reactions in Table 1 are the adsorption and desorption of NH3 with the catalyst surface – these determine the equilibrium coverage of the catalyst.

Then there are three selective catalytic reactions (3-5) (highlighted in Table 2) with distinct stoichiometry and kinetics. They all break down NOx using the associated NH3, and the relative speed depends on the ratio between NO:NO2. The first of these reactions (3) is called the fast SCR reaction, which requires both NO and NO2 to be present, and which is most effective at NO:NO2 ratios close to 1. Any excess NO feeds the second, slower reaction (4), which is often considered the standard SCR reaction. Excess NO2 gets converted via the third reaction (5), which is typically even slower than the standard reaction.
The sixth reaction in Table 1 is the oxidation of surface NH₃, which leads to a loss of NH₃. The seventh reaction is the oxidation of nitric oxide (NO) into nitrogen dioxide (NO₂), which is not a relevant reaction in most SCR catalysts, but it does occur at significant rates in an oxidation catalyst.

There is a further reaction (8) for NOₓ, which is the primary source of N₂O. Due to the low reaction rate this is not typically relevant for the NO₂ balance, but it is essential if N₂O emissions have to be modelled.

As an alternative to the Arrhenius kinetics, [9] proposes to use the sticking equation to model the adsorption reaction. It is based on a stochastic model of locality alone without reference to activation energy, leading to a slightly different model of the dynamics.

Table 2 – Key SCR Reactions

| Ser. | Ammonia | Nitrogen Oxides | Ratio NH₃:NOₓ | Name       |
|------|---------|-----------------|---------------|------------|
| (3)  | 2 NH₃   | 2 (1 NO + 1 NO₂)| 1:1           | Fast SCR   |
| (4)  | 4 NH₃   | 4 NO            | 1:1           | Standard SCR |
| (5)  | 4 NH₃   | 3 NO₂           | 4:3           | NO₂ SCR    |

**Time Scales**

The relevant effects of the SCR system happen on very different time scales, and from a control point of view it can be very helpful to separate them. An overview of the different effects is shown in Table 3, and a structured block diagram can be found in Figure 2. The fastest time scale is the transport and reaction in the gas phase, which typically only takes fractions of a second.

Finally the ageing and poisoning of the system happens over hundreds of hours. Poisoning can be partially reversed using regeneration cycles, while ageing is typically a one way process. An example for tracking these processes is given in [11].

Table 3 – System Time Scales

| Time Scale | < seconds | Ca 1-10 min. | Days to years |
|------------|-----------|--------------|--------------|
| Name       | Quasi stationary | Short term | Long term |
| Effects    | Gas phase | Gas transport | NOₓ dynamics | NH₃ coverage dynamics | Substrate temperature dynamics | Sensor drift | Actuator drift | Catalyst aging | Urea quality variations |
| Relevance  | Uncontrollable quasi-stationary modelling is sufficient | SCR control, Thermal management | Through life performance |

**Nonlinearities**

The SCR model typically exhibits strong nonlinearities, which originates from the reaction kinetics of the chemical reactions. This means that the behavior of the model is highly dependent on the system operating point. It is tempting to linearize the model, and to use fixed gain or gain scheduled linear controllers designed for specific operating points. However, this can lead to a significant loss of accuracy, and it can prevent the system from reaching the best possible NOₓ conversion over a wide range of operating conditions.

A very prominent nonlinearity appears due to the cross-sensitivity of the NOₓ sensor to NH₃. This leads to an ambiguity, because elevated sensor readings could indicate excess NOₓ or excess NH₃. In extreme cases, this can destabilize the control system [12]. The use of an NH₃ sensor can help to avoid this ambiguity, because the NH₃ sensor is not sensitive to NO [13] (although there is an issue with high NO₂ levels). From a control point of view, neither a perfect NOₓ sensor nor a perfect NH₃ are currently available.

The most important nonlinearity is dependent on the temperature of the catalyst. The interaction between the different reactions means that SCR catalysts are only efficient within a certain temperature window. The exact temperature limits depend on the catalyst technology and parameters, but the general shape is surprisingly little affected, as shown in Figure 3. At low temperatures, conversion is insufficient because the reaction rates are low (and injection may not be possible due to potential deposits). At higher temperatures, desorption is so fast that it becomes impossible to maintain sufficient NH₃ coverage without excessive NH₃ emissions [14].
Finally, the system performance is not only dependent on the temperature, but also on the flow rate (or space velocity), as pointed out by [16].

**CONTROL METHODS**

The traditional control methods of SCR systems are considered first, followed by typical modern control methods. The review then proceeds to advanced experimental methods, which have been developed to meet expected future vehicle emissions legislation.

