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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 (NO_x) tailpipe emissions with relatively low fuel consumption. Future emission legislation is pushing the boundaries for SCR control systems to achieve high NO_x conversion within a tailpipe ammonia (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 NO_x sensor-based control strategy with cross-sensitivity compensation. It proved to be superior in terms of transient adaptation and taking an NH_3 slip constraint into account.

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

NOMENCLATURE

Abbreviations and subscripts

a	Ambient.
ads	Ammonia adsorption.
des	Ammonia desorption.
exh	Exhaust gas.
fa	Fast [in SCR reaction (4)].
g	Gas phase.
oxno	Ammonia oxidation [in SCR reaction (6)].
oxn2	Ammonia oxidation [in SCR reaction (7)].
ref	Reference.
s	Substrate catalyst.
sl	Slow [in SCR reaction (5)].
st	Standard [in SCR reaction (3)].

Variables

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

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 NO_x conversion rates, this technology offers a fuel saving potential; engines can be calibrated for higher engine out nitrogen oxides (NO_x) emissions (and corresponding lower fuel consumption, and thus lower CO_2 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 NO_x and particulate matter (PM) emissions: additional 80% and 50% reductions to meet the proposed Euro-VI 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 NO_x and ammonia (NH_3) emissions during real-world driving conditions and limits on performance degradation during useful life will be introduced.

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Fig. 1. Automotive urea SCR system layout [3].

With the need for high NO_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_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 NH_3 slip constraint by controlling the ammonia surface coverage on the catalyst. Using feedback information of an NH_3 sensor, this strategy also offers robustness against system variance. This new strategy overcomes practical issues related to available cross-sensitive NO_x sensors and to NH_3 slip control for Zeolite-type catalysts. The potential of the NH_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_x reduction in the SCR catalyst, an aqueous urea solution (trade name: Ad-Blue) is injected through a nozzle, such that it is atomized in the exhaust pipe. The following main steps can be distinguished in the NH_3 formation process:

Thermal decomposition (1) takes place upstream of the SCR catalyst. However, the amount of formed NH_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_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_3), the nitrogen oxides (NO_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:

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_x conversion can be limited due to NH_3 oxidation

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_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_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

$$k_j(T_s) = k_j^0 e^{-E_j/RT_s} \quad f(\theta) = \theta^* \left[1 - e^{-\theta/\theta^*} \right].$$

The desorption dynamics are assumed to follow Temkin-type desorption kinetics with surface coverage dependent activation energy [10]. For each segment, the NH_3 surface coverage θ and substrate temperature T_s dynamics are described by two coupled differential equations shown at the bottom of the page.

$$\begin{bmatrix} \dot{\theta} \\ \dot{T}_s \end{bmatrix} = \begin{bmatrix} k_{\text{ads}}(T_s)C_{\text{NH}_3}[1 - \theta] - [k_{\text{des}}(T_s) + k_{\text{oxno}}(T_s) + k_{\text{oxn2}}(T_s)]\theta \\ - [k_{\text{st}}(T_s)C_{\text{NO}} + 2k_{\text{fa}}(T_s)C_{\text{NO}}C_{\text{NO}_2} + \frac{4}{3}k_{\text{st}}(T_s)C_{\text{NO}_2}]f(\theta) \\ \frac{1}{(1-\varepsilon)\rho_s C_{p,s}} \left[h_{gs}a_{gs}(T_g - T_s) - h_{sa}a_{sa}(T_s - T_a) + \Omega \sum_j r_j \Delta H_j \right] \end{bmatrix}$$

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 NH_3 CROSS-SENSITIVITY OF NO_x SENSOR)

