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Experimental Demonstration of a New Model-Based SCR Control Strategy for Cleaner Heavy-Duty Diesel Engines

Frank Willems and Robert Cloudt

Abstract—Selective catalytic reduction (SCR) is a promising diesel aftertreatment technology that enables low nitrogen oxides (\(\text{NO}_x\)) tailpipe emissions with relatively low fuel consumption. Future emission legislation is pushing the boundaries for SCR control systems to achieve high \(\text{NO}_x\) conversion within a tailpipe ammonia (\(\text{NH}_3\)) slip constraint, and to provide robustness to meet in-use compliance requirements. This work presents a new adaptive control strategy that uses an ammonia feedback sensor and an online ammonia storage model. Experimental validation on a 12-liter heavy-duty diesel engine with a 34-liter Zeolite SCR catalyst shows good performance and robustness against urea under- and over-dosage for both the European steady-state and transient test cycles. The new strategy is compared with a sensor-based control strategy with cross-sensitivity compensation. It proved to be superior in terms of transient adaptation and taking an \(\text{NH}_3\) slip constraint into account.

Index Terms—Adaptive control, diesel engines, emission control, model-based control, robustness.

I. INTRODUCTION

The vast majority of European truck manufacturers apply urea-based selective catalytic reduction (SCR) technology to meet the current Euro-V emission targets. Due to the achievable high SCR \(\text{NO}_x\) conversion rates, this technology offers a fuel saving potential; engines can be calibrated for higher engine out nitrogen oxides (\(\text{NO}_x\)) emissions (and corresponding lower fuel consumption, and thus lower emissions). In most cases, the desired SCR performance is realized by map-based feedforward control, see, e.g., [1], [2].

Future emission legislation requires further reduction of \(\text{NO}_x\) and particulate matter (PM) emissions: additional 80% and 50% reductions to meet the proposed Euro-VI \(\text{NO}_x\) and PM targets, respectively. Low temperature performance has also to be optimized, since cold start emissions in the US transient cycle and the new World Harmonized Transient Cycle (WHTC) have to be considered. Furthermore, requirements for on-board diagnostics (OBD) and for in-use compliance have to be met. More precisely, limits on tailpipe \(\text{NO}_x\) and ammonia (\(\text{NH}_3\)) emissions during real-world driving conditions and limits on performance degradation during useful life will be introduced.

NOMENCLATURE

Variables

\(a\) Specific area for heat transfer \([\text{m}^{-1}]\).
\(h\) Heat transfer coefficient \([\text{J} \cdot \text{s}^{-1} \cdot \text{m}^{-2} \cdot \text{K}^{-1}]\).
\(k\) Pre-exponential factor.
\(m\) Mass flow \([\text{kg} \cdot \text{s}^{-1}]\).
\(r\) Reaction rate \([\text{s}^{-1}]\).
\(t\) Time \([\text{s}]\).
\(v\) Gas velocity \([\text{m} \cdot \text{s}^{-1}]\).
\(x\) Position along catalyst axis \([\text{m}]\).
\(C\) Concentration \([\text{mol} \cdot \text{m}^{-3}]\).
\(C_p\) Specific heat \([\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}]\).
\(E\) Activation energy \([\text{J} \cdot \text{mol}^{-1}]\).
\(H\) Reaction enthalpy \([\text{J}]\).
\(R\) Universal gas constant \([\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}]\).
\(SV\) Space velocity \([\text{h}^{-1}]\).
\(T\) Temperature \([\text{K}]\).
\(\varepsilon\) Catalyst porosity \([\text{–}]\).
\(\theta\) Ammonia surface coverage \([\text{–}]\).
\(\theta^*\) Critical ammonia surface coverage \([\text{–}]\).
\(\rho\) Density \([\text{kg} \cdot \text{m}^{-3}]\).
\(\Omega\) Adsorption capacity \([\text{mol} \cdot \text{m}^{-3}]\).

Abbreviations and subscripts

\(a\) Ambient.
\(ads\) Ammonia adsorption.
\(des\) Ammonia desorption.
\(exh\) Exhaust gas.
\(fa\) Fast [in SCR reaction (4)].
\(g\) Gas phase.
\(oxn_0\) Ammonia oxidation [in SCR reaction (6)].
\(oxn_2\) Ammonia oxidation [in SCR reaction (7)].
\(ref\) Reference.
\(s\) Substrate catalyst.
\(sl\) Slow [in SCR reaction (5)].
\(st\) Standard [in SCR reaction (3)].
With the need for high NO\textsubscript{x} conversion rates, SCR system control becomes challenging, since safety margins have to be reduced and dynamic performance becomes more important. In that case, the risk of unacceptable NH\textsubscript{3} slip increases, especially for Zeolite-type catalysts, which are used in combination with particulate filters on US EPA 2010 and Euro-VI applications. In addition, the SCR control system has to be robust in order to meet in-use compliance and conformity of production requirements. A new model-based SCR control strategy is presented. It deals with the slip constraint by controlling the ammonia surface coverage on the catalyst. Using feedback information of an sensor, this strategy also offers robustness against system variance. This new strategy overcomes practical issues related to available cross-sensitive sensors and to slip control for Zeolite-type catalysts. The potential of the NH\textsubscript{3} sensor-based SCR control is demonstrated on an engine dynamometer.

II. SCR SYSTEM DESCRIPTION

Fig. 1 shows a typical layout of an automotive urea SCR system. In this system, three subsystems can be distinguished: the urea dosage system, catalyst system and control system. The dosage and catalyst subsystems will be discussed in more detail below. The control system is dealt with in Section III.

A. Urea Dosage System

To form the required reducing reagent for NO\textsubscript{x} reduction in the SCR catalyst, an aqueous urea solution (trade name: AdBlue) is injected through a nozzle, such that it is atomized in the exhaust pipe. The following main steps can be distinguished in the NH\textsubscript{3} formation process:

\begin{align*}
\text{H}_4\text{N}_2\text{CO} & \rightarrow \text{NH}_3 + \text{HNCO} \quad (1) \\
\text{HNCO} + \text{H}_2\text{O} & \rightarrow \text{NH}_3 + \text{CO}_2. \quad (2)
\end{align*}

Thermal decomposition (1) takes place upstream of the SCR catalyst. However, the amount of formed NH\textsubscript{3} depends on temperature and space velocity (i.e., reciprocal of residence time) [4]. From measurements in a flow reactor, it is seen that the contribution of the hydrolysis reaction (2) to NH\textsubscript{3} formation upstream of the SCR catalyst is negligible [5]. The hydrolysis needs to be catalyzed; it occurs inside the SCR catalyst.

B. SCR Catalyst System

Using the formed reagent (NH\textsubscript{3}), the nitrogen oxides (NO\textsubscript{x}) emitted by the engine are reduced and converted to harmless products (nitrogen and water) over an SCR catalyst. This is realized according to the following reaction mechanisms:

\begin{align*}
4\text{NH}_3 + 4\text{NO} + \text{O}_2 & \rightarrow 2\text{N}_2 + 6\text{H}_2\text{O} \quad (3) \\
4\text{NH}_3 + 2\text{NO} + 2\text{NO}_2 & \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O} \quad (4) \\
8\text{NH}_3 + 6\text{NO}_2 & \rightarrow 7\text{N}_2 + 12\text{H}_2\text{O}. \quad (5)
\end{align*}

The most desirable pathway is the “fast-SCR” reaction (4), which is considerably faster than the “standard SCR” reaction (3) and reaction (5). For high temperatures, maximal achievable NO\textsubscript{x} conversion can be limited due to NH\textsubscript{3} oxidation

\begin{align*}
\text{NH}_3 + 5\text{O}_2 & \rightarrow 4\text{NO} + 6\text{H}_2\text{O} \quad (6) \\
4\text{NH}_3 + 3\text{O}_2 & \rightarrow 2\text{N}_2 + 6\text{H}_2\text{O}. \quad (7)
\end{align*}

C. SCR System Model

To model the studied SCR system, TNO’s SIMCAT simulation package is used [6]–[8]. With this modular tool, various SCR system configurations can be modeled. It consists of 1-D models for urea decomposition in the exhaust pipe, pre-oxidation catalyst, diesel particulate filter (DPF), SCR catalyst, and NH\textsubscript{3} oxidation catalyst. The SCR system model is based on first-principle modeling, including mass and energy balances, and is capable of real-time implementation on an automotive control unit (time step \(0.1\) s). The SCR system modeling approach used is similar to [9], [10]. A dedicated fit tool and test sequence is developed to fit the models based on engine test bench data [7], [8].

The new NH\textsubscript{3} sensor-based control strategy comprises a real-time 1-D model, in which the SCR catalyst is divided into 12 longitudinal segments. In the applied model, the effect of urea decomposition on catalyst performance is assumed to be negligible. With the notation given in the nomenclature, general reaction rate expressions and a surface coverage limiting factor [10] are defined as

\[
\frac{k_3(T_s) - k_3^0 e^{-E_3/kT_s}}{1 - e^{-E_3/kT_s}} f(\theta) = \theta^* \left[ 1 - e^{-\theta^*} \right].
\]

The desorption dynamics are assumed to follow Temkin-type desorption kinetics with surface coverage dependent activation energy [10]. For each segment, the NH\textsubscript{3} surface coverage \(\theta\) and substrate temperature \(T_s\) dynamics are described by two coupled differential equations shown at the bottom of the page.
TABLE I
OVERVIEW OF ADVANCED SCR CONTROL STUDIES (FF = FEEDFORWARD CONTROLLER; ESC = EUROPEAN STEADY-STATE CYCLE; ETC = EUROPEAN TRANSIENT CYCLE; FTP = US TRANSIENT CYCLE; JE05 = JAPANESE TRANSIENT CYCLE; NON-CROSS-SENSITIVE = COMPENSATION FOR NH₃ CROSS-SENSITIVITY OF NOₓ SENSOR)

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Affiliation</th>
<th>Engine</th>
<th>SCR catalyst type</th>
<th>Controller</th>
<th>Model</th>
<th>Feedback information</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>Engelhard/ TNO</td>
<td>6-cyl. HD diesel</td>
<td>FF</td>
<td>2nd order filter</td>
<td>(Tₑ, NOₓ engine)</td>
<td>ETC</td>
<td></td>
</tr>
<tr>
<td>[2]</td>
<td>Bosch</td>
<td>6-cyl. HD diesel</td>
<td>FF</td>
<td>Time delay + 1st order filter</td>
<td>(Tₑ, NOₓ engine)</td>
<td>ETC</td>
<td></td>
</tr>
<tr>
<td>[4, 11]</td>
<td>ETH Zurich Liebherr D926</td>
<td>10 l, 6-cyl. Vanadium (19.9 l)</td>
<td>Model-based FF + PI control</td>
<td>Cat temp. + NH₃ surface coverage</td>
<td>Cross-sensitive NOₓ</td>
<td>Load steps, ESC, ETC</td>
<td></td>
</tr>
<tr>
<td>[12]</td>
<td>Michigan Tech/ International</td>
<td>7.6 l, 6-cyl. Fe-Zeolite Navistar 16</td>
<td>Observer-based nonlinear state feedback</td>
<td>NH₃ surface coverage</td>
<td>Non-cross-sensitive NOₓ</td>
<td>Load steps</td>
<td></td>
</tr>
<tr>
<td>[13]</td>
<td>Delft University of Technology</td>
<td>3-cyl. LPW3, 8 kW</td>
<td>Vanadium (1.0 l)</td>
<td>Model-based FF</td>
<td>Neural net engine-out NOₓ</td>
<td>Stationary</td>
<td></td>
</tr>
<tr>
<td>[14]</td>
<td>Cummins</td>
<td></td>
<td></td>
<td>Model-based FF + gain scheduled PI control</td>
<td>Time delay + 1st order lead/lag filter (catalyst dynamics)</td>
<td>Non-cross-sensitive NOₓ</td>
<td>Step</td>
</tr>
<tr>
<td>[15]</td>
<td>Ford</td>
<td></td>
<td></td>
<td>FF + observer-based feedback</td>
<td>NH₃ surface coverage</td>
<td>Non-cross-sensitive NOₓ</td>
<td></td>
</tr>
<tr>
<td>[16]</td>
<td>Cummins</td>
<td>15 l, 6-cyl. ISX-450</td>
<td>Vanadium</td>
<td>Model Reference Adaptive Control</td>
<td>1st order filter (catalyst dynamics)</td>
<td>Non-cross-sensitive NOₓ</td>
<td>Hot FTP</td>
</tr>
<tr>
<td>[17]</td>
<td>Ford</td>
<td></td>
<td></td>
<td>Sliding mode control</td>
<td>NH₃ surface coverage</td>
<td>NOₓ</td>
<td>FTP</td>
</tr>
<tr>
<td>[18]</td>
<td>Waseda univ.</td>
<td>4 l, 4-cyl. Diesel</td>
<td>Zeolite (4.3 l)</td>
<td>FF</td>
<td>Temperature-based NH₃ surface coverage compensation</td>
<td>NOₓ</td>
<td>JE05</td>
</tr>
<tr>
<td>[19]</td>
<td>Honda</td>
<td></td>
<td></td>
<td>Minimum seeking control</td>
<td></td>
<td>Cross-sensitive NOₓ</td>
<td></td>
</tr>
</tbody>
</table>

For a segment, the model state $x$, input $u$ and output $y$ are given by

$$
\begin{align*}
    x^T &= [\theta \ T_e] \\
    u^T &= [C_{NO,in} \ C_{NO2,in} \ C_{NH3,in} \ T_{g,in} \ T_e \ \bar{m}_{exh}] \\
    y^T &= [C_{NO,ot} \ C_{NO2,ot} \ C_{NH3,ot} \ T_{G,ot} \ \bar{m}_{out}] .
\end{align*}
$$

Assuming quasi-stationary conditions, the spatial concentrations for NO, NO₂, and NH₃ are determined from the mass balances of the gaseous species

$$
\begin{align*}
    v \frac{\partial C_{NO}}{\partial x} &= -\Omega [k_{ae}(T_e) C_{NO} f(\theta) + k_{fo}(T_e) C_{NO} C_{NG2} f(\theta)] - k_{oxd}(T_e) \theta \\
    v \frac{\partial C_{NO2}}{\partial x} &= -\Omega [k_{ae}(T_e) C_{NO2} f(\theta)] + k_{fo}(T_e) C_{NO} C_{NO2} f(\theta) \\
    v \frac{\partial C_{NH3}}{\partial x} &= -\Omega [k_{ae}(T_e) C_{NH3} (1 - \theta) - k_{ico}(T_e) \theta].
\end{align*}
$$

The exhaust gas temperature varies over the catalyst length $x$ according to

$$
\frac{v}{\varepsilon \bar{\rho}_g C_{P,g}} \frac{\partial T_e}{\partial x} = -\frac{1}{\varepsilon \bar{\rho}_g C_{P,g}} h_{gs} a_{gs}(T_g - T_e).
$$

III. SCR CONTROL

A. Overview of SCR Control Strategies

Table I gives a brief overview of the progress in SCR control development. It is based on studies found in the open literature. Whenever available, details about the engine, SCR system, control system, and tests are listed.

1) Feedforward SCR Controller: Map-based urea dosage strategies are the current standard in vehicles, see, e.g., [1], [2], [5]. These feedforward strategies have proven to be sufficient to meet Euro-IV and Euro-V emission standards. They are inspired on steady-state operation of the SCR catalyst and basically adjust the NH₃ to NOₓ stoichiometric dosing ratio (NSR). Simple model functionality is incorporated to improve catalyst
Fig. 2. Model fit results for two consecutive European steady-state cycles (ESC).

temperature prediction [1], [2], improve engine-out NO\textsubscript{x} prediction [1], [2], [13], or as a crude model of the SCR catalyst dynamics [2], [14].

Driven by the required increasing NO\textsubscript{x} reduction rates and introduction of Zeolite catalysts, research focuses on NH\textsubscript{3} surface coverage control to maintain high NO\textsubscript{x} conversion in combination with decent control over the NH\textsubscript{3} slip. In its simplest form, the feedforward urea dosing is compensated for the amount of NH\textsubscript{3} desorbed during a temperature rise [18]. Improved NH\textsubscript{3} slip control is provided by strategies comprising a first principles, reduced order model for the NH\textsubscript{3} surface coverage, e.g., [4], [12], [15].

2) Feedback SCR Controllers: Due to reduced safety margins and robustness issues, feedback SCR control attracts considerable attention. Most feedback strategies rely on PI control or on a surface coverage observer with state feedback control. It is noted that other control approaches are found too: model reference adaptive control [16], sliding mode control [17], and minimum seeking control [19]. Currently available NO\textsubscript{x} sensors are cross-sensitive to NO\textsubscript{x}, which poses potential instability problems when not addressed correctly. The cross-sensitivity of NO\textsubscript{x} sensors is dealt with in [4], [11], [19]. Experimental results of a strategy based on perturbation of the urea injection are presented in [4] and [11] for a setup comprising a Vanadium SCR catalyst.

B. Tested SCR Control Strategies

In this work, a new adaptive strategy for combined surface coverage and NH\textsubscript{3} slip control is presented. With the recent availability of an NH\textsubscript{3} sensor [3], [20], the opportunity of adjusting the urea injection based on NH\textsubscript{3} slip feedback information becomes feasible. The NH\textsubscript{3} surface coverage part of the strategy is based on a high-fidelity real-time first principles model, as is described in Section II. The model fit results for two consecutive ESC are shown in Fig. 2. Due to on-board diagnostics requirements, engines will be equipped with a tailpipe NO\textsubscript{x} sensor. This sensor could also be used for SCR control. In this study, this new adaptive surface coverage and NH\textsubscript{3} slip control strategy is compared with a more traditional map-based strategy extended with a NO\textsubscript{x} sensor feedback scheme.

1) NH\textsubscript{3} Sensor-Based Control: Closed-loop NH\textsubscript{3} control is attractive, because maximum NO\textsubscript{x} conversion is pursued under a given NH\textsubscript{3} slip constraint. From Fig. 3, it can be concluded that under low or decreasing temperature conditions, NH\textsubscript{3} slip feedback control tends to load the SCR catalyst with ammonia, especially for Zeolite-type SCR catalysts. Although high NH\textsubscript{3} surface coverage is beneficial for NO\textsubscript{x} conversion, it can cause NH\textsubscript{3} slip peaks during an increase of the catalyst temperature. Therefore, this surface coverage has to be controlled to a level that is safe from causing unacceptable NH\textsubscript{3} slip peaks, but does maintain considerable NO\textsubscript{x} conversion.

The applied SCR control strategy is illustrated in Fig. 4. This strategy combines the following two control modes.

- NH\textsubscript{3} Surface Coverage Control: Using the 1-D SCR model described in Section II, the spatial distribution of the NH\textsubscript{3} surface coverage, $\theta$, is estimated online. The averaged value $\theta_{\text{avg}}$ over the 12 longitudinal segments is compared with a reference value $\theta_{\text{ref}}(T)$. This is essentially the maximum allowable NH\textsubscript{3} storage (see
Fig. 3), which results in a 25 ppm NH₃ slip peak during a worst-case temperature increase [21]. A PI controller adjusts the urea dosage to track the reference coverage \( \theta_{\text{ref}} \).

- **NH₃ Slip Feedback Control:** NH₃ slip feedback information is used to directly adjust the urea injection to control the NH₃ slip towards the reference concentration level \( \theta_{\text{ref}} \) using a PID controller. The average NH₃ slip has to be below 10 ppm. Here, we used \( \theta_{\text{avg}} \) of 8 ppm for safety.

Both controllers contain integrator anti-wind up. The controller switches between NH₃ slip feedback control mode and NH₃ surface coverage control mode, depending on the measured NH₃ slip and estimated averaged surface coverage. This is shown in the equation at the bottom of the page, where \( E_{\theta} = \theta_{\text{ref}}(T_s) - \theta_{\text{avg}} \), \( E_{NH_3} = NH_3_{\text{ref}} - NH_3_{\text{eres}} \) and \( U(s) \) the Laplace transform of the urea solution dosing rate \( u \) (in g/h).

To enhance the robustness of the proposed strategy, the \( \theta_{\text{ref}} \) map is scaled by an adaptation factor. This map is adapted such that the NH₃ slip feedback control mode is active during high and increasing catalyst temperatures (where NH₃ slip is expected or NH₃ slip feedback control is feasible) and NH₃ surface coverage control is active in all other cases. A more detailed description of the adaptation mechanism is given in [21].

The controller is parameterized by manual tuning at the test stand; the applied control gains are listed in Table II. The rate of adaptation was calibrated such that \( \theta_{\text{avg}} \) can decrease with 1% per second relative to the original \( \theta_{\text{ref}} \) map, and increase with 0.5% per second. Note that the adaptation capabilities of the proposed control strategy are heavily dependent on the behavior of the SCR catalyst temperature.

2) **NOₓ Sensor-Based Control:** The applied NOₓ sensor-based strategy consists of a feedforward part that applies urea injection based on an engine-out NOₓ signal, nominal stoichiometric ratio (NSR) map and a dynamic desorption compensation. The dosing signal is corrected using feedback information from the post-SCR NOₓ sensor. To prevent the feedback control loop from becoming unstable, the NH₃ cross-sensitivity of the NOₓ sensor has to be taken into consideration. The applied cross-sensitivity compensation is based on the filtering effect of the SCR catalyst on tailpipe emissions. By applying a pulsating urea flow, amplitudes of a couple of ppm for the pulses

<table>
<thead>
<tr>
<th>( \theta ) control</th>
<th>NH₃ slip control</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{P,\theta} ) = 6.3 \times 10^4 g h(^{-1})</td>
<td>( K_{P,NH_3} ) = 0.015 g h(^{-1}) ppm(^{-1})</td>
</tr>
<tr>
<td>( K_{I,\theta} ) = 1.9 \times 10^3 g h(^{-1}) s(^{-1})</td>
<td>( K_{I,NH_3} ) = 3.1 \times 10^2 g h(^{-1}) ppm(^{-1}) s(^{-1})</td>
</tr>
</tbody>
</table>
| \( K_{D,NH_3} \) = 10 g h\(^{-1}\) ppm\(^{-1}\) s\(^{-1}\) | \( \tau = 20 \) s

\[
U(s) = \begin{cases} 
K_{P,\theta} + \frac{K_{I,\theta}}{s} E_{\theta}(s), & \text{if } \theta_{\text{avg}} > \theta_{\text{ref}}(T_s) \\
K_{P,NH_3} + \frac{K_{I,NH_3}}{s} + \frac{K_{D,NH_3}}{\tau + 1} E_{NH_3}(s), & \text{if } NH_3_{\text{eres}} > NH_3_{\text{ref}} \text{ and } \theta_{\text{avg}} \leq \theta_{\text{ref}}(T_s)
\end{cases}
\]
in the NO\textsubscript{X} concentration signal are pursued. If the pulses are too high, the algorithm increases the urea injection. If they are too small, NH\textsubscript{3} slip is likely, and the algorithm reduces the nominal urea injection. Alternative strategies can be found in, e.g., [4], [11], [19].

This principle has proven to function, but requires stationary operating conditions for adaptation. The variations in the NO\textsubscript{X} sensor signal have to be clearly linked to the pulsating urea flow and not to a change of the engine operating point. Moreover, the proposed NO\textsubscript{X} based control strategy requires a fast response to variations of the urea injection. Consequently, it requires a high SCR temperature \(330^\circ\text{C}\) in order to apply the feedback correction.

The requirement for stationary conditions severely limits the robustness and applicability of feedback control using a cross-sensitive NO\textsubscript{X} sensor. Furthermore, the proposed strategy does not offer any control over the absolute NH\textsubscript{3} slip level; it relies on the correlation between the filtering effect of the SCR catalyst on the fluctuating emissions and the occurrence of NH\textsubscript{3} slip. Compared to the studies in [4] and [11], a much larger perturbation of the urea injection was necessary for the studied engine and Fe-Zeolite SCR catalyst combination. This ultimately led to the pulsating urea delivery shown in Fig. 5. More details about the proposed NO\textsubscript{X}-based strategy can be found in [21].

IV. ENGINE TEST RESULTS

A. Test Setup

The test setup comprises: 1) a 12-liter heavy-duty diesel engine equipped with exhaust gas recirculation (EGR); 2) a catalyzed diesel particulate filter (CDPF) with an upstream diesel oxidation catalyst (DOC); and 3) a 34-liter Fe-Zeolite SCR system with air-assisted urea dosage system. The SCR catalyst and urea injection point are located downstream of the CDPF. NO\textsubscript{X} and NH\textsubscript{3} sensors are installed on the locations that are depicted in Fig. 6.

Engine-out NO\textsubscript{X} levels comply with US 2007 standard. TNO’s urea dosage strategy and real-time SCR model are implemented on a rapid prototyping controller, which communicates with the engine ECU, dosing system and NH\textsubscript{3} and NO\textsubscript{X} sensors through CAN interfaces. The SCR model has been fitted to the applied Fe-Zeolite SCR catalyst in the test setup, based on experimental data from engine dynamometer tests [6], [7]. The model and measurement show good agreement (see Fig. 2); the model error for NO\textsubscript{X} conversion is less than 5\% over two ESC tests and the error in average and peak NH\textsubscript{3} slip is less than 1 and 10 ppm, respectively. More especially, the accurate NH\textsubscript{3} slip prediction gives confidence about the accuracy of the online NH\textsubscript{3} storage estimation.

B. Adaptive Surface Coverage and NH\textsubscript{3} Slip Control Performance

To validate the NH\textsubscript{3} sensor-based control strategy, it has been tested on both the European steady-state cycle (ESC) and the European transient cycle (ETC). As a disturbance, 30\% urea over-dosage was applied. This represents any disturbance source which can cause an increased NH\textsubscript{3} slip, like, e.g., SCR catalyst ageing or inaccuracy in urea dosing, in exhaust flow determination or in pre-SCR NO\textsubscript{X} signal. Several consecutive test cycles were run to investigate whether the NH\textsubscript{3} sensor-based control strategy is capable of compensating for the 30\% increased urea injection. An overview of the test cycle results is given in Table III.

Fig. 7 illustrates the actions of the proposed NH\textsubscript{3} sensor-based control strategy for three consecutive ESC. In the first ESC test, 30\% urea over-dosage results in a 79 ppm NH\textsubscript{3} slip peak. Every time the measured NH\textsubscript{3} slip exceeds the NH\textsubscript{3} slip reference level, the algorithm switches from surface coverage...
control to NH₃ slip feedback control. If NH₃ slip feedback control is active during a period where NH₃ slip is undesired (temperature dependent), the algorithm reacts by lowering the desired SCR NH₃ storage in the \( \theta \) map. These actions are clearly visible in Fig. 7; the reference NH₃ storage level for the online SCR model is reduced by more than a factor 2 during the first ESC. Finally, the peak NH₃ slip drops from 79 to 24 ppm in the third ESC. The realized NH₃ emissions meet the targets set in this study: peak and average NH₃ slip of 25 and 10 ppm, respectively.

The proposed control strategy also gives good results during ETC test conditions (see Table III); the peak NH₃ slip drops from 38 to 4 ppm within three consecutive cycles. These extremely low NH₃ slip values compromise on NOₓ conversion.

### C. Comparison With NOₓ Sensor-Based Strategy

For ESC, the performance of the adaptive surface coverage and NH₃ slip control strategy is compared with the performance of the map-based strategy with NOₓ sensor feedback. Note that this comparison can only be made on the ESC, since the presented based strategy is not applicable to the transient conditions in the ETC. Consecutive ESC with both 30% urea dilution and 30% urea overdosing were tested to observe the robustness of these control strategies. The results of these tests are presented in Table IV.

In Fig. 7, it has already been illustrated that the NH₃ based control strategy is capable of adaptation to the 30% urea overdosage. The strategy lowers the desired NH₃ storage level for the online SCR model, which results in less slip. For the 30% dilution case, the algorithm increases the reference NH₃ storage level for the online SCR model, as can be seen in Fig. 8. This causes the peak NH₃ slip to increase from 9 to 15 ppm during the four ESC, which is well within the 25 ppm peak NH₃ limit.

The NOₓ based SCR control strategy is also capable of adaptation for the applied disturbances of urea injection. In case of the 30% higher urea injection, the NOₓ-based algorithm reduces the peak NH₃ slip in the ESC from 44 to 24 ppm, while maintaining a NOₓ conversion of roughly 90%. Fig. 9 shows the adaptation behavior of the NOₓ-based algorithm for the 30% urea dilution case. The correction factor on the stoichio-

### Table IV

<table>
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<th>Measurements</th>
<th>Control strategy</th>
<th>Disturbance</th>
<th>ESC</th>
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Fig. 8. Control and adaptation behavior of the NH₃-based control strategy on four consecutive ESC with 30% urea dilution. (Control mode: 0 = no injection, 2 = NH₃ slip feedback control, 3 = surface coverage control).

Fig. 9. Adaptation behavior of NOₓ-based control on four consecutive ESC with 30% urea dilution.

strategies show convergence within eight cycles for the studied disturbances [21].

V. CONCLUSION

A new adaptive surface coverage and NH₃ slip control strategy has been presented, which uses ammonia sensor information. This strategy deals with the NH₃ slip constraint by adjusting the ammonia buffering in the SCR catalyst. In addition, it offers robustness against system deviations by ammonia feedback control.

The NH₃ sensor-based control strategy was successfully implemented on the test setup, which comprised a 12-liter diesel engine equipped with a 34-liter Fe-Zeolite SCR system. A high fidelity, phenomenological SCR system model was fitted on engine dynamometer data and accurately describes the SCR system behavior. This real-time model is embedded in the controller and facilitates dependable ammonia surface coverage control.

The potential of the proposed strategy experimentally was validated for two cases: 30% urea under- and overdosage. The new strategy excels in avoiding NH₃ slip while maintaining a high NOₓ conversion level. With targeted average and peak ammonia slips of 10 and 25 ppm, respectively, NOₓ conversion as high as 92% is achieved for both ESC and ETC, despite the large disturbances in urea dosage.

Comparison with a NOₓ sensor-based control strategy with cross-sensitivity compensation shows that the NH₃ sensor-based strategy gives better performance and robustness for the studied cases. The NOₓ sensor-based strategy can adapt only in stationary conditions, while the proposed NH₃ sensor-based strategy copes well with the European transient cycle as well.

Due to OBD requirements, engine platforms are likely to be equipped with a tailpipe NOₓ sensor. Current research focuses on the application of an SCR observer, using information from different combinations of NOₓ and NH₃ sensors. The ultimate goal is an Integrated Emission Management Strategy that optimizes the synergy between engine and aftertreatment system. For instance, strategies for systems with close-coupled SCR catalysts [22], EGR/SCR balancing and different thermal management strategies are being examined to enhance low temperature performance of SCR systems.

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REFERENCES