**Traditional SCR Control Methods**

The following section presents an overview of research within the field of traditional SCR control methods.

**Open Loop Control**

The principle of the open loop control strategy is simple and based on calculation of the required amount of urea as a fraction of the estimated or measured NOx content in the exhaust gas, and it is provided via a urea injector (see Figure 4). Due to the nature of open-loop control, it cannot compensate for measurement errors, which means that errors in the required NH3 dosage will accumulate in the catalyst and eventually lead to higher NOx or higher NH3 emissions of the same order as the measurement error.

Still, open-loop approaches have proven to be sufficient to meet Euro-4 and Euro-5 emission standards [17], with a conversion of 60%-80% [18] being easily achievable. If operating conditions change only slowly, open-loop controllers are an especially suitable solution to the SCR control design problem [16].

On the other hand, the study in [17] suggests that open-loop control cannot handle engine transient exhaust gas conditions well, because the delay caused by the NH3 storage in the system is not considered. Therefore, rapidly changing conditions necessitate the use of advanced closed-loop SCR control techniques.

**Conventional PID Control**

Conventional controllers can be seen in most control systems of SCR aftertreatment. They typically follow an output feedback approach (see Figure 5), which can be combined with an additional feedforward branch. A typical sensor/actuator pair would be NOx conversion to ammonia dosing, as direct control of the tailpipe NOx concentration is not an appropriate control problem.

Although the results show that it works as expected, the output feedback approach is not entirely convincing from a theoretical perspective. Because ammonia slip causes a sign reversal, the control loop can easily become unstable at high conversion or when an excess of ammonia is present in the catalyst. The basic control structure is only stable and feasible at low conversion where NH3 slip is rare. Even with gain scheduling, the control remains fragile, as shown by [16].

To avoid this, an accurate way of slip detection is required, for example using a model of the SCR system. This causes additional complexity similar to model based control, without providing the benefits expected of modern systems in terms of clear structure and model-based design. There are examples of early attempts to combine classical PI control with a model-based approach, such as [18]. The benefit of this latter approach compared to a modern, observer based, approach is in its reduced complexity, but this also means that the performance is less than ideal.

Alternatively, a nonlinear model of an SCR system can be used together with a PID control scheme with NH3 slip detection [19]. Further examples of PI/PID control techniques that have been used in SCR control are shown in Table 4, along with their references.
Slip Detection

NH₃ slip is the amount of NH₃ released at the catalyst tailpipe. This can happen due to over-dosage of NH₃ beyond the capacity of the catalyt, or due to the faster desorption at higher temperatures. This has three negative effects:

- it causes potentially harmful emissions,
- it causes the loss of ammonia for the SCR reaction,
- and it can also lead to erroneous readings from the NOₓ sensor due to cross sensitivity to NH₃.

The cross sensitivity can cause a sign reversal in the system response, which can render classical control unstable.

A typical extension of classical control is therefore a separate slip detection function, which will identify a situation of excess tailpipe NH₃ and reset the system by stopping urea dosing for a period of time. There have been many studies focusing on the detection of NH₃ slip [14,19,24-28]. They are typically model-based, and may use sensor information to improve the accuracy of the detection. For example, a simple first order model is used for the NH₃ slip in [14]. The NH₃ slip model gets activated when the NH₃ storage on the catalyst is around 95% to 100% full, although it is not clear whether this refers to percent coverage or another maximum level.

| Table 4 – Examples of PI/PID control techniques used in SCR system |
|---|---|---|---|---|
| Ref. | Year | Controller | Further Information | Model Type | Test |
| [20] | 2012 | Fuzzy PID | NO₂ emission, NH₃ slip | Non-linear | MATLAB/Simulink and ESC/ETC |
| [21] | 2011 | PI | NO₂ emission, NH₃ slip | Non-linear | MATLAB/Simulink |
| [22] | 2010 | PI / Adaptive PI | NH₃ storage | Linear | MATLAB/Simulink |
| | | PI / Adaptive PI | NH₃ and NO₂ slip | Linear | MATLAB/Simulink |
| | | PI / Adaptive PI | NH₃ and NO₂ slip | Non-linear | MATLAB/Simulink |
| [19] | 2009 | PI | NH₂ sensor | Non-linear | Real-time SCR chemistry model |
| [23] | 2009 | A multi-loop PID approach | NH₃ flow feedback | Non-linear | MATLAB/Simulink and Cayuga Unit 1 |
| [18] | 2009 | PI | NO₂ emission | Linear | MATLAB/Simulink |
| [18] | 2002 | PI | NO₂ emission | Linear | MATLAB/Simulink |

[19,24] proposed a model-based control system for SCR urea dosing that employed an embedded real-time SCR model and an NH₃ sensor. Furthermore, [19] demonstrated the potential of an NH₃ sensor for on-board diagnostics. Instead of an actual NH₃ sensor, a model can be used for determining reaction rates and NH₃ emissions. However, it is to be expected that this kind of forward simulation model is rather sensitive to disturbances and the accumulation of model errors.

