COMPARISON OF PLASMA-CATALYST AND ACTIVE LEAN NO_x CATALYST

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A number of NO_x control systems are being discussed for potential application to diesel engines. Unfortunately, it can be difficult to compare systems on an equal basis because data are run under different conditions, or reported against different test cycles, or not shown over a range of operating conditions. In addition, the fuel consumption penalty associated with the NO_x control technologies is not always reported.

In this paper, we compare two diesel NO_x aftertreatment systems:

- Plasma-Catalyst (PC): a nonthermal plasma followed by a catalyst
- Active Lean NO_x Catalyst (ALNC): a NO_x catalyst designed to selectively reduce NO_x using hydrocarbon (HC) in the form of diesel fuel. Fuel is added to the exhaust to increase HC above normal diesel levels.

These systems will be described in more detail below.

The systems are compared using a simple model developed in the Ford Research Laboratory. This is a quasi-steady state model calculating system performance at one-second intervals. Input data are:

- Vehicle measured emissions
- Vehicle exhaust flow
- Exhaust temperature
- Catalyst performance data from laboratory testing

No dynamics are modeled. The model calculates the following parameters for each second of the driving cycle:

- NO_x after the catalyst (g/s)
- HC added to the exhaust to maintain a desired HC: NO_x ratio (grams)
- For the PC system, electrical energy (J)

These values are summed over the cycle to estimate NO_x conversion efficiency and the fuel consumption penalty due to HC addition and electrical power.

The test cycle is the US FTP cycle. Typical vehicle speed, exhaust flow, and temperature data are shown in Figure 1. The test vehicle is a 1997 model year 2.5L DI/TCI Ford Transit Van, calibrated to Euro-II standards. This vehicle does not use EGR.

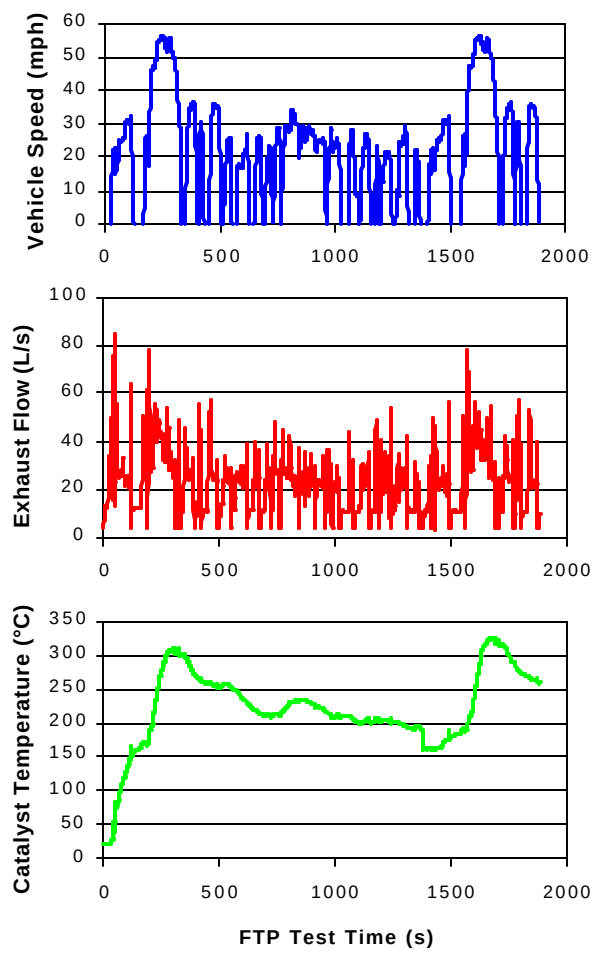

Figure 1 Vehicle speed, exhaust flow, and catalyst temperature on the FTP cycle.

PLASMA CATALYST (PC) SYSTEM

The plasma catalyst system has been previously described (1-3). The plasma is created in a tube array discharge reactor. This device has a set of parallel tubular alumina tubes. The inside of each tube is coated with conductive material, and alternate tubes have opposing voltage polarity in the AC discharge. Thus, plasma is formed in the gap between tubes. Gas flow is perpendicular to the tube axes. A catalyst is located in the flow downstream of the plasma. The catalyst is in beaded form and is a proprietary zeolitic, non-precious-metal catalyst. This catalyst has been identified as "catalyst B" in prior publications.

