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3rd Generation SCR System Using Solid Ammonia Storage and Direct Gas Dosing: *- Expanding the SCR window for RDE*

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Amminex A/S:
A Danish CleanTech company

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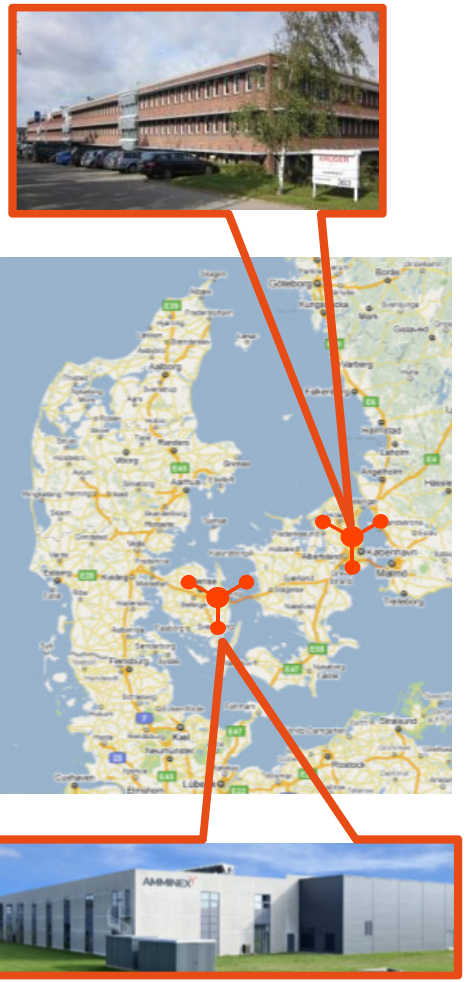
- **TechCenter:**
  Located approximately 20 km from Copenhagen airport

- Prototype workshop

- Laboratories with advanced equipment:

- Component testing:
  - Climatic chambers
  - Vibration stands



- **Manufacturing plant:**
  - Land: 45.800 m2
  - Building: 6.500 m2

Evolution of SCR on vehicles

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- 1st Generation:
  - Air-assisted injection of urea-solution

- 2nd Generation:
  - Air-less injection of urea-solution enables urea-SCR on vehicles without on-board compressed air.

Challenges with low-T, deposits and 'controlling' the liquid reductant

- 3rd Generation:
  - Direct dosing of ammonia gas
  - Solid storage with high volumetric storage capacity

Focus: Expand SCR 'window',
Real Driving Emissions (**RDE**) & low CO_2

Urban air quality (NO_2) remains a major challenge …

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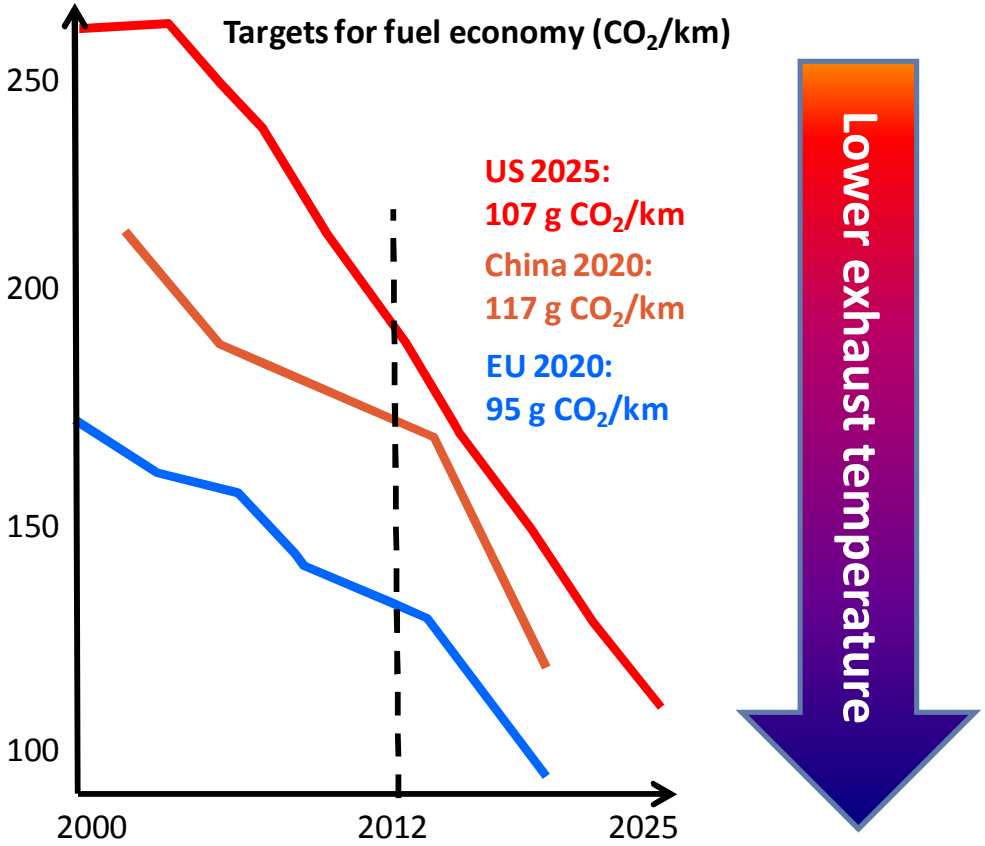
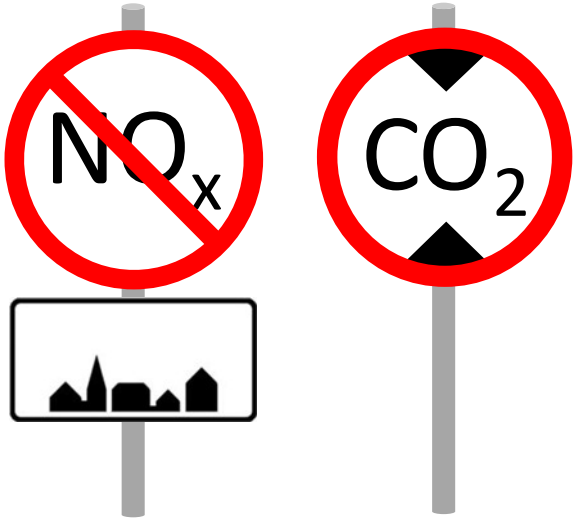
… in particular in view of future CO_2 targets



Lower exhaust temperature



Cold exhaust ⇒ key challenge for emission control systems.

