DEVELOPMENT OF UREA-SCR FOR HEAVY-DUTY TRUCKS DEMONSTRATION UPDATE

William Miller
Mack Trucks, Inc.

INTRODUCTION

This paper is an update to SAE 2000-01-0190 "The Development of Urea-SCR Technology for US Heavy Duty Trucks" [1]. Since that paper was published in March 2000, several events have occurred. The demonstration truck was updated to include a 200 cpsi catalyst, engine calibration with lower engine-out NO_X, and urea-SCR system calibration with improved NO_X reduction efficiency. NO_X before and after the catalyst was measured over-the-road and compared with previous results. The truck was then placed in Mack Trucks' fleet for daily operation in a real-world environment.

This project was initiated in March 1998 and has included four phases as shown in Figure 1. The first emissions cell study was conducted in 1998 using a 100 cpsi catalyst. The results of this study were applied to a truck in 1999 and over-the-road tests were completed. A second emissions cell study was conducted in late-1999 using a 200 cpsi catalyst and lower engine-out NO_X level. The truck was then updated in 2000 with the new catalyst and calibrations. This paper will include information from Phase 3 as shown in SAE 2000-01-0190 and the results of truck tests from Phase 4.

Phases of Project

1 -	Test Cell Study	1998	100 cpsi
2 -	Truck Study	1999	100 cpsi
3 -	Test Cell Study	1999	200 cpsi
4 -	Truck Study	2000	200 cpsi

Figure 1

OBJECTIVES

This study included engine cell and vehicle tests. The engine cell tests are aimed at determining NO_X reduction using the US-transient and OICA emissions test cycles. These cycles will be included in future US HD emissions standards. The vehicle tests will show urea-SCR system performance during real-world operation. These tests will prove that the technology can be successfully implemented and demonstrated over-the-road. The program objectives are to :

a. apply urea-SCR to a US HD diesel engine
b. determine engine cell emissions reduction during US-transient and OICA cycles
c. apply urea-SCR to a US HD diesel truck
d. determine NO_X reduction and urea consumption during over-the-road operation

HARDWARE DESCRIPTIONS

ENGINE – The diesel engine used in this study was a US HD 12-liter 4VH inline-6 shown in Figure 2. This engine is turbocharged and aftercooled. Fuel injection is provided by electronically-controlled cam-actuated unit pumps. The engine was calibrated to produce torque levels of 1021 lb-ft at 1800 rpm (rated speed) and 1360 lb-ft at 1200 rpm (peak torque speed). The only engine modifications were changes to the injection timing control map in order to better suit the application of the urea-SCR system. The emissions cell and vehicle tests used 1999 engine hardware and a timing map which produced approximately 5 g/bhp-hr NO_X on both the US-transient and OICA test cycles.

Engine Description

- US HD diesel
- 12 liter 4VH I-6
- 350 bhp
- production hardware
- timing maps modified

Figure 2

UREA-SCR SYSTEM – The general system configuration is identical to the one described in detail in [2]. The SCR catalyst was a homogeneous, extruded base metal catalyst (TiO_2-V_2O_5-WO_3) as shown in Figure 3. This catalyst has a volume of 45 liters and a cell density of 200 cpsi. An oxidation catalyst was not used upstream or downstream of the SCR catalyst to assure system compatibility with current fuel sulfur levels, minimize sulfate formation, and eliminate the risk of N_2O formation.

Catalyst Description

- extruded base-metal (TiO_2-V_2O_5-WO_3)
- 45 liters
- 200 cpsi
- under-cab design
- no oxidation catalyst

Figure 3

TEST CELL MEASUREMENTS

Emissions were measured in a transient test cell with DC dynamometer and partial dilution tunnel. NO_X, CO, CO_2, HC, and PM were measured using accepted analyzers and procedures. NH_3 was measured with an FTIR analyzer calibrated for very low NH_3 concentrations. Standard 2D diesel fuel with 400-500 ppm sulfur content was utilized for all tests. The SCR reductant was urea solution with 32.5% by weight and demineralized water.

During urea-SCR optimization tests, a series of OICA cycles were run at various urea dosing levels. Figure 4 shows the tradeoff between increasing urea dosing levels to achieve higher NO_X reduction and the resulting increase in average NH_3 slip. The system minimizes NH_3 slip using control strategies and algorithms which determine the optimum urea injection rate based on engine operating conditions. Conservative dosing levels were selected for both emissions cell and vehicle tests to follow.