Laboratory data for the system was taken over a range of operating variables. Simple curves were fit to the data, assuming no interactions exist between variables.

Figure 2 shows the effect of catalyst temperature on NO_x efficiency for the PC system. Peak conversion is obtained around 200°C. The curve is the equation fit.

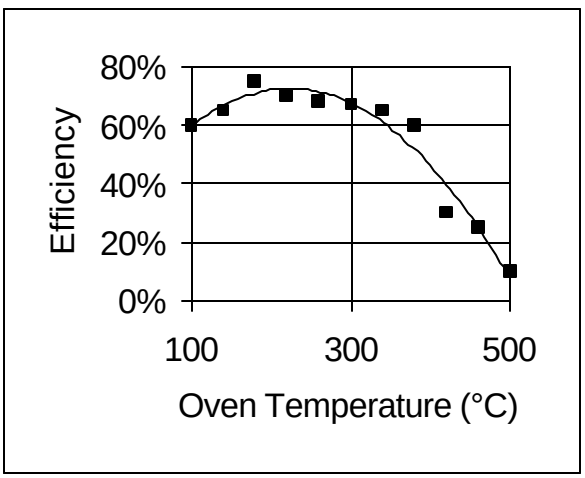

Figure 2 PC NO_x efficiency versus temperature. 10K hr^{-1} SV, 8:1 HC: NO_x ratio, 23 J/L.

Figure 3 shows NO_x efficiency normalized to the nominal condition (200°C, 10K hr^{-1} SV, 23 J/L and 2000 $ppmC_1$ HC = 8:1 HC:NOx ratio) versus space velocity. Space velocity is defined as the inverse of residence time within the catalyst volume. Thus, high gas flow causes high space velocity. Highest efficiency is obtained at rather low space velocity.

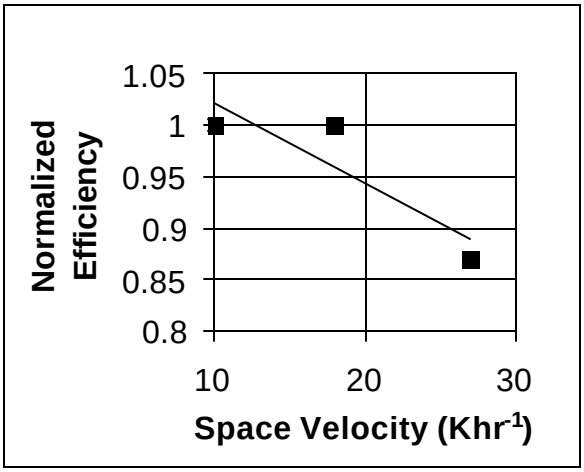

Figure 3 PC NOx efficiency versus space velocity. 200°C, 23 J/L, 8:1 HC: NO_x

Figure 4 shows the effect of plasma energy deposition. The power is measured power deposited in the gas and so does not include inefficiencies in the power supply; they will be discussed below. Highest efficiency is obtained around 20 J/L and above. The vertical scatter in the plotted data points is reflects the various temperatures tested. This shows that there is, in fact, an interaction between temperature and energy deposition; however, the model uses a simple curve fit because there is not adequate data available for a more sophisticated model.

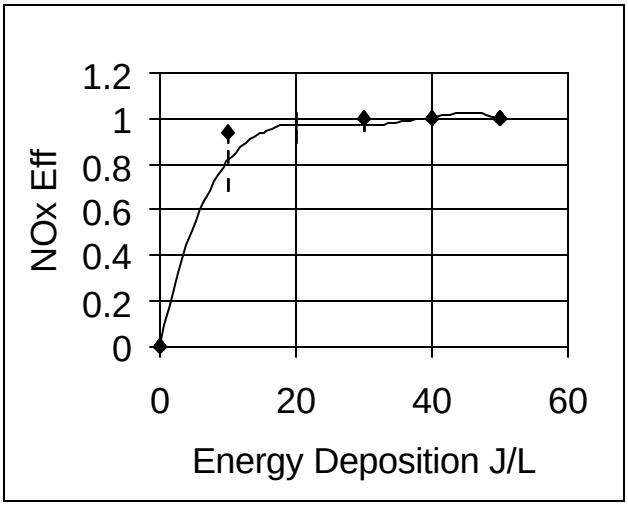

Figure 4 PC NO_x efficiency versus energy deposition. 10K hr^{-1} SV, 8:1 HC: NO_x ratio, 100-250°C.