Ref.	Affiliation	Engine	SCR catalyst type	Controller	Model	Feedback information	Test
[1]	Engelhard/ TNO			FF	2 nd order filter ($T_{\text{cat}}, \text{NO}_{x,\text{engine}}$)		ETC
[2]	Bosch	6-cyl. HD diesel		FF	Time delay + 1 st order filter ($T_{\text{cat}}, \text{NO}_{x,\text{engine}}$)		ETC
[4, 11]	ETH Zurich	10 l, 6-cyl. Liebherr D926	Vanadium (19.9 l)	Model-based FF + PI control	Cat temp. + NH_3 surface coverage	Cross-sensitive NO_x	Load steps, ESC, ETC
[12]	Michigan Tech/ International	7.6 l, 6-cyl. Navistar I6	Fe-Zeolite	Observer-based non- linear state feedback	NH_3 surface coverage	Non-cross-sensitive NO_x	Load steps
[13]	Delft University of Technology	3-cyl. LPW3, 8 kW	Vanadium (1.05 l)	Model-based FF	Neural net engine-out NO_x		Stationary
[14]	Cummins			Model-based FF + gain scheduled PI control	Time delay + 1 st order lead/lag filter (catalyst dynamics)	Non-cross-sensitive NO_x	Step
[15]	Ford			FF + observer-based feedback	NH_3 surface coverage	Non-cross-sensitive NO_x	
[16]	Cummins	15 l, 6-cyl. ISX-450	Vanadium	Model Reference Adaptive Control	1 st order filter (catalyst dynamics)	Non-cross-sensitive NO_x	Hot FTP
[17]	Ford			Sliding mode control	NH_3 surface coverage	NO_x	FTP
[18]	Waseda univ.	4 l, 4-cyl. Diesel	Zeolite (4.3 l)	FF	Temperature-based NH_3 surface coverage compensation		JE05
[19]	Honda			Minimum seeking control		Cross-sensitive NO_x	

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

$$\begin{aligned}
 x^T &= [\theta \quad T_s] \\
 u^T &= [C_{\text{NO},\text{in}} \quad C_{\text{NO}_2,\text{in}} \quad C_{\text{NH}_3,\text{in}} \quad T_{g,\text{in}} \quad T_a \quad \dot{m}_{\text{exh}}] \\
 y^T &= [C_{\text{NO},\text{out}} \quad C_{\text{NO}_2,\text{out}} \quad C_{\text{NH}_3,\text{out}} \quad T_{g,\text{out}}] .
 \end{aligned}$$

Assuming quasi-stationary conditions, the spatial concentrations for NO , NO_2 , and NH_3 are determined from the mass balances of the gaseous species

$$\begin{aligned}
 v \frac{\partial C_{\text{NO}}}{\partial x} &= -\Omega [k_{st}(T_s) C_{\text{NO}} f(\theta) + k_{fa}(T_s) C_{\text{NO}} C_{\text{NO}_2} f(\theta) \\
 &\quad - k_{\text{oxno}}(T_s) \theta] \\
 v \frac{\partial C_{\text{NO}_2}}{\partial x} &= -\Omega [k_{st}(T_s) C_{\text{NO}_2} f(\theta) \\
 &\quad + k_{fa}(T_s) C_{\text{NO}} C_{\text{NO}_2} f(\theta)] \\
 v \frac{\partial C_{\text{NH}_3}}{\partial x} &= -\Omega [k_{\text{ads}}(T_s) C_{\text{NH}_3} (1 - \theta) - k_{\text{des}}(T_s) \theta] .
 \end{aligned}$$

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

$$v \frac{\partial T_g}{\partial x} = - \frac{1}{\varepsilon \rho_g C_{p,g}} h_{gs} a_{gs} (T_g - T_s) .$$

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 NH_3 to NO_x 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_x prediction [1], [2], [13], or as a crude model of the SCR catalyst dynamics [2], [14].

Driven by the required increasing NO_x reduction rates and introduction of Zeolite catalysts, research focuses on NH_3 surface coverage control to maintain high NO_x conversion in combination with decent control over the NH_3 slip. In its simplest form, the feedforward urea dosing is compensated for the amount of NH_3 desorbed during a temperature rise [18]. Improved NH_3 slip control is provided by strategies comprising a first principles, reduced order model for the NH_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_x sensors are cross-sensitive to NH_3 , which poses potential instability problems when not addressed correctly. The cross-sensitivity of NO_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_3 slip control is presented. With the recent

availability of an NH_3 sensor [3], [20], the opportunity of adjusting the urea injection based on NH_3 slip feedback information becomes feasible. The NH_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_x sensor. This sensor could also be used for SCR control. In this study, this new adaptive surface coverage and NH_3 slip control strategy is compared with a more traditional map-based strategy extended with a NO_x sensor feedback scheme.