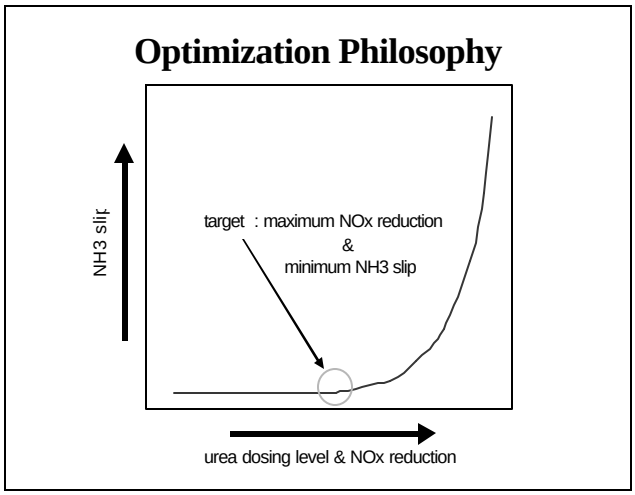

Figure 4

Emissions measurements were recorded from the baseline (engine-out) and after optimization of the urea-SCR system with 200 cpsi catalyst (catalyst-out). Cold US-transient, hot US-transient, and OICA results are shown in Figures 5, 6, and 7. Cold US-transients were run after an overnight cool-down. Hot US-transient results are shown for the first hot test after the cold test and 20-minute engine stop per the proper procedures.