NO_x conversion requires the presence of hydrocarbons. The effect of the HC: NO_x ratio, where HC is expressed as $ppmC_1$, is shown in Figure 5. Best conversion occurs when there is

a ratio above 6:1. Since this value is higher than typical diesel exhaust, HC must be added. This results in a fuel economy penalty discussed below.

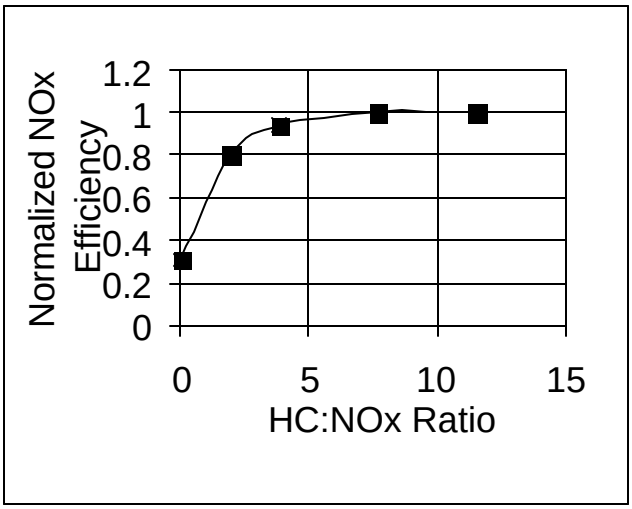

Figure 5 PC NO_x efficiency versus HC: NO_x ratio. 10K hr^{-1} SV, 200°C, 23 J/L.

The fuel economy impact of the PC system is a combination of HC addition and electrical power consumption. Since the energy deposition described above is measured deposition in the exhaust gas, we must account for the high voltage power supply, vehicle alternator, and engine losses. We have assumed the following cycle averaged efficiencies and applied them for all times during the cycle:

- 35% engine brake thermal efficiency. That is, 35% of the thermodynamic lower heating value of the fuel is available as shaft work.
- 85% efficient conversion of shaft work to vehicle electrical power (14 or 42 volts). This is higher than current alternators but not out of the range of possible devices.
- 80% efficient conversion of vehicle electrical voltage to plasma high voltage. This efficiency rules out several (inexpensive) types of high voltage power supply, but should be feasible with careful design.
- Fuel energy is the thermodynamic lower heating value, 35.6 MJ/L.

Given these assumptions, we can calculate the fuel energy required per unit of plasma energy delivered to the exhaust:

$$E_{fuel} = \frac{E_{plasma}}{\eta_{engine} \times \eta_{alternator} \times \eta_{transformer}} = 4.2 \times E_{plasma}$$

Due to inefficiencies in engine and electrical system, 4.2 times as much fuel energy is required as will be placed in the exhaust. It would, of course, be easy to design electrical components with lower efficiency and thus degrade this performance!

Given all of these assumptions, we can now estimate the cycle NO_x efficiency and associated fuel economy penalty. In this, we hold constant the specific energy deposition (Joules of energy per liter of exhaust gas). This implies that the power supply must vary the power as the exhaust flow varies. Figure 6 shows the calculated results. For this curve, HC: NO_x ratio is 5.5:1 and catalyst volume is 5 L, equal to twice engine displacement (non-constant space velocity). Plasma specific energy deposition varies from zero (lower left) to 30 J/L (upper right). 60.2% conversion requires 5.6% fuel economy penalty and occurs with 15 J/L.

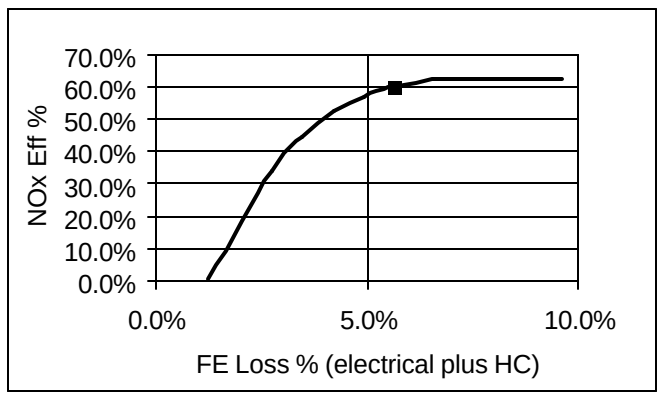

Figure 6 Model projected NO_x efficiency versus fuel economy penalty for PC system, varying energy.