1) *NH_3 Sensor-Based Control*: Closed-loop NH_3 control is attractive, because maximum NO_x conversion is pursued under a given NH_3 slip constraint. From Fig. 3, it can be concluded that under low or decreasing temperature conditions, NH_3 slip feedback control tends to load the SCR catalyst with ammonia, especially for Zeolite-type SCR catalysts. Although high NH_3 surface coverage is beneficial for NO_x conversion, it can cause NH_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_3 slip peaks, but does maintain considerable NO_x conversion.

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

- *NH_3 Surface Coverage Control*: Using the 1-D SCR model described in Section II, the spatial distribution of the NH_3 surface coverage, θ , is estimated online. The averaged value θ_{avg} over the 12 longitudinal segments is compared with a reference value $\theta_{\text{ref}}(T_s)$. This is essentially the maximum allowable NH_3 storage (see

Fig. 3. Steady-state and maximum allowable NH_3 storage as a function of catalyst temperature, for a 34-liter SCR catalyst, space velocity = 5000 h^{-1} , NSR = 1.2 and engine-out NO_x = 250 g/h . Maximal allowable storage is the NH_3 storage amount that causes an NH_3 slip peak of 25 ppm at a simulated worst-case temperature increase of 5°C/s .

Fig. 3), which results in a 25 ppm NH_3 slip peak during a worst-case temperature increase [21]. A PI controller adjusts the urea dosage to track the reference coverage θ_{ref} .

- **NH_3 Slip Feedback Control:** NH_3 slip feedback information is used to directly adjust the urea injection to control the NH_3 slip towards the reference concentration level $\text{NH}_{3,\text{ref}}$ using a PID controller. The average NH_3 slip has to be below 10 ppm. Here, we used $\text{NH}_{3,\text{ref}}$ of 8 ppm for safety.

Both controllers contain integrator anti-wind up. The controller switches between NH_3 slip feedback control mode and NH_3 surface coverage control mode, depending on the measured NH_3 slip and estimated averaged surface coverage. This is shown in the equation at the bottom of the page, where $E_\theta = \theta_{\text{ref}}(T_s) - \theta_{\text{avg}}$, $E_{\text{NH}_3} = \text{NH}_{3,\text{ref}} - \text{NH}_{3,\text{meas}}$ and $U(s)$ the Laplace transform of the urea solution dosing rate u (in g/h). The NH_3 slip control mode is triggered when the reference value $\text{NH}_{3,\text{ref}}$ is exceeded. However, θ control always has the highest priority ($\theta_{\text{avg}} > \theta_{\text{ref}}(T_s)$), since unacceptable ammonia loading has to be avoided. Urea dosing is kept constant through bumpless transfer when switching control mode.

Fig. 4. Block scheme of TNO's adaptive surface coverage and NH_3 slip control strategy.

TABLE II
OVERVIEW OF APPLIED CONTROL GAINS

θ control	NH_3 slip control
$K_{P,\theta} = 6.3 \cdot 10^4 \text{ g h}^{-1}$	$K_{P,\text{NH}_3} = 0.015 \text{ g h}^{-1} \text{ ppm}^{-1}$
$K_{I,\theta} = 1.9 \cdot 10^3 \text{ g h}^{-1} \text{ s}^{-1}$	$K_{I,\text{NH}_3} = 3 \cdot 10^{-4} \text{ g h}^{-1} \text{ ppm}^{-1} \text{ s}^{-1}$
	$K_{D,\text{NH}_3} = 10 \text{ g h}^{-1} \text{ ppm}^{-1} \text{ s}$
	$\tau = 20 \text{ s}$