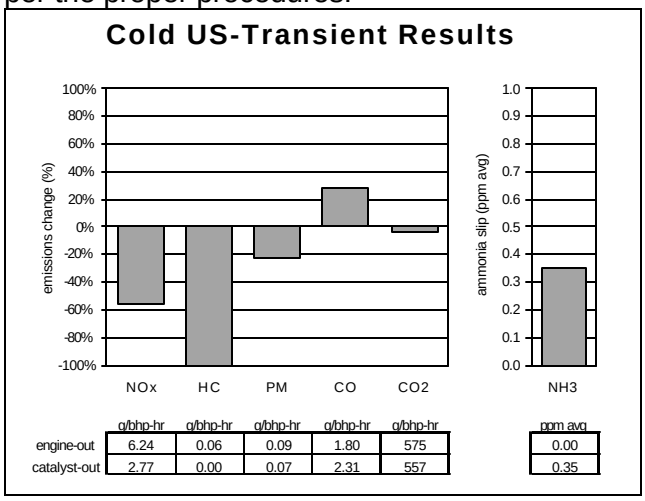

Figure 5

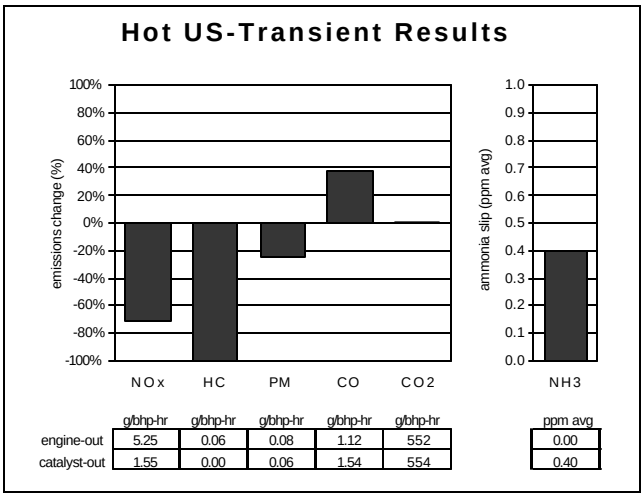

Figure 6

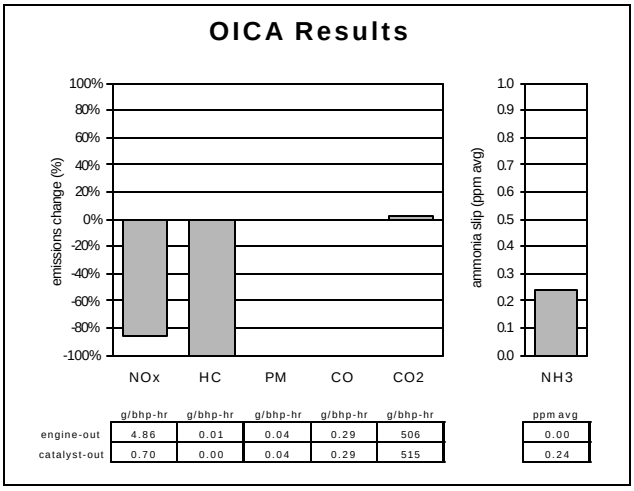

Figure 7

Using urea-SCR, NO_X is reduced in cold US-transient, hot US-transient, and OICA cycles by 55.6%, 70.5%, and 85.6% respectively. HC was reduced below measurable levels. PM was reduced in the US-transients by 22.2% and 25.0%. NH_3 slip was controlled to averages of 0.35, 0.40, and 0.24 ppm through the cycles. These low NH_3 levels are a result of the conservative urea dosing level selected. CO increased in the US-transients by 28.3% and 37.5%. This may have been a byproduct of urea hydrolysis or partially oxidized HC; however, these levels are considered low with respect to the current CO standards. CO_2 showed no significant change.

OVER-THE-ROAD MEASUREMENTS

APPLICATION OF UREA-SCR TO TRUCK - The type of truck chosen for this project was a Class-8 highway truck as shown in Figure 8. Class-8 trucks are capable of GVW (gross vehicle weight) ratings of above 33,000 lb. This truck weighed 16,500 lb. and loaded test trailer weighed 53,500 lb. for a total GVW of 70,000 lb. which is typical for interstate carriers.

Urea-SCR Class-8 Truck

Figure 8

Figure 9 shows the previous component arrangement on the truck using the 100 cpsi catalyst. The components shown left to right are : urea tank, urea dosing unit, and catalyst with integral muffler. The two smaller tanks shown to the far right are the compressed air tanks which were not relocated. The passenger steps are shown mounted outboard from the catalyst brackets.

Previous Urea-SCR Arrangement

Figure 9

The new component arrangement on the truck using the 200 cpsi catalyst is shown in Figure 10. The smaller catalyst allowed side fairings to be mounted. The integral muffler was eliminated in favor of a conventional vertical type. The urea control unit was relocated to the platform behind the cab. Overall, the design features of the new catalyst result in greater compatibility with US HD truck designs.

New Urea-SCR Arrangement

Figure 10

NO_X MEASUREMENT TECHNIQUE – Prototype NO_X/O_2 sensors utilizing the thick film ZrO_2 concept were used in this study [3]. These sensors have measurement ranges of 0-2000 ppm NO_X and 0-18% oxygen. Sensors were mounted in the exhaust stream before and after the catalyst. NO_X output was recorded using a datalogger at 10 Hz. The data was time shifted to account for gas travel delay between sensor

locations. The NO_X measurements were compared to determine transient reduction and average reduction during tests.

A correlation curve was developed by comparing prototype NO_X sensor and chemiluminescent NO_X analyzer outputs in an engine test cell. Sensor and analyzer outputs were recorded over a wide range of steady state points. The correlation curve was found to be linear and repeatable. The NO_X sensor correlation curve shown in Figure 11 was applied to all over-the-road data.

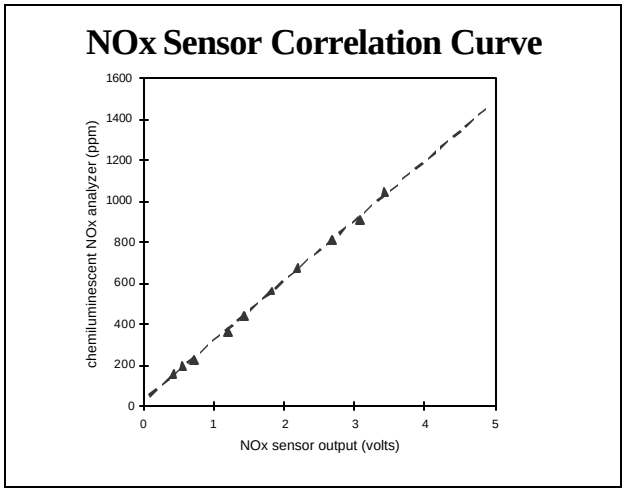

Figure 11

NO_X REDUCTION RESULTS – Three plots of over-the-road data are included below. In each case NO_X is shown before and after the catalyst during over-the-road operation with a loaded test trailer at 70,000 lb. GVW.