Figure 7 shows a similar plot varying the HC: NO_x ratio. Only 20% NOx conversion is obtained with the native HC level, rising to 59% conversion at 5.5% FE penalty.

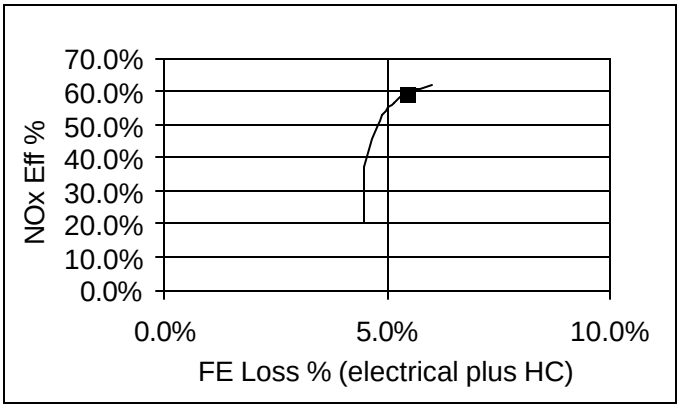

Figure 7 Model projected NO_x efficiency versus fuel economy penalty for the PC system, varying HC: NO_x ratio. 15 J/L, 5L catalyst volume.

Figure 8 is a similar plot varying catalyst volume. A larger catalyst helps conversion, but about twice engine displacement (2 X 2.5L = 5 L) gets nearly the maximum conversion available.

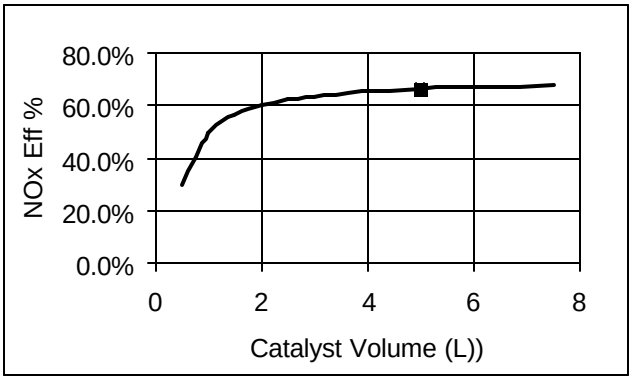

Figure 8 Model projected NO_x efficiency versus fuel economy loss varying catalyst volume. 15 J/L, 5.5:1 HC: NO_x ratio.

ACTIVE LEAN NO_x CATALYST (ALNC) SYSTEM

Data for the ALNC was taken using a proprietary platinum-alumina zeolitic monolith catalyst. The catalyst was tested on engine exhaust in a dynamometer test cell. The engine was a Ford DIATA 1.2L TDI engine. Post-combustion injection was used to adjust the HC: NO_x ratio.

Data versus temperature was obtained by ramping the catalyst temperature in the upward direction. This means that the catalyst can store HC at lower temperature which assist NO_x conversion as the temperature rises.

Figure 9 shows NO_x efficiency versus temperature. This shows a peaked characteristic over a fairly narrow temperature range.

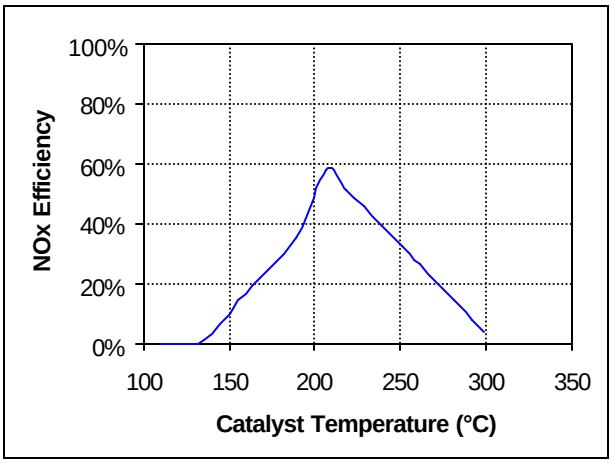

Figure 9 ALNC NO_x efficiency versus temperature. 24K hr^{-1} SV, 10:1 HC: NO_x ratio.