Adapted from T. Johnson, Corning
SAE paper 2012-01-0368

Expanding the SCR "window" while eliminating deposits

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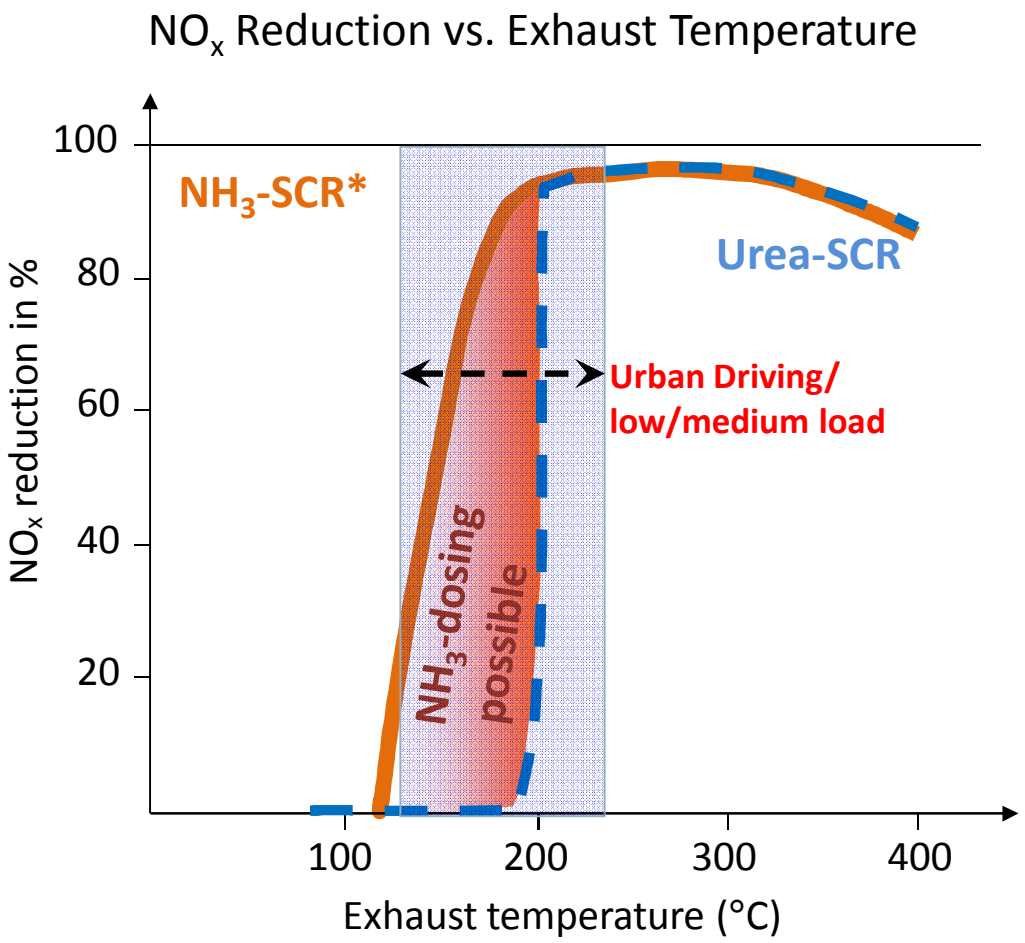

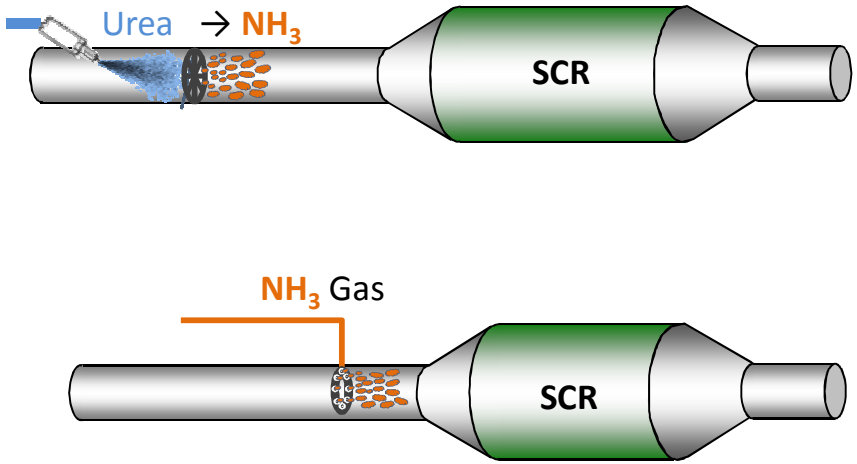

Direct NH_3-dosing enables full benefit of the SCR catalyst.
Zero deposit risk

* NH_3-SCR efficiency: W. Tang et al. BASF, DOE-DEER conference, October 4th 2011, p.3