The response of the urea-SCR system to being turned OFF is shown in Figure 12. There is a period after switching the system OFF when the NO_X reduction decreases to zero as stored NH_3 within the catalyst is depleted. After about 45 seconds, the NO_X sensors agree and track each other. This test helps to develop confidence in the measurement technique and was repeated periodically to confirm sensor agreement.

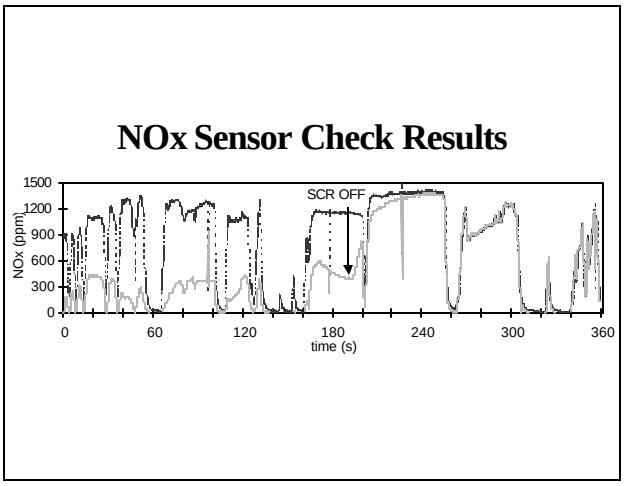

Figure 12

Figure 13 shows NO_X data from the 1999 and 2000 over-the-road truck evaluations recorded on the same section of mountain highway. The average NO_X reduction efficiency improved from 63% in 1999 to 71% in 2000. The 2000 results show improvement in engine-out NO_X achieved by injection timing retard as well as the improved NO_X reduction efficiency achieved using the 200 cpsi catalyst.

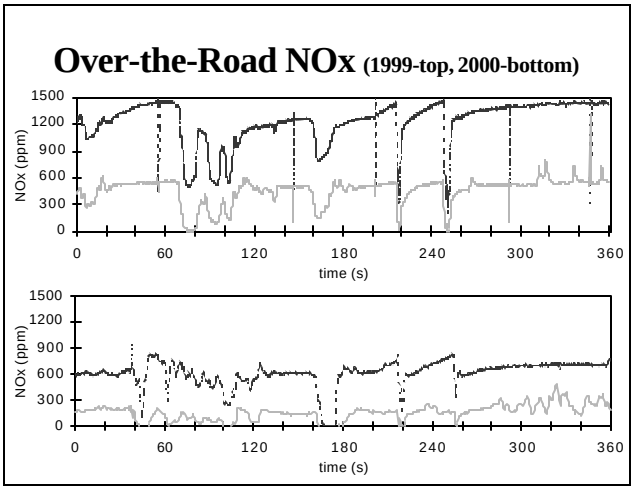

Figure 13

A summary of over-the-road NO_X reduction results for the 1999 and 2000 evaluations is shown in Figure 14. The 2000 test produced improvements of 9%, 8%, and 6% on level highway, mountain highway, and urban operation respectively. The 2000 results showed an overall reduction of 73% which was an 8% improvement versus 1999.

Over-the-Road NOx Reduction

	1999	2000	
level highway	-68%	-77%	(-9%)
mountain highway	-63%	-71%	(-8%)
urban	-72%	-78%	(-6%)
overall average	-65%	-73%	(-8%)

Figure 14

FLEET OPERATION AND UREA CONSUMPTION RESULTS - The demonstration truck was placed in Mack Trucks' fleet in July 2000. This truck carries engine parts primarily between Hagerstown, MD and Macungie, PA. With additional side trips to other facilities, the truck averages 365 miles per day. This truck will continue to operate in the fleet to gain experience with the urea-SCR system.

Urea solution is stored in 55 gallon barrels and distributed using a diaphragm pump as shown in Figure 15. This simple arrangement is adequate for a small-scale test. The pumping station will be moved into a heated garage to avoid freezing in winter months.