Figure 10 shows a three-dimensional plot of NO_x efficiency versus temperature and space velocity. Lower space velocity improves conversion; the temperature of peak NO_x activity is relatively constant.

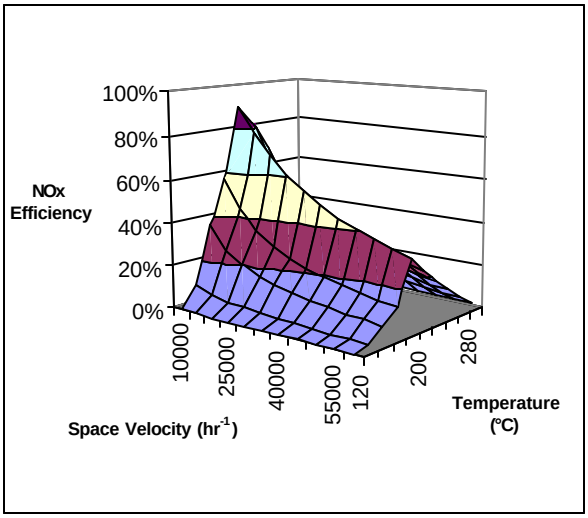

Figure 10 ALNC NO_x efficiency versus temperature and space velocity at 10:1 HC: NO_x ratio.

Figure 11 shows the effect of HC: NO_x ratio on ALNC efficiency. Efficiency continues to improve as the HC:NOx ratio is increased.

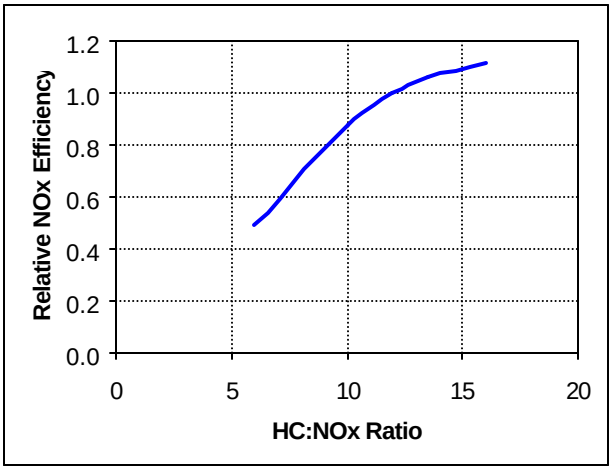

Figure 11 Effect of HC: NO_x ratio on ALNC NOx efficiency. 24K hr^{-1} SV, normalized to 12:1 HC:NOx ratio.

Figure 12 shows the effect of catalyst volume on NO_x efficiency. In this range, larger catalysts improve efficiency.

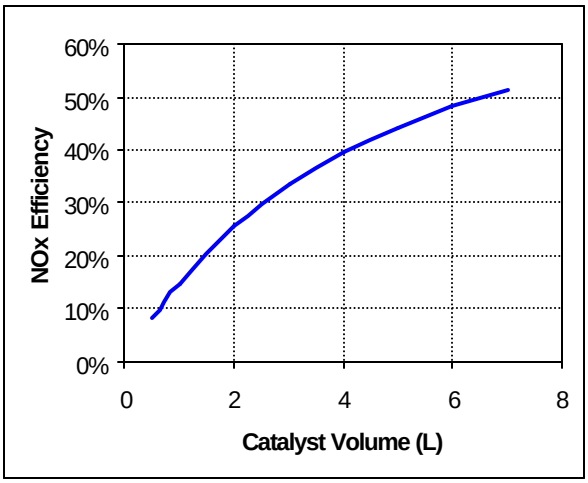

Figure 12 ALNC NO_x efficiency versus catalyst volume. HC:NOx = 10.

With this data and the vehicle input, we can predict NO_x efficiency and fuel economy penalty over the driving cycle, Figure 13. In this figure, HC: NO_x ratio is varied from 6 (lower left) to 16:1 (upper right).