AdAmmine™: Makes ammonia safe and compact

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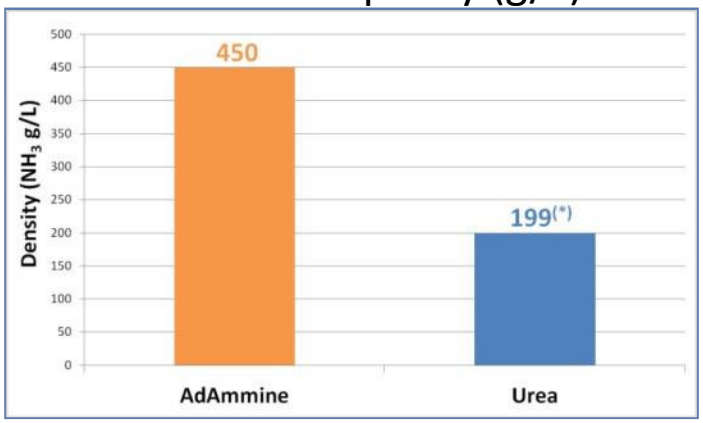
- AdAmmine™: Solid storage provides NH_3-safety and **more than twice** the volumetric capacity of ammonia in AdBlue/DEF
- Room temperature: **Not pressurized** (0.4 bar)

Ammonia capacity (g/L)



* Does not take into account the 'void' needed for freeze expansion

Production: $SrCl_2$ + 8**NH_3** + special formulation = AdAmmine™

Ammonia release: Controlled thermal desorption

$$Sr(NH_3)_XCl_2 \leftrightarrow Sr(NH_3)_{X-1}Cl_2 + \mathbf{NH_3}$$

Usable capacity:
~ 450g NH_3 per liter AdAmmine™

Core components of ASDS: Ammonia Storage and Delivery System

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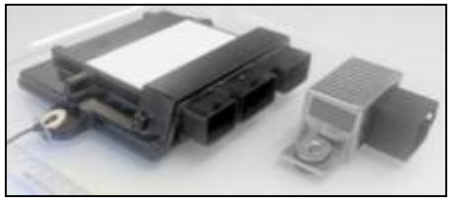
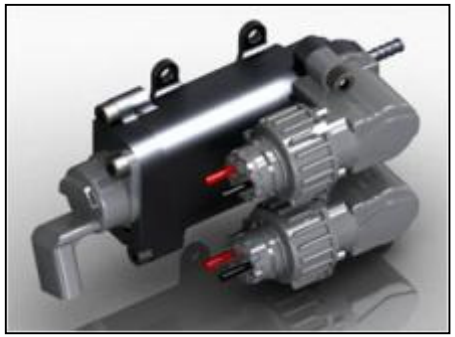
- Main Units (MU); replaceable *cartridges*
- Start-Up Unit (STU)
- Compact **A**mmonia **F**low **M**anifold (AFM)
- Heaters/relays
- Algorithms (on ECU or DCU) for Ammonia Release Functionality
- **Input**: 12V, CAN (NH_3 demand)
- **Output**: Dynamic NH_3 dosing and system feedback

NH3-dosing possible from $T_{SCR} \approx 100°C$

DCU & Relay





Examples of plug 'n' play test systems

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ASDS for PC/LD:

- Dosing turn-down ratio: 1:100
- Dosing accuracy: ± 5% on actual value
- **Cartridge size: 2 x 3.6 liter**
- Ammonia capacity: 2 x 1.6 kg

Corresponding to
≈ 18 liter Urea tank

ASDS for MD applications:

- Dosing turn-down ratio: 1:100
- Dosing accuracy: ± 5% on actual value
- **Cartridge size: 2 x 11 liter**
- Ammonia capacity: 2 x 4.5 kg

Corresponding to
≈ 48 liter Urea tank

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Exhaust interface & examples of DeNOx performance

Ammonia gas: Simplicity and flexibility for exhaust system design

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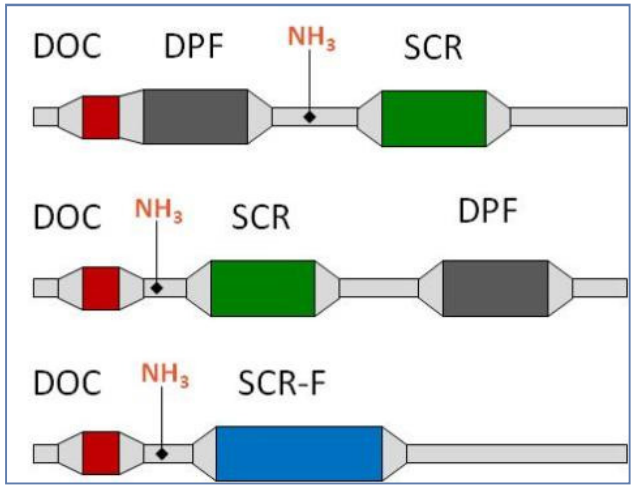
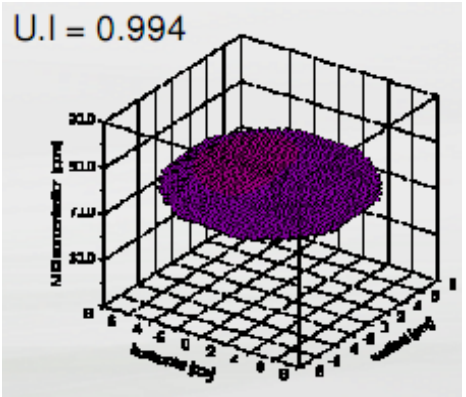
- Flexibility in SCR configuration:
  - DPF → SCR
  - SCR → DPF
  - SCR-coated filter
- Exhaust interface advantages:
  - No injector and no liq. evaporation (cooling)
  - Mixing is possible with lower back-pressure
  - Short mixing length & high uniformity (>0.98)
  - No deposit risk; low corrosion potential

  → **Reduced and predictable development effort for compact exhaust system**

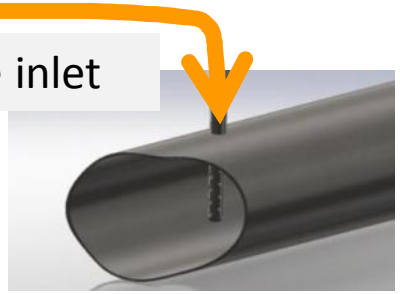




HONDA

Source: M. Fischer. Honda R&D Europe

NH_3 gas & steel tube inlet



OEM consortium demonstrating high performance during real-world driving.

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- Urban driving with under-floor SCR position.
- Test vehicle: Volvo S-80 with Amminex system
- **One-calibration-fits-all**
- 2-hour drive with 152°C avg. SCR temperature
- Dosing in 89% of the trip
- **83% NOx conversion during urban driving**

HONDA JAGUAR LAND ROVER TOYOTA VOLVO

- 24.5 km circle in Berlin
- 12.2 km/h average speed
- 152°C avg SCR_{inlet}
- 100°C NH_3 dosing release
- Dosing on 89% of cycle
- 100% pre-stored NH_3
- 83% NO_x conversion

Source: "Out of the Blue", MinNOx 2012
http://www.out-of-the-blue.at/

Messages from OEM consortium: Simplified SCR calibration

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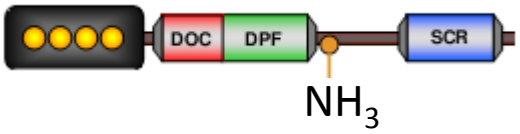
- Single SCR calibration for all driving conditions
- Dosing release temperature set at 100°C upstream SCR
- Robust dosing strategy with low ammonia slip
- Gas dosing system beneficial for low temperature SCR activity
- Very good NOx conversion on off-cycle with no recalibration.

Source: "Out of the Blue", MinNOx 2012
http://www.out-of-the-blue.at/



HONDA JAGUAR LAND ROVER TOYOTA VOLVO

Example of low-T dosing giving improved DeNOx capabilities

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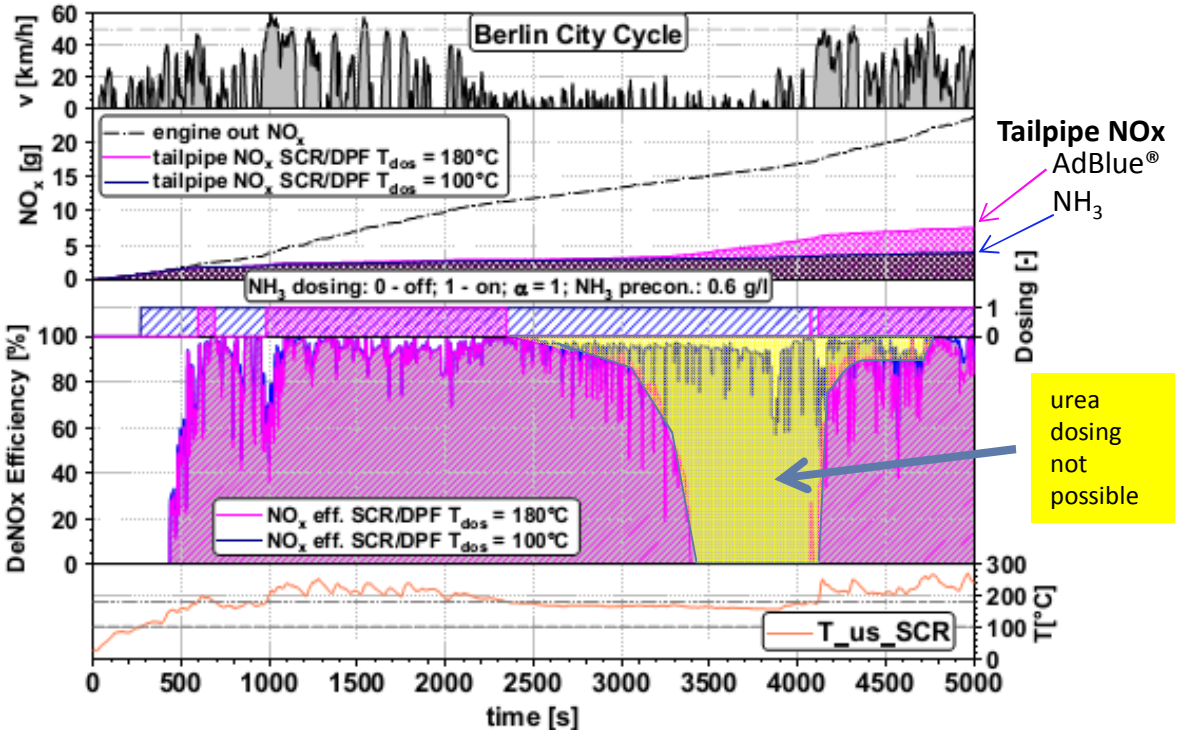
- Urban driving profile (Berlin city cycle)
- Periods with T_{SCR} lower than 180°C
  ⇒ depletion of NH_3 on the SCR catalyst
  ⇒ conversion → zero
- Tailpipe NOx: **Direct NH_3-dosing** (from 100°C) gives almost **half tailpipe emissions** compared with dosing from 180°C (liquid urea).

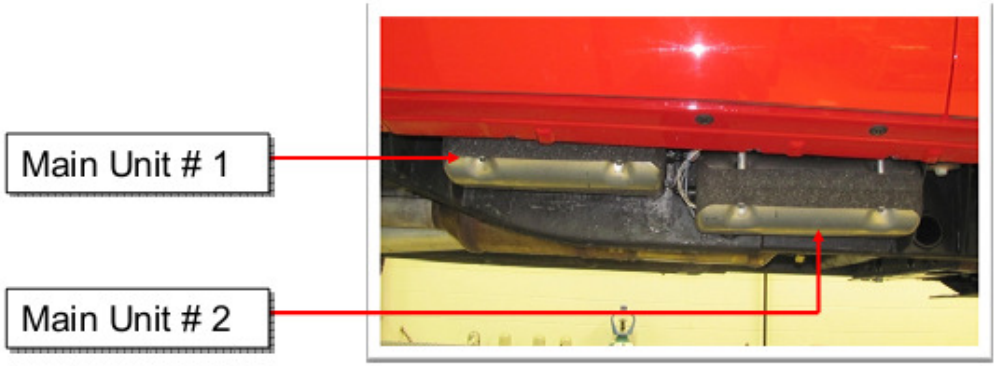


Source: F. Brunau (IAV), MinNOx 2012

ASDS integration on a Silverado pick-up truck

- Tenneco owned 2011 Silverado with OEM DEF & exhaust system
- ASDS prototype fitted on the vehicle
  - 2 x cartridges, STU, AFM, exhaust inlet for NH_3
- Test Objectives:
  - Maintain functionality of OEM DEF system & Solid SCR test system
  - Enable quick switching for A:B comparison
- No change to OEM engine/DEF calibration
- NH_3 dosing strategy for ASDS on separate controller

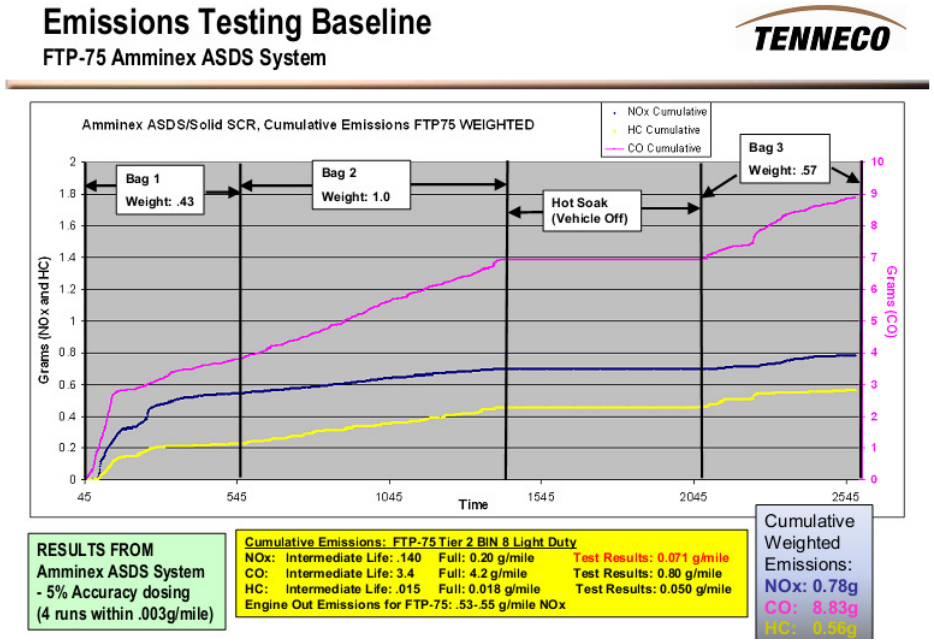
ASDS (2 x 3.6 L cartridges + aux. HW) easily fitted with protective cover on existing platform with OEM **DEF** (~20 liter) system

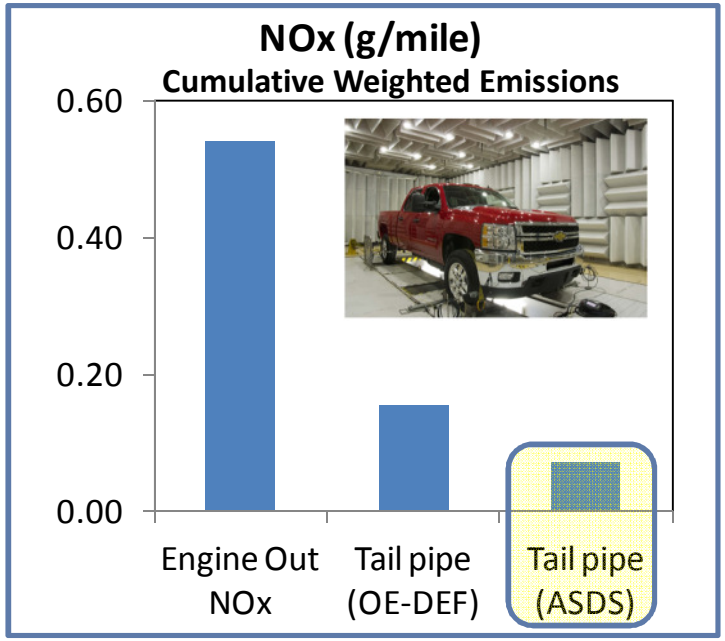


Source: Brian Kunkel, Tenneco, Grass Lake

FTP75 comparison: DEF vs. ASDS

- Tail pipe NOx (Cumulative Weighted Emissions) in FTP75:
  - OEM DEF system: **1.73 g/mile**
  - ASDS/AdAmmine: **0.78 g/mile**
- Reduction of tail pipe NOx was demonstrated with ASDS
- High repeatability (4 runs within 0.003 g/mile)
- **Opportunity: Explore fuel economy improvement enabled by low-temperature dosing of ammonia gas.**





Source: Brian Kunkel, Tenneco, Grass Lake

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Simulation tools for development & vehicle integration