To enhance the robustness of the proposed strategy, the θ_{ref} map is scaled by an adaptation factor. This map is adapted such that the NH_3 slip feedback control mode is active during high and increasing catalyst temperatures (where NH_3 slip is expected or NH_3 slip feedback control is feasible) and NH_3 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 θ_{ref} can decrease with 1% per second relative to the original θ_{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) **NO_x Sensor-Based Control:** The applied NO_x sensor-based strategy consists of a feedforward part that applies urea injection based on an engine-out NO_x signal, nominal stoichiometric ratio (NSR) map and a dynamic NH_3 desorption compensation. The dosing signal is corrected using feedback information from the post-SCR NO_x sensor. To prevent the feedback control loop from becoming unstable, the NH_3 cross-sensitivity of the NO_x 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

$$U(s) = \begin{cases} \left[K_{P,\theta} + \frac{K_{I,\theta}}{s} \right] E_\theta(s), & \text{if } \theta_{\text{avg}} > \theta_{\text{ref}}(T_s) \\ \left[K_{P,\text{NH}_3} + \frac{K_{I,\text{NH}_3}}{s} + \frac{K_{D,\text{NH}_3}s}{\tau s + 1} \right] E_{\text{NH}_3}(s), & \text{if } \text{NH}_{3,\text{meas}} > \text{NH}_{3,\text{ref}} \text{ and } \theta_{\text{avg}} \leq \theta_{\text{ref}}(T_s) \end{cases}$$

Fig. 5. Experimental demonstration of post-SCR NO_x sensor behavior for pulsating urea flow with Fe-Zeolite catalyst.

in the NO_x concentration signal are pursued. If the pulses are too high, the algorithm increases the urea injection. If they are too small, NH_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_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_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_x sensor. Furthermore, the proposed strategy does not offer any control over the absolute NH_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_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_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_x and NH_3 sensors are installed on the locations that are depicted in Fig. 6.

Engine-out NO_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_3 and NO_x sensors through CAN interfaces. The SCR model has been

Fig. 6. Scheme of test setup (LDS = laser diode spectrometer).

TABLE III
MEASURED CYCLE RESULTS FOR NH_3 SENSOR-BASED CONTROL STRATEGY
IN CASE OF 30% UREA OVER-DOSAGE

Test cycle	NO_x	Avg.	max
	conv. %	NH_3 slip ppm	NH_3 slip ppm
1 st ESC	88	13	79
2 nd ESC	90	7	26
3 rd ESC	91	6	24
1 st ETC	87	6	38
2 nd ETC	84	2	14
3 rd ETC	72	1	4

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_x conversion is less than 5% over two ESC tests and the error in average and peak NH_3 slip is less than 1 and 10 ppm, respectively. More especially, the accurate NH_3 slip prediction gives confidence about the accuracy of the online NH_3 storage estimation.

B. Adaptive Surface Coverage and NH_3 Slip Control Performance

To validate the NH_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_3 slip, like, e.g., SCR catalyst ageing or inaccuracy in urea dosing, in exhaust flow determination or in pre-SCR NO_x signal. Several consecutive test cycles were run to investigate whether the NH_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_3 sensor-based control strategy for three consecutive ESC. In the first ESC test, 30% urea over-dosage results in a 79 ppm NH_3 slip peak. Every time the measured NH_3 slip exceeds the NH_3 slip reference level, the algorithm switches from surface coverage

Fig. 7. Control and adaptation behavior of the NH_3 based control strategy on three consecutive ESC with 30% urea over-dosage. (Control mode: 0 = no injection, 2 = NH_3 slip feedback control, 3 = surface coverage control).

control to NH_3 slip feedback control. If NH_3 slip feedback control is active during a period where NH_3 slip is undesired (temperature dependent), the algorithm reacts by lowering the desired SCR NH_3 storage in the θ map. These actions are clearly visible in Fig. 7; the reference NH_3 storage level for the online SCR model is reduced by more than a factor 2 during the first ESC. Finally, the peak NH_3 slip drops from 79 to 24 ppm in the third ESC. The realized NH_3 emissions meet the targets set in this study: peak and average NH_3 slip of 25 and 10 ppm, respectively.