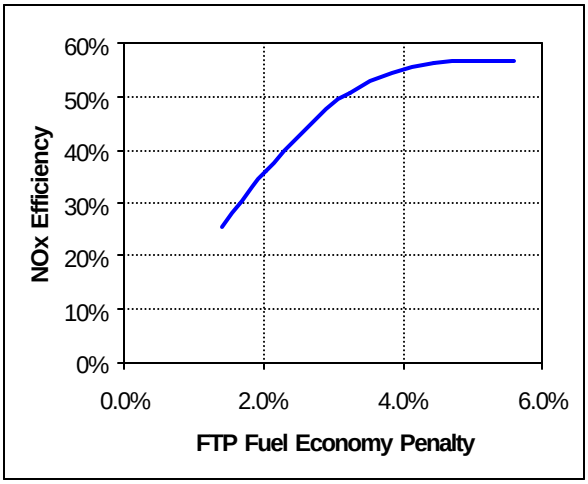

Figure 13 Model projection of ALNC NO_x efficiency versus fuel economy penalty. catalyst volume 5 L.

COMPARISON

We can now compare the PC and ALNC systems using these models. Figure 14 shows model projected FTP cycle NO_x efficiency versus fuel economy cost for each system. In the figure, ALNC has varying HC addition while PC has varying energy deposition.

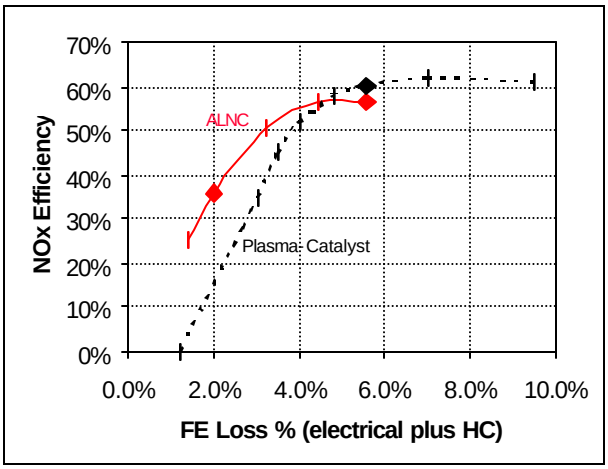

Figure 14 Model projected FTP cycle NO_x efficiency versus fuel economy cost for PC (dashed line) and ALNC (solid line).

At lower NO_x conversions, ALNC has lower fuel economy cost. However, as the NO_x efficiency target increases the PC system achieves higher maximum conversion.

Table 1 Range of values for several variables, for the PC system at 15 J/L, 5 L catalyst volume.

Item	Units	Minimum	Maximum	Average
Exhaust Flow	L/sec	4.2	84.0	22.0
Space Velocity	Khr^{-1}	3.1	61.0	16.0
Power	W	64	1264	334
Engine Out HC:NOx	Ratio	0	22	2.8

Table 1 shows the range and average of several parameters over the FTP driving cycle. Exhaust flow varies roughly 40:1 from minimum to maximum. Space velocity is calculated based on 5 liter catalyst volume (twice engine displacement). Power is the electrical power deposited in the gas for the plasma system at 15 J/L. Finally, the engine-out HC: NO_x ratio range is shown.

The advantages of the ALNC system are:

- More mature technology
- Lower cost and better fuel economy with NO_x efficiency of 40-50% is adequate.

The advantages of the PC system are:

- Better NO_x efficiency if the fuel economy loss is acceptable
- High NO_x efficiency over a wider range of temperature; potentially important on other driving cycles
- Being a less developed system, there may be more room for improvement in future developments.

CONCLUSIONS

A simple model is used to compare active lean NO_x catalyst (ALNC) and plasma-catalyst (PC) systems for FTP cycle NO_x efficiency and fuel economy cost. Both systems have a significant fuel economy cost to achieve high NO_x reduction, and both systems required added fuel HC as a reductant. The PC system achieves higher NO_x efficiency and has good efficiency over a wider temperature range, but has a large fuel economy cost except at the highest NO_x conversions.

REFERENCES

1. J. Hoard and M.L. Balmer, “Analysis of Plasma-Catalysis for Diesel NO_x remediation”, SAE paper 982429.
2. M.L. Balmer et.al., “Diesel NO_x Reduction on Surfaces in Plasma”, SAE paper 982511.
3. R. Tonkyn et.al., “Lean NO_x Reduction in Two Stages : Non-thermal Plasma Followed by Heterogeneous Catalysis”, SAE paper 2000-01-2896.

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