Urea Storage and Distribution

Figure 15

Urea consumption results from the 1999 and 2000 truck tests are shown in Figure 16. Fuel consumption from 1999 was measured using a loaded test trailer with 70,000 lb. GVW. The improvement to 6.2 mpg fuel consumption in 2000 is due to lower GVWs from hauling partial loads in actual fleet operation. The urea consumption improvement from 94 mpg (5.5%) to 161 mpg (3.9%) resulted from the new engine calibration and lower GVWs producing less NO_X on a mass basis. Since less urea is required, the operating range using a 15 gallon on-board tank increased from 1410 miles to 2415 miles. At the fuel mpg for 70,000 lb. GVW, the urea consumption and operating range were calculated at 135 mpg and 2025 miles.

Urea Consumption

	1999	2000
fuel mpg	5.2	6.2 (due to lower GVW)
urea mpg	94	161 (~135 @ higher GVW)
urea/fuel ratio	5.5%	3.9%
urea range (mi)	1410	2415 (~2025 @ higher GVW)

Figure 16

MACK SCR ENVIRONMENTAL PROJECT

As part of Mack Trucks' consent decree settlement with the EPA, an environmental project has been initiated to place ten trucks with urea-SCR in customer fleets in mid-2001. Five of these trucks will also have particulate filters to determine the interactions of these technologies. This program will include in-use testing to assess the vehicle emissions at 6 months, 1 year, and 2 years. Northeast States for Coordinated Air Use Management (NESCAUM) will be coordinating the project. Other companies involved include Donaldson, Engelhard, Hydro-Agri, NGK-Locke, and Siemens. Milestones are shown in Figure 17.

Project Milestones

- EPA approved - June 21, 2000
- fleet selections - Oct 2000
- urea station set-up - mid-2001
- truck delivery - Jul-Oct 2001
- in-use tests - 6 mo, 1 yr, and 2 yr

Figure 17

IMPLEMENTATION CONCERNS

Several issues not investigated as part of this study must be addressed prior to urea-SCR implementation into high-volume HD truck production. The most significant issue is the development of a urea distribution infrastructure for the HD truck industry. Urea freezing must also be addressed either by additive or system heating. Other issues include system durability, packaging, tamper resistance, and strategies for light-load applications with low exhaust temperatures. The upcoming 10-truck environmental project will provide opportunities to gain additional experience in these areas.

CONCLUSIONS

1. OVER-THE-ROAD NO_X REDUCTION
   Truck measurements using the 200 cpsi catalyst showed an average of 73% NO_X reduction. This is an 8% improvement versus previous tests using the 100 cpsi catalyst.

2. FIRST TRUCK PLACED IN FLEET
   The demonstration truck was placed in Mack Trucks' fleet for daily operation. The truck is achieving 161 mpg urea consumption. The 15-gallon on-board urea tank allows a 2415 mile operating range in this application.

3. 10-TRUCK ENVIRONMENTAL PROJECT
   As part of Mack Trucks' consent decree settlement with the EPA, 10 trucks with urea-SCR will be placed in customer fleets in mid-2001. Five trucks will also include particulate filters to assess interactions between technologies.

4. FUTURE OF UREA-SCR
   Although emissions results are encouraging, implementation concerns must be addressed before widespread usage is possible. If resolved, urea-SCR may emerge as a key part of 2007 HD emissions control systems.

ACKNOWLEDGMENTS

The author would like to thank Donaldson, NGK-Insulators, Siemens, Southwest Research Institute, and coworkers at Mack Trucks for providing support during this project.

REFERENCES

1. W. Miller, J. Klein, R. Mueller, W. Doelling, and J. Zuerbig, "The Development of Urea-SCR Technology for US Heavy Duty Trucks," SAE 2000-01-0190, March 2000
2. N. Fritz, R. Mueller, J. Zuerbig, and W. Mathes, "On-Road Demonstration of NO_X Emission Control for Diesel Trucks with SINOx Urea SCR System," SAE 1999-01-0111, March 1999
3. N. Kato, N. Kokune, B. Lemire, and T. Walde, "Long-Term Stable NO_X Sensor with Integrated In-Connector Control Electronics," SAE 1999-01-0202, March 1999