ASDSim™

Simulation Model: ASD*Sim*

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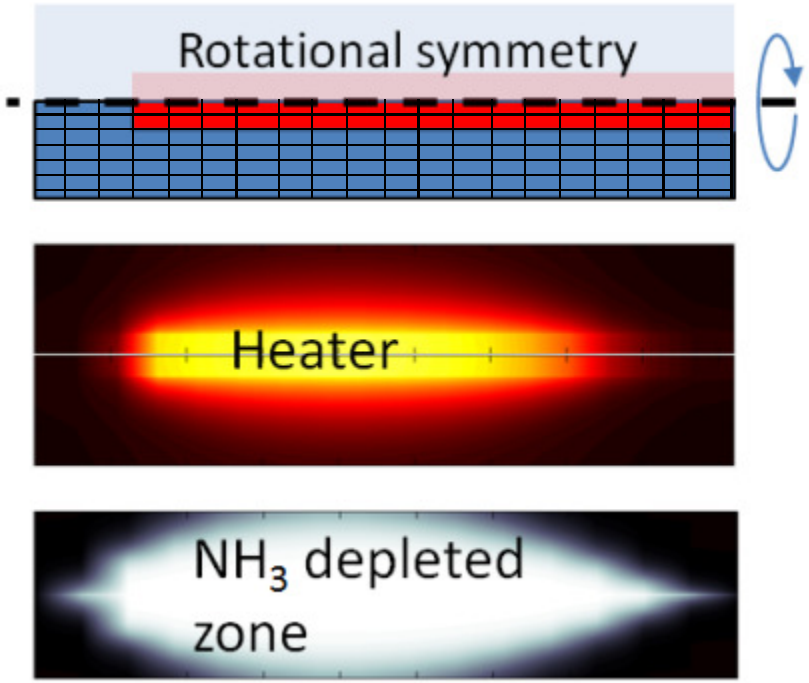
- A physical and chemical FEM model describing the full spatial distribution of temperature and ammonia inside the STU and the MU (cartridge)
- Needs only material properties (measurable)
- Robust and predictive beyond the known (tested) ranges

Start-up unit



Example of simulation of temperature and NH3 distribution (saturation) in a partially empty STU during warm-up

Graphical User Interface

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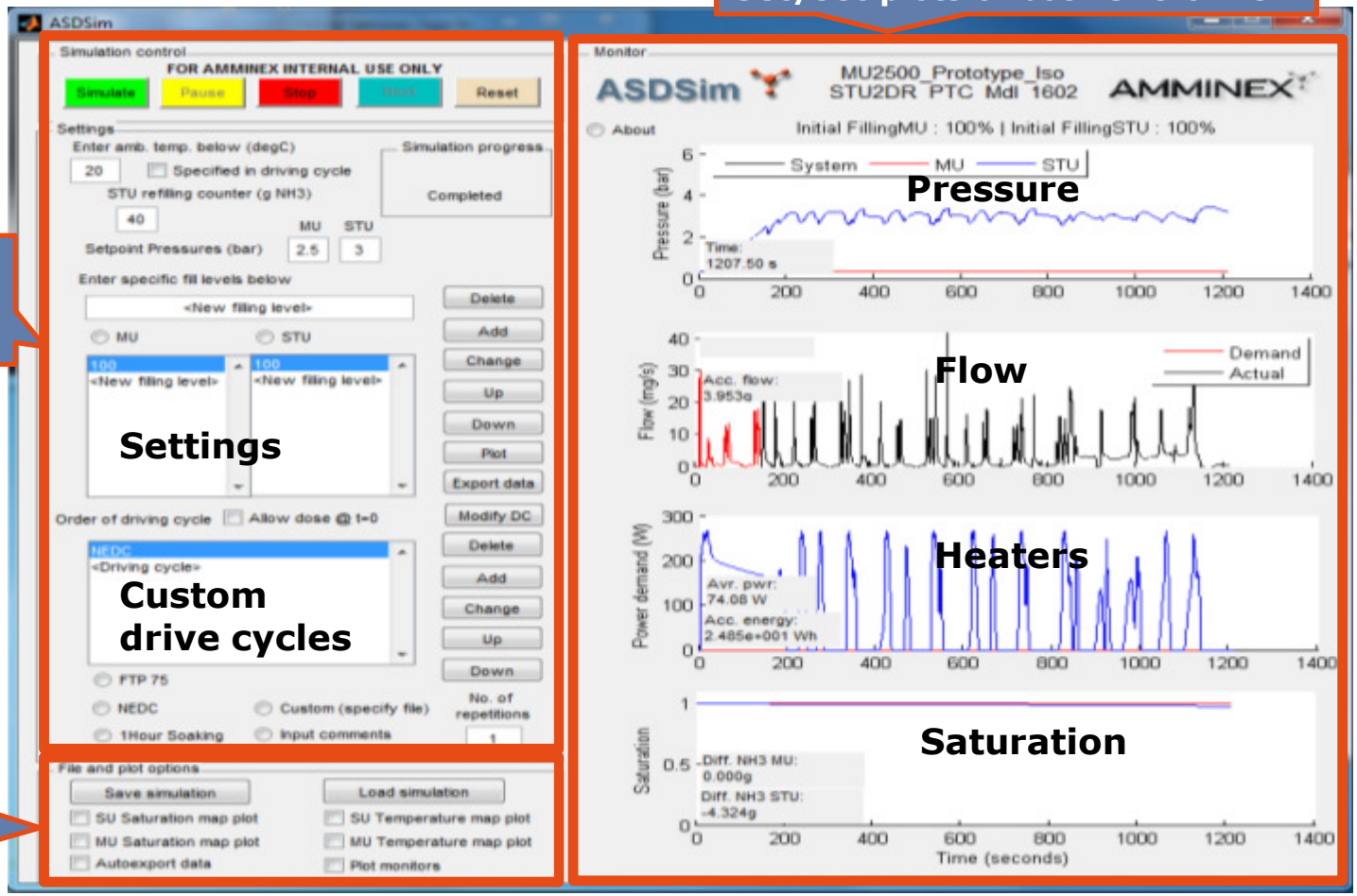
Simple Graphical User Interface (GUI) to aid the user:

2 Results
Sec/sec plots of both STU & MU

1 User inputs & simulation control

3 Save & plot options



Simulation example:
The influence from STU mounting

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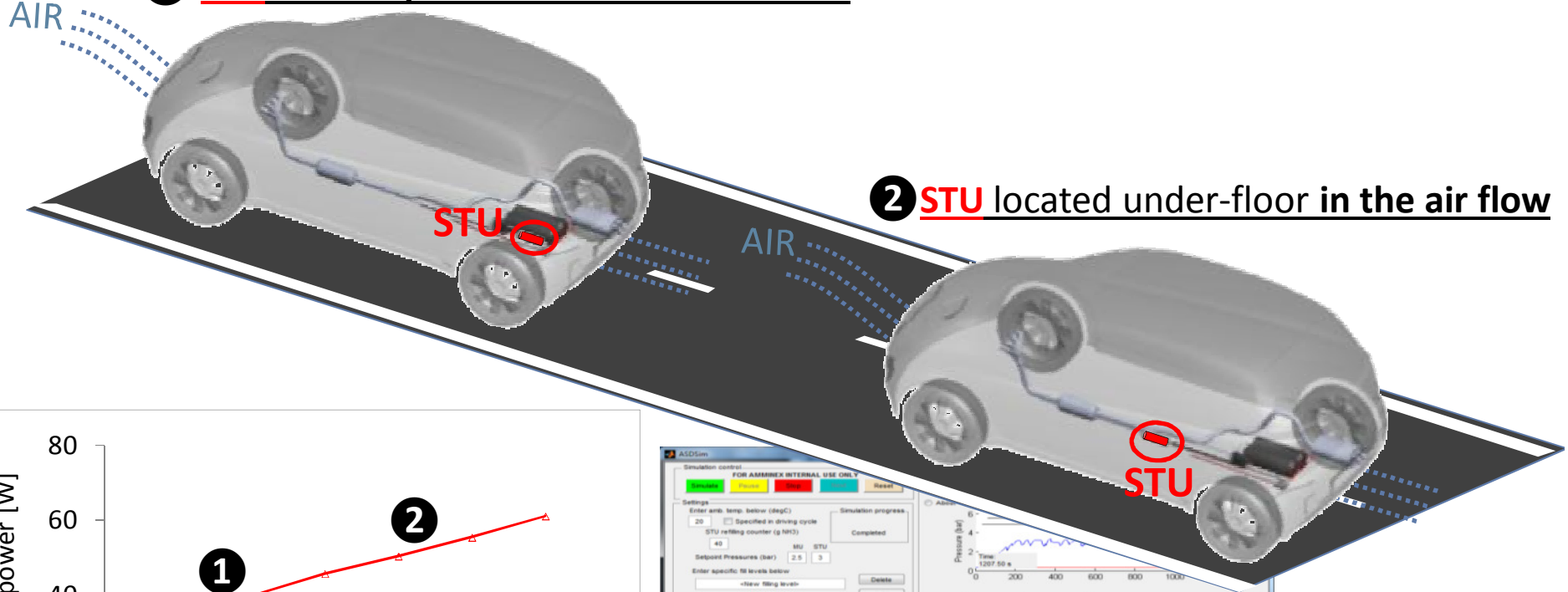
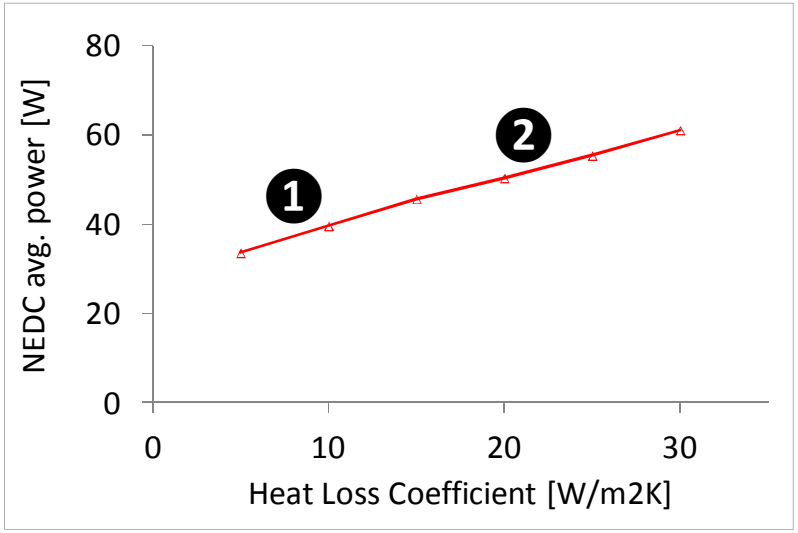
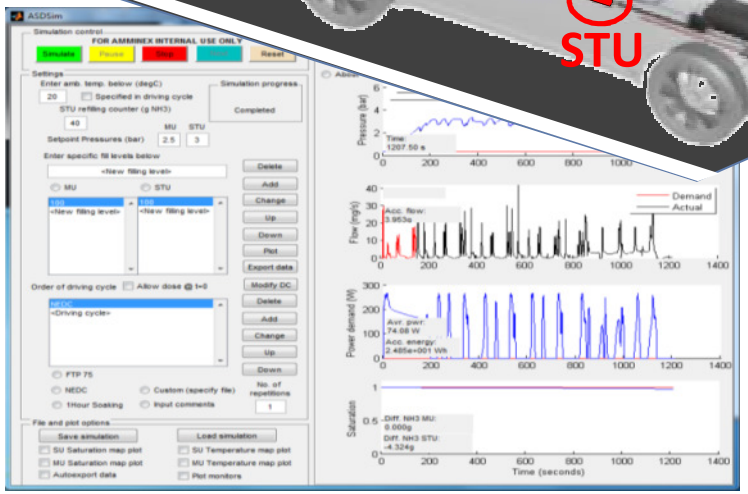
1 **STU** located **protected** from the air flow



2 **STU** located under-floor **in the air flow**





ASDSim™

Simulation example:
Average power consumption and time-to-dose

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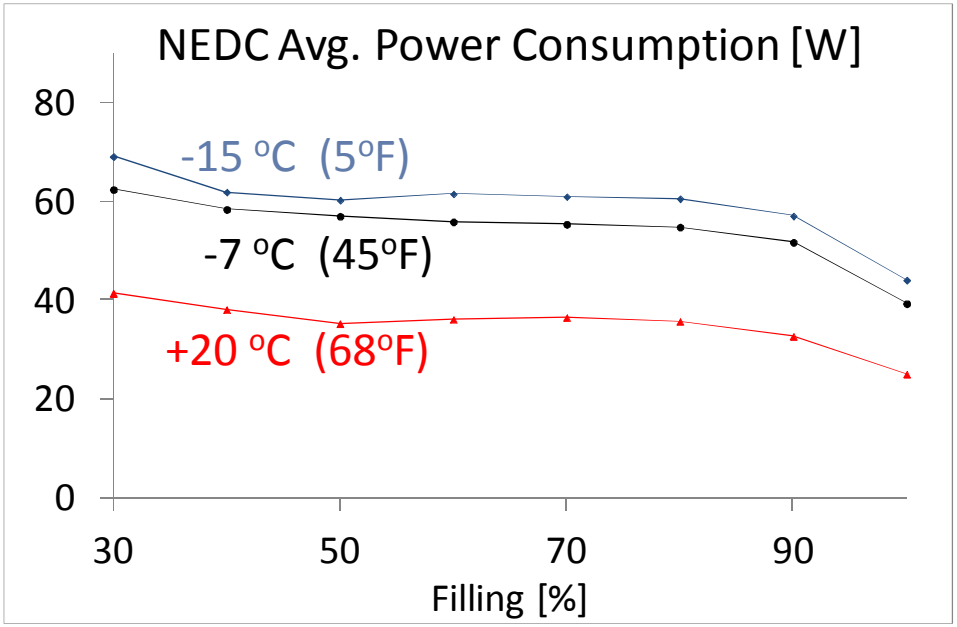
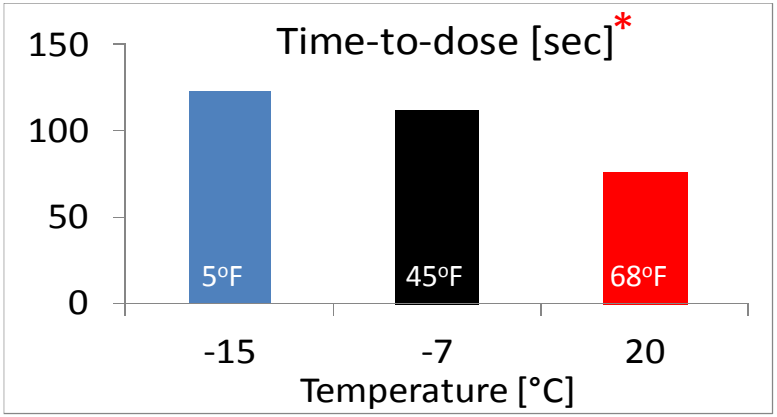
- **Purpose:** To simulate the effect of ambient temperature during NEDC cycle
- Low impact on performance from different STU fill levels.
- Low ambient temperature gives slightly higher power consumption.
- **Freezing temperatures:**
  Even at -15 °C there is short time-to-dose.
  There is no '*thawing-of-ice*' required (solid/liquid phase transition)





* Performance example of one STU.
Time-to-dose Can be tailored to OEM requirements

Process for AdAmmine manufacturing

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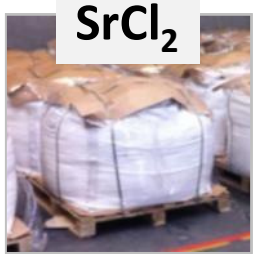

$SrCl_2$

Drying

Saturation

Compaction & Cartridge assembly

NH_3

Metal housing

Full-scale production plant in Denmark

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AdAmmine processing & system concepts

Video from Amminex production facility
shown in the exhibition booth

Examples of system layouts by

faurecia

Summary

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- NOx reduction under all conditions
  - Low/medium engine load; low ambient temperature
  - Works when the SCR catalyst is active
  - Robust SCR calibration
- Positive impact on fuel economy
  - Eliminate or reduce warm-up strategies
  - Reduced pressure drop in 'mixing' zone
- Exhaust interface & calibration
  - Simple interface & no injector
  - No risk of deposits
  - Simplified SCR calibration
- Authorities: Tampering is very difficult
- No shelf life issues for NOx reductant
  - No degradation or freezing; unlimited shelf life
- Compact & customer friendly
  - Service interval capacity is an option
  - No contamination risk

- *On-going work & Challenges*
  - *Implementation of cartridge distribution network in cooperation with Tier-1*
  - *Standardization of cartridge sizes among OEMs for 'similar' applications*