Clean Diesel Technologies

Selective Catalytic Reduction and Exhaust Gas Recirculation Systems Optimization

Abstract

- The first generation of on-board vehicle urea-selective catalytic reduction systems generally employed compressed air to achieve efficient injection and the atomization of urea into the exhaust stream and for uniform ammonia delivery fro reduction of nitrogen oxides across the SCR catalyst. The field experience with these SCR systems has shaped the requirements for the next generation of systems. These requirements include substantially reduced system cost and complexity, enhanced durability and accuracy of urea delivery, to control injection across the full duty cycle and operating temperatures, and to maintain system cleanliness, avoiding potential for injector and system deposits.

- This experience has resulted in the demand for a new generation of airless injection systems, such as the airless ARIS® technology, which incorporates single fluid return flow liquid cooled injection for reliability, simplicity and low cost. The ARIS airless injection system and control technologies have imbedded a series of performance refinements. The ARIS approach provides robust and flexible designs for SCR systems in OEM or retrofit applications.

- In order to enable manufacturers and Tier One suppliers to optimize NOx and PM control while minimizing fuel consumption, the strategy for the combination of EGR with SCR was invented. This patented EGR - SCR approach from Clean Diesel Technologies was shown to readily meet the 2010 requirements for NOx and PM emissions, through independent test programs. This strategy enables the engine manufacturer to optimize in-cylinder combustion conditions with EGR, and to integrate with SCR at reduced EGR rate to achieve low NO_x emissions with fuel efficiency over the entire engine operating range. This combination can be optimal using an efficient SCR injection and control strategy such as ARIS. The operating principles and examples of applications experience with these systems will be provided.

Urea / Ammonia injection: Enabling SCR technology

- Initial SCR systems designed for EURO IV Heavy duty employed air assisted Urea injection systems to ensure adequate injector cooling and urea dispersion in the exhaust
- Next Generation Airless Urea Injection systems have become available, offering simplified and more cost effective solutions for Urea injection
- Urea (Diesel Emissions Fluid - DEF or AdBlue aqueous solution) has become the preferred reagent for SCR applications in Europe and the U.S.

SCR technology optimization

Electrical/Electronic

- Power to operate system including pump and injector. Information from the CAN bus communication providing information on engine load and rpm. Additional system inputs include: ambient humidity, exhaust temperature and back-pressure as well as urea tank level.

Hydraulic

- Adequate urea supply pressure is required for proper atomization of urea. Plus the system must provide adequate flow volume for cooling purposes due to the harsh environment the injector is subjected to.

Mechanical

- The injector must be controlled by the ECU to inject the precise amount of urea required for any exhaust flow condition. The injector must be sized and controlled to be able to deliver the maximum amount of urea required.

SCR technology optimization

Chemical

- Urea needs to be supplied to match the exhaust rate of flow and the NOx concentration so the formation of ammonia occurs in correct proportion to maximize effectiveness and minimize slippage.

Fluid Dynamics

- The mixing of the injected urea in the exhaust stream must be complete and atomized adequate to thoroughly interact with exhaust chemistry. The exhaust stream prior to the SCR catalyst inlet must be engineered to provide for adequate residence time for decomposition of the urea mixing of the exhaust. All of this has be completed in a extremely short interval of time.

Catalytic Activity

- SCR Catalyst must be sized correctly to allow for adequate residence time for catalytic activity to occur and not adversely affect engine back-pressure. The correct catalyst type is required to match the exhaust temperature requirements of the engine.