The proposed control strategy also gives good results during ETC test conditions (see Table III); the peak NH_3 slip drops from 38 to 4 ppm within three consecutive cycles. These extremely low NH_3 slip values compromise on NO_x conversion.

C. Comparison With NO_x Sensor-Based Strategy

For ESC, the performance of the adaptive surface coverage and NH_3 slip control strategy is compared with the performance of the map-based strategy with NO_x sensor feedback. Note that this comparison can only be made on the ESC, since the presented NO_x 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 NH_3 based control strategy is capable of adaptation to the 30% urea over-dosage. The strategy lowers the desired NH_3 storage level for the online SCR model, which results in less NH_3 slip. For the 30% dilution case, the algorithm increases the reference NH_3 storage level for the online SCR model, as can be seen in Fig. 8. This causes the peak NH_3 slip to increase from 9 to 15 ppm during the four ESC, which is well within the 25 ppm peak NH_3 limit.

The NO_x 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 NO_x -based algorithm reduces the peak NH_3 slip in the ESC from 44 to 24 ppm, while maintaining a NO_x conversion of roughly 90%. Fig. 9 shows the adaptation behavior of the NO_x -based algorithm for the 30% urea dilution case. The correction factor on the stoichio-

TABLE IV
MEASURED ESC RESULTS FOR NO_x AND NH_3 -BASED CONTROL STRATEGIES IN CASE OF 30% UREA DILUTION AND 30% UREA OVERDOSAGE

Measurements					
Control strategy	Disturbance	ESC #	NO_x conv.	Avg. NH_3 slip	max NH_3 slip
			%	ppm	ppm
NH_3 -based	30% over-dosage	1	88	13	79
		2	90	7	26
		3	91	6	24
NH_3 -based	30% dilution	1	90	3	9
		2	92	3	10
		3	92	5	11
		4	92	5	15
NO_x -based	30% over-dosage	1	93	15	44
		2	89	9	33
		3	88	6	25
		4	90	5	24
NO_x -based	30% dilution	1	80	4	17
		2	77	3	16
		3	77	3	20
		4	80	3	24

metric feedforward urea injection approaches its expected value of $1/0.7 = 1.42$ after four ESC. The fluctuating post-SCR NO_x emissions are caused by the pulsating urea injection. The pulsations seem to lead to lower NO_x conversion than would have resulted from continuous urea injection. In comparison with the NH_3 -based strategy, the NO_x -based strategy achieves roughly 10% less NO_x conversion for the urea dilution case.

During tests, maximally four consecutive cycles are run. From these results, it is difficult to draw conclusions on convergence. A simulation study illustrated that both nonlinear

Fig. 8. Control and adaptation behavior of the NH_3 -based control strategy on four consecutive ESC with 30% urea dilution. (Control mode: 0 = no injection, 2 = NH_3 slip feedback control, 3 = surface coverage control).

Fig. 9. Adaptation behavior of NO_x -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 NH_3 slip control strategy has been presented, which uses ammonia sensor information. This strategy deals with the NH_3 slip constraint by adjusting the ammonia buffering in the SCR catalyst. In addition, it offers robustness against system deviations by ammonia feedback control.

The NH_3 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 NH_3 slip while maintaining a high NO_x conversion level. With targeted average and peak ammonia slips of 10 and 25 ppm, respectively, NO_x conversion as high as 92% is achieved for both ESC and ETC, despite the large disturbances in urea dosage.

Comparison with a NO_x sensor-based control strategy with cross-sensitivity compensation shows that the NH_3 sensor-based strategy gives better performance and robustness for the studied cases. The NO_x sensor-based strategy can adapt only in stationary conditions, while the proposed NH_3 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 NO_x sensor. Current research focuses on the application of an SCR observer, using information from different combinations of NO_x and NH_3 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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