A patent [25] proposes the use of a test signal (“wiggle test”) to determine the differential response of the NOₓ sensor to changes in urea dosing. The change in response can be used to resolve the sensor ambiguity and therefore to distinguish NH₃ slip conditions from low NOₓ conversion. However, this approach is limited to steady-state operation, otherwise the effect of NOₓ volatility tends to dominant the slow response to urea dosing.

**Model-Based SCR Control Methods**

**State Feedback**

Typically, the main goals of a feedback controller are stability, reduced sensitivity to disturbances, and reduced effects of the most detrimental sources of error. Such errors can include inaccurate estimation of NOₓ concentration, or a systematic error between desired and injected amounts of urea solution [18].

The dominant dynamics of the SCR system are based on the level of NH₃ coverage on the SCR catalyst. The influence of urea dosing on NH₃ coverage is very direct, and therefore control loop stability not the main issue. The most difficult problem is how to establish the ammonia coverage in the catalyst, since it is not directly measurable, model parameters have significant uncertainties, and state estimation is only effective in some operating conditions. Another challenging problem is to define and track the optimal operating point, which has to simultaneously provide both high NOₓ conversion and minimal NH₃ slip.

| Table 5 – Potential control variables |
|---|---|---|---|---|
| Variable | Source | Control Dynamics | Disturbance Dynamics | Significance | Reference |
| NH₃ Coverage (solid) | Dominant state | Slow & simple | Slow & complex | Key state | Temperature dependent |
| NH₃ concentration (gas) | Fast state or output | Minimal delay | Slow | System limit | Constant |
| NO₂ concentration (gas) | Fast state or output | Complex | Fast | System goal | Mostly constant |
| NO₂ conversion | Division of outputs | Slow & complex | Fast | Subsystem goal | Constant |
Another key choice is how to draw the boundaries of the control problem, as demonstrated in Figure 6. Using only urea dosing as a control input leaves large parts of the system uncontrollable. Including the calibration of the air and fuel system of the Internal Combustion Engine (ICE) as a control input increases the control authority and range significantly, because exhaust NOx concentration and exhaust temperature offer additional control inputs in an integrated control scheme.

The choice of the control variables is important from this point of view. The seemingly obvious choice of controlling tailpipe NOx concentrations turns out to be a poor choice from a control point of view, because it responds quickly to disturbances from the engine, but only slowly to changes in the control. It is therefore more effective to control the NH3 coverage, which leads to better and faster disturbance rejection. An overview of the key dynamics and variables is given in Table 5. The choice of variable is also temperature dependent: at low temperature storage estimation is critical, but at high temperature storage is much lower, which can leads to challengingly fast system dynamics.

Most approaches in the literature use a nonlinear reference for the desired coverage, based on temperature and flow rate, and then apply linear state feedback control using urea dosing to achieve this level.

An extreme form of state feedback, the use of switching mode control, has been studied by [29]. They use a first order model for the dynamics of the SCR system, and extend the model with an integral weighting function, and then define a switching surface in this two-dimensional state space. Switching mode control works very well in this case because of the simple dynamics of the system. It delivers excellent suppression of disturbances and good robustness. However, it is not clear what the effect of the “all or nothing” input signal is on the urea dosing actuator. It may simplify the design, or it may cause problems by switching the injector on and off at high frequency. It could also create an increased risk of deposits and uneven distribution of ammonia across the catalyst.

State Estimation

Figure 7 – State Estimation Feedback Control Structure

The very limited measurement possibilities and the complexity of the involved chemical processes are critical issues that make control of SCR quite challenging. Therefore, there is a need to estimate the values of required variables for control design. The state estimate can then be used as an input for the controller as shown in Figure 7.

Many model-based approaches have appeared in the literature on state estimation in linear or linearized SCR systems [30,31]. The basic idea is to find a state estimate \( \hat{x} \) using a parallel model and output feedback

\[
\dot{\hat{x}} = A\hat{x} + Bu + L(y - Cx)
\]

However, linear approaches are limited due to the presence of nonlinearities, parametric uncertainties and variable disturbances [32,33]. The use of sliding mode observers for state estimation can have some benefits in dealing with nonlinearities, disturbance and transient situations because of their robust characteristics with respect to state estimation. A sliding mode observer using a sliding mode state observer is presented by [32]. It is shown that the sliding mode observers are capable of detecting sensor faults effectively.

Recent papers have applied the extended Kalman filter (EKF) to the SCR problem [32–34]. The two key differences to the linear approach is that a system linearization around the current state estimate is being used, and that the optimal observer gain \( L \) is calculated dynamically based on linearized model and current covariance. This increases the computational complexity significantly, and therefore it is feasible only for rather simple models.

The paper [35] investigates three different outlet SCR sensor configurations, with two NH3 coverage states in each of 13 axial elements, and all reactions of Table 1. In order to reduce computational burden, the authors of [34] take the NH3, NO and NO2 outlet concentrations and NH3 coverage as the states of a single element lumped-parameter model, neglecting modelling reactions (5, 6, and 8) of Table 1, and compare the continuous-discrete EKF variant with an ordinary EKF.
Estimation can also be used to cover the ageing state of the system. The approach in [32,33] neglects the dynamics of the fast reaction (3) to simplify the model, and investigates the addition of a slowly time-varying NH₃ storage capacity state to the model for estimating ageing effects. The separation into nominal dynamics and ageing dynamics is shown in Figure 5.

In summary, the most relevant state estimation techniques used in SCR systems are shown in Table 6 [11,30-36].

### Advanced SCR Control Methods

While modern control is very successful at maintaining the right NH₃ coverage, it fails to achieve optimal operation of the SCR system within the context of other systems as discussed above. For a more comprehensive approach, advanced control methods are being considered, that often include an element of online optimization. This allows compromises to be made between conflicting demands such as urea consumption, system degradation and efficiency. In the following sections, an overview of the research within the field of advanced SCR control methods will be given.

#### Model-Based Predictive Control (MPC)

Progressively increasing constraints and conflicting control objectives of SCR aftertreatment systems make advanced control techniques such as model-based predictive control (MPC) attractive, and the improved computing power of today’s processors means that its implementation is becoming practical [37,38]. The nature of MPC makes this method a logical next step in the evolution of SCR control technology over other available techniques presented in this review.

The research by [39] is the first example of the use of MPC for an SCR system. Their MPC is based on a first-order linear-time-varying approximation of an embedded fourth-order nonlinear model. They chose to use an infinite prediction horizon using a terminal cost term to guarantee stability, and a control horizon fixed at three. The cost function consists of two parts: the output NOₓ inefficiency tracking error term, and the input ANR increment penalty term. Furthermore, the MPC algorithm uses feedback from NOₓ and NH₃ cross-sensors. Significant simplifications to avoid on-line computational effort included omission of a constrained optimization in favor of a heuristic back-off saturation law.
An adaptive MPC demonstrated reduced variability in performance under changing conditions [40].

Another interesting example of MPC control of an SCR system was published in [37]. In this work, a linearized state-space SCR model was used in a standard unconstrained GPC-type formulation with NO\textsubscript{x} efficiency, NH\textsubscript{3} slip, and urea dosing as controlled variable targets in the cost function, in addition to the urea input increment penalty term.

**Adaptive Control**

Several SCR control designs for automotive applications have been proposed in recent years that use adaptive control [41-44]. This can be considered a variation of a nonlinear estimator, but the analysis and design is significantly different. The uncertainly is addressed in the controller, not in the estimator, and usually a global stability analysis is performed for the design.

For instance, [19] proposed a closed loop PI controller, based on real time NH\textsubscript{3} surface coverage computations, and using NH\textsubscript{3} sensor feedback. The advantage of adaptive control schemes is that they can reduce the mismatch between the model and the actual system behavior by adjusting the model parameters. An overview of further adaptive approaches can be found in Table 7.

**Table 7 – Examples of adaptive control techniques used in SCR system**

| Ref | Controller | Model | Control Input | Control Output |
|-----|------------|-------|--------------|----------------|
| [44] | Adaptive | 2\textsuperscript{nd}-order dynamic system | Catalyst temperature | NO / NO\textsubscript{x} ratio |
| [40] | Adaptive MPC | 1\textsuperscript{st}-order on-line linearization | Molar ratio of gaseous NH\textsubscript{3} to NO\textsubscript{x} | NO\textsubscript{x} conversion, back-off NH\textsubscript{3} slip constraint |
| [37] | MPC | Fourth-order 1-D | Injection rate | NO\textsubscript{x} conversion, NH\textsubscript{3} slip, injection rate |
| [43] | Adaptive | 0-D control-oriented | Injection rate | NH\textsubscript{3} storage (NH\textsubscript{3} coverage ratio) |
| [22] | Adaptive PI | 1-D model | Injection rate | NH\textsubscript{3} slip/coverage |
| [19] | Adaptive | 1-D model | Injection rate | NH\textsubscript{3} slip/coverage |
| [42] | Adaptive | 1-D model | Injection rate | NH\textsubscript{3} slip/coverage |
| [17] | Adaptive | 1\textsuperscript{st} order | Injection rate | NH\textsubscript{3} slip/coverage |
| [41] | MRAC | 2-D model | Injection rate | Reduction in NO\textsubscript{x} mass flow |

**Integrated Strategies**

Many efforts have been made to simultaneously minimize both fuel consumption and emissions from combustion engines. High NO\textsubscript{x} conversions within allowable NH\textsubscript{3} slip limits are achieved by separately controlling both the engine and SCR systems in response to varying operating conditions. The growing complexity of these two systems, due in turn to the growing number of actuators, sensors, and sub-systems, make it a challenge to optimize the overall performance. The calibration effort using basic tuning methods increases exponentially with the number of actuators, which have been increasing significantly during the last decade. Therefore, maintaining separate controls for the engine and aftertreatment systems is no longer considered to be practical to meet future emission legislation, and an integrated control approach between the engine and SCR is considered to be the way forward. The key difference is that the engine is now considered as a part of the plant that is subject to control as shown in Figure 9.

Research in this area of Integrated Emission Management strategies is still in the development phase and only limited publications on the interaction between engine and aftertreatment control systems are found in the literature [45].

An example of such a strategy is presented by [46]. The structure of the proposed concept is shown in Figure 10 below. The proposed strategy deployed a supervisory controller that would aim at satisfying the commanded torque by determining the optimal combination of control moves originating from the sub-controller level. To obtain an optimal balance between the control moves, an overall objective function is developed that is minimized by taking into accounts all the constraints and trade-offs.

Another example of a combined heavy duty diesel engine and SCR system is presented by [45]. The proposed optimization method is based on a Sequential Quadratic Programming (SQP) algorithm and is claimed to have been successful in finding the instantaneous optimal balance between NO\textsubscript{x} reduction across the combined engine-SCR system and engine fuel economy. Recently, [47] presented a new design of the Integrated Emission Management strategy. The Integrated Emission Management functions as a supervisory controller, which determines the desired control settings for the different low-level controllers using online optimization.
control approach. MPC methods deal directly with multivariable dynamics and multiple (potentially conflicting) objectives and constraints such as legislated emissions targets, and so can accurately predict and avoid undesirable situations such as NH₃ slip whilst providing near-optimal NOₓ conversion. Existing proposed formulations have so far avoided on-line constrained optimizations because of the associated computational burden, but this may change if more computational power becomes easily available.

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Summary / Conclusions

In this paper, we have surveyed some recent advances in SCR systems control. Model developments have been reviewed and control problems based on these models have been discussed. Basic theories and methods for dealing with control problems of SCR systems were introduced and a few challenging issues were raised. Subsequently, we paid particular attention to control problems of nonlinear complex SCR systems with sensors.

The main conclusion is that sensor information is critical to address the SCR control problem. Good selection of sensors and sensible sensor placement can help to mitigate some of the control issues. Still, basic methods such as open loop control or PID control struggle with the complex non-linear dynamics, especially at high conversion. Therefore non-linear methods are indicated especially for the state estimation problem.

Different ways of framing the system can also have a huge impact on system performance. The most important choice is whether the catalyst temperature is controller or not, which is usually achieved via adjustments in the air and fuel system of the engine.

Finally, powerful control methods such as MPC are very attractive for this application, especially for an integrated
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Definitions/Abbreviations

AmOx – Ammonia Oxidation Catalyst
ANR – Ammonia NOx Ratio
ASC – Ammonia Slip Catalyst (same as AmOx)
DeNOx – remove NOx
DOC – Diesel Oxidation Catalyst
DPF - Diesel Particulate Filter
EGR – Exhaust Gas Recirculation
EKF – Extended Kalman Filter
ICE – Internal Combustion Engine
MPC – Model Predictive Control
NH3 – Ammonia
N2O – Nitrous Oxide (coll. laughing gas)
NO – Nitric Oxide, a clear gas
NOx – Nitrogen Oxide, specifically NO and NO2
OBD – On-Board Diagnostics
PID – Proportional Integral Differential (Controller)
\( R_u \) – universal gas constant
SCR – Selective Catalytic Reduction
T – Temperature
VGT/VTG – Variable Geometry Turbocharger

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