Airless technology vs. compressed air

Most Heavy Duty vehicles have compressed air for braking purposes. Most Light Duty vehicles especially passenger vehicles do not have compressed air Airless solutions are advantageous to both markets

- Air compressor adds cost
- Maintenance and reliability of an air compressor is an undesirable feature
- Power required to operate an air compressor reduces fuel efficiency
- Compressed air lines can be troublesome with vibration breakage and moisture accumulation resulting in potential freeze problems.
- Fouling of intake filters adds to required maintenance
- Weight of a compressor adds load to an engine
- Locating a compressor and lines on a vehicle can be challenging and costly

Advanced Reagent Injection System (ARIS)

Airless Urea Injection

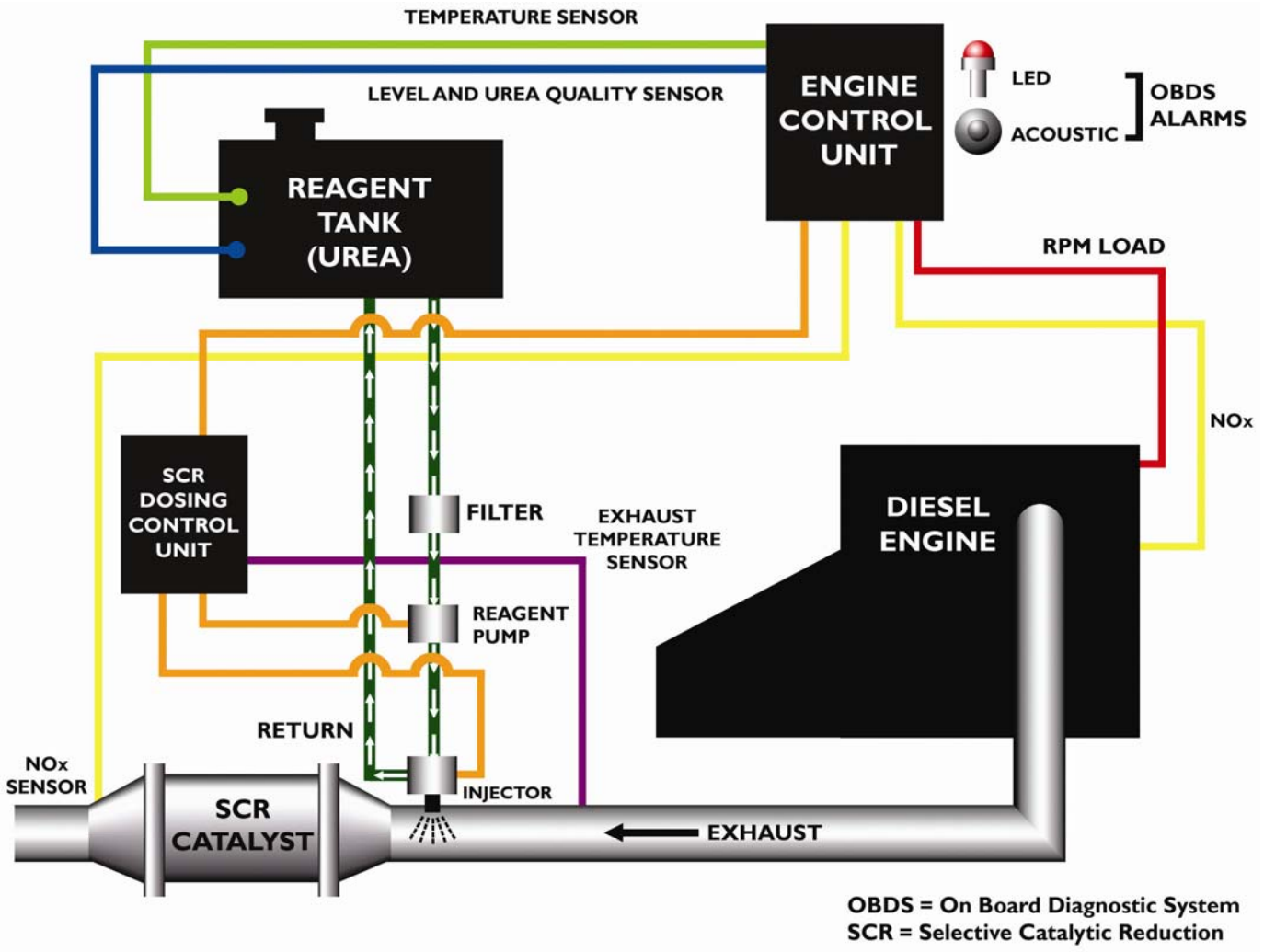
Overview:

- Clean Diesel Technologies' Advanced Reagent Injection System (ARIS) removes the requirement for air by using a return flow of urea to cool the injector head. This enables a simple (both in concept and installation) and effective solution which lends itself exceptionally well to both OE and retrofit applications
- Available under license
- Licensed to major tier one suppliers and retrofit manufacturers worldwide.

Key ARIS features

- Enabling SCR technology for NOx reduction
- Single fluid injector (integral cooling)
- Eliminates need for compressed air
- Opens up light duty and passenger car market
- Protected by world wide patents
- Low heat transfer
- Fine Atomization Control
- Precise injection control via solenoid actuation

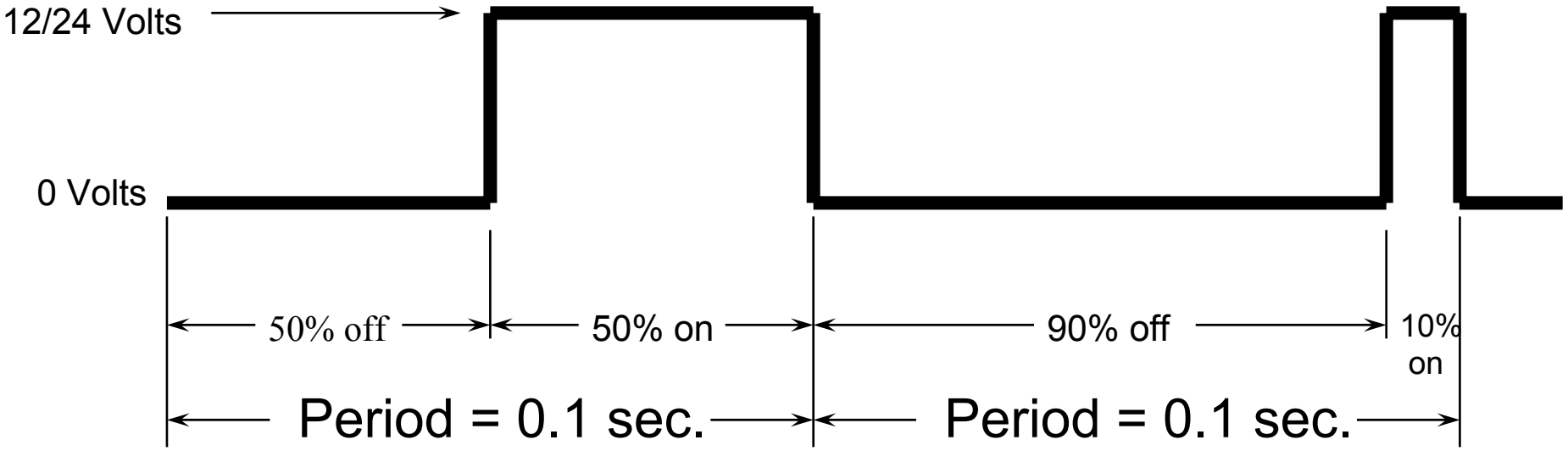
Advanced reagent injection system (ARIS)



Key advantages of ARIS technology

Urea reagent 'bulky'	✓ Potential for reduced urea usage
Urea freezing	✓ No adverse influence
Urea crystallization	✓ No adverse influence
Nozzle fouling	✓ Minimized due to return flow cooling
Component heavy	✓ Simplified design
Compressor cost	✓ Not required
Tampering & compliance	✓ Potential for sensor positioning at point of injection

Injector control pulse width modulation (PWM)



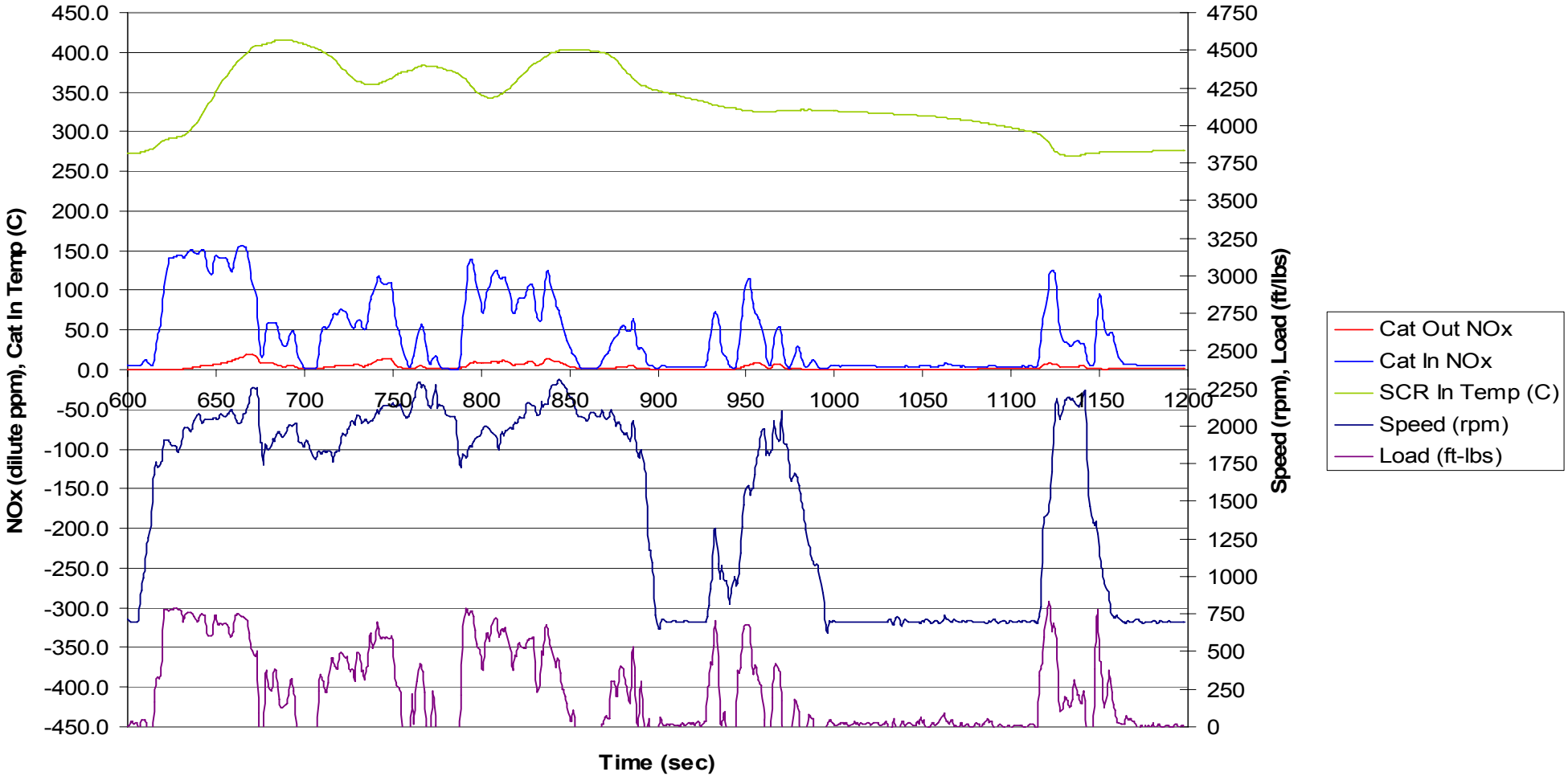
10 Hz typical injection frequency

Pulse width injector on time illustrated at 50% and 10%. The industry standard is to specify between 20% and 80% on-time to maintain accuracy & reliability

Urea SCR ARIS laboratory performance

- Caterpillar 3126
- HDD transient and steady state modes
- Steady state NOx:
  - 5.1 g/bhp-hr in
  - 0.4 g/bhp-hr out
  - 92% NOx conversion

CDT ARIS Gen 1 SCR Technology
Ability to Follow Load and Speed Changes
(Caterpillar 3126 Engine)



Diesel SCR: Example applications

On-Road

Heavy Duty

Off Road

Heavy Duty

ARIS: Light duty diesel SCR retrofit case study

Vehicle

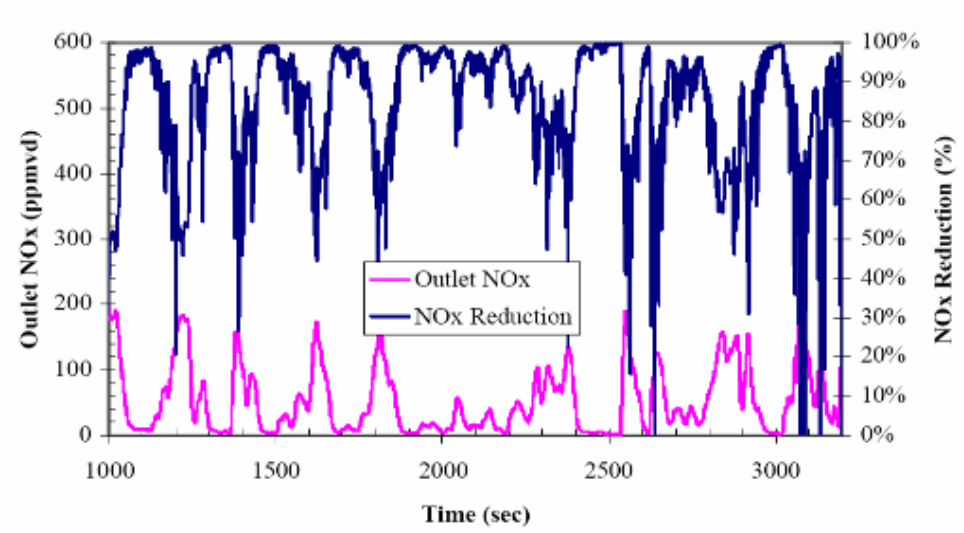
- LDV (GMC W3500)
- Isuzu turbo intercooled diesel engine rated at 175 hp at 2700 RPM.

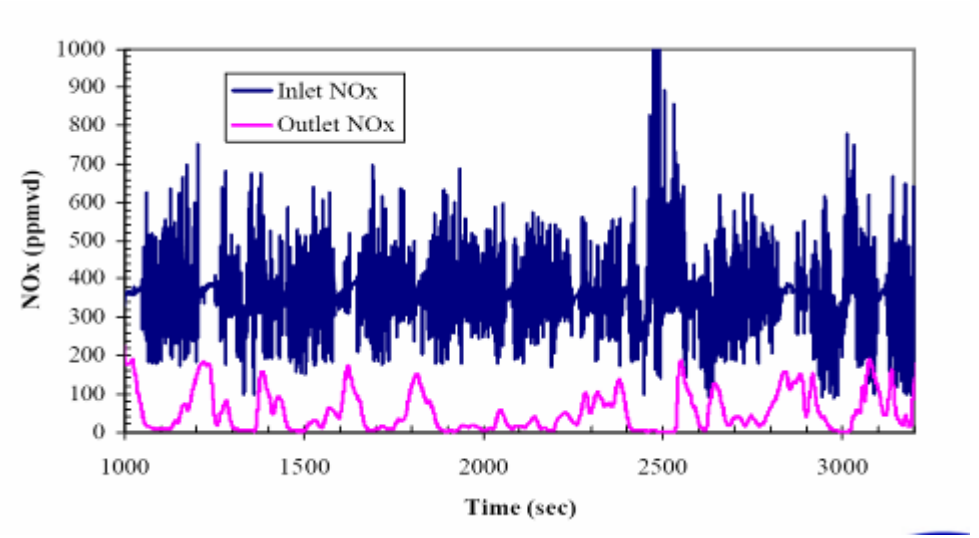
Test

- Mainly Highway
- Some stop and go
- Inlet & outlet NOx measured

Results

- > 80% NOx Reduction





ARIS SCR for alternative fuel vehicles: LPG

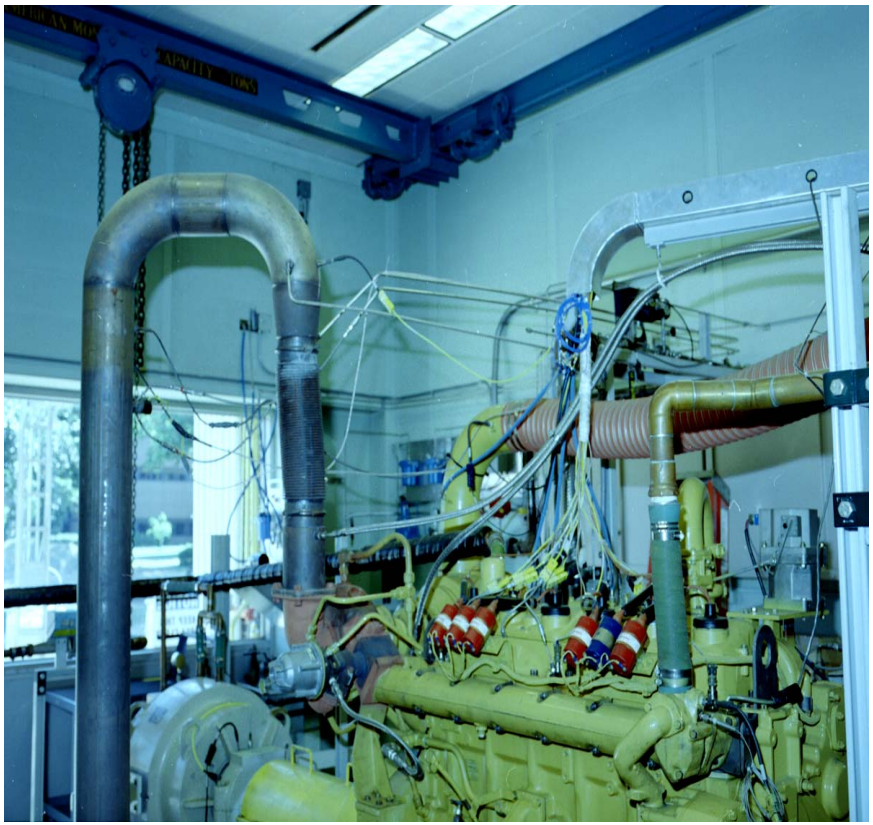
Los Angeles Dept. Public Works
Propane Powered Transit bus

SCR Installation

Urea Reservoir

ARIS-based retrofit SCR system: LPG Buses

Urea SCR field performance: Natural gas engine



- Caterpillar G3406
- 389 bhp natural gas engine
- 3700 ppm NOx
- Guaranteed 90% NOx reduction
- Achieved >95% NOx reduction

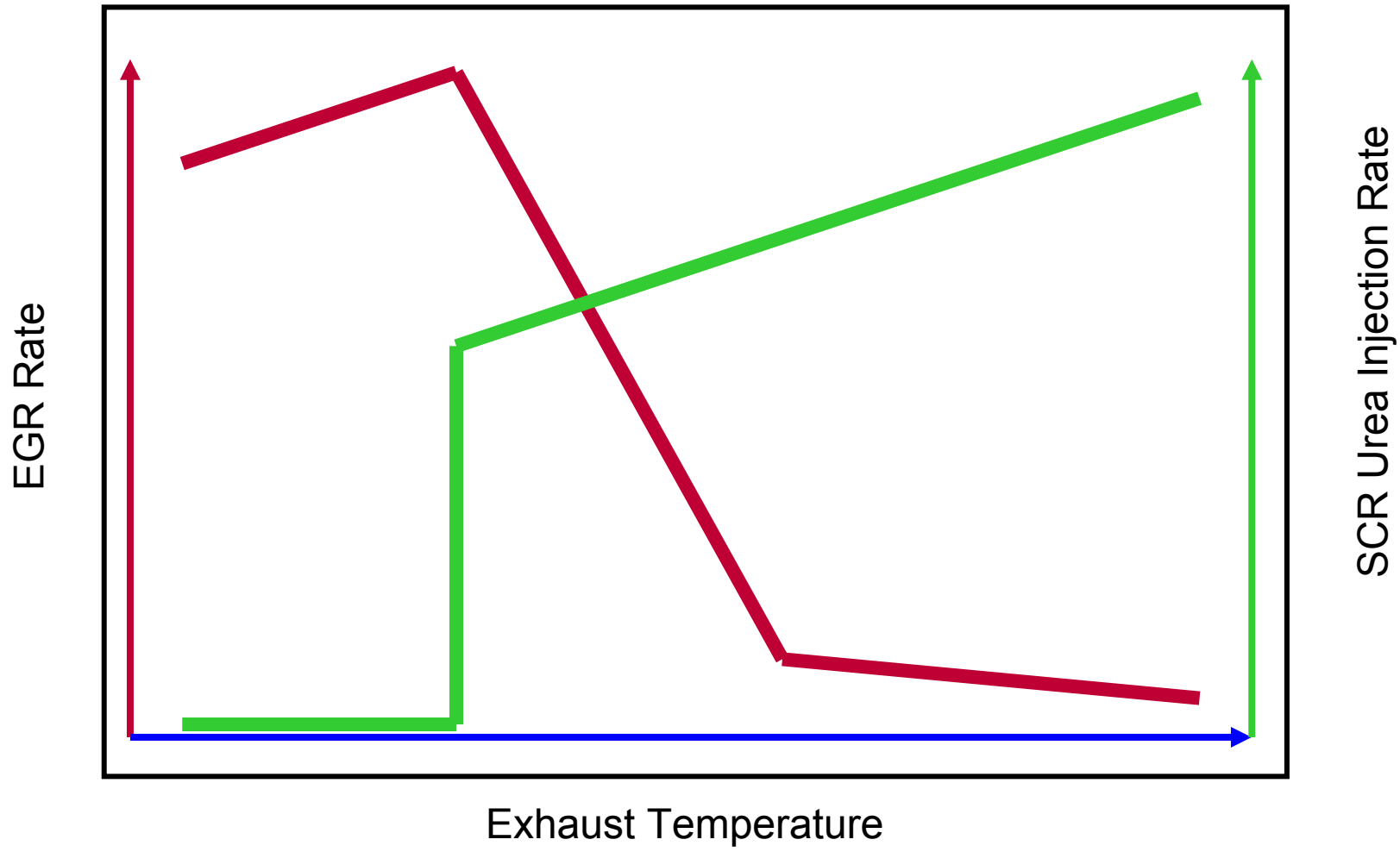
EGR-SCR concept

- Patent combines SCR control with EGR for NOx reduction
- Based on Clean Diesel research / test program at independent lab
- Systems approach enables optimization of diesel vehicle fuel economy and emissions performance:
  - ✓ *control fuel combustion for highest efficiency*
  - ✓ *Apply EGR at low temperature cycles, then reduce EGR rate*
  - ✓ *remove residual NOx via SCR at temperature*
  - ✓ *reduce urea consumption associated with SCR*

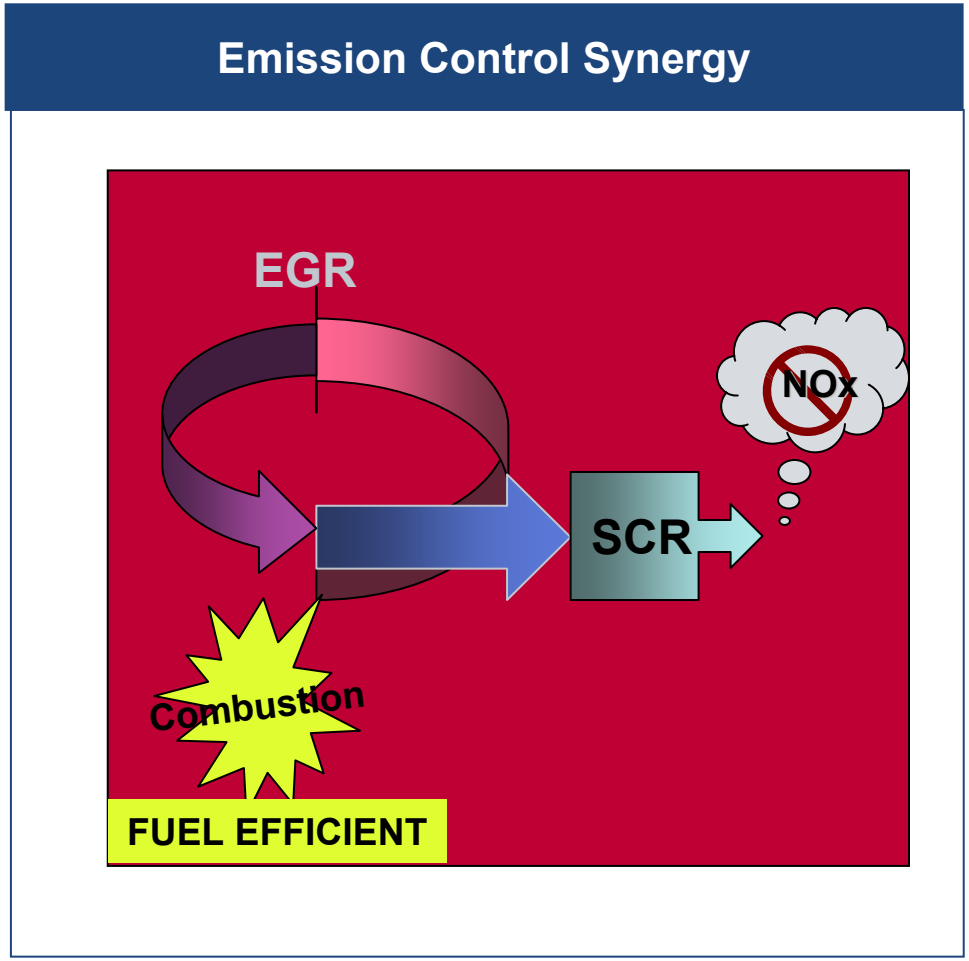
EGR-SCR optimization

- With both EGR and SCR in place, engines can be fine-tuned to deliver improved fuel efficiency and greater emissions reduction.
- At low temperature operation, EGR rate is maximized to effectively reduce NOx.
  - ✓ Higher EGR rates generally result in losses of fuel efficiency
- Achieving threshold temperatures are required for urea injection to permit liberation of ammonia and to activate the SCR catalyst.
- The SCR operates at a higher temperature when the catalyst is fully active and EGR is operated at low recirculation rate to optimize fuel efficiency.

EGR-SCR optimization



SCR + EGR summary



- ✓ Fundamental Innovations for Fuel Economy and NOx Emission Control
- ✓ Clean Diesel provides key patents on EGR and SCR combined
- ✓ EGR + SCR is the approach of choice for NOx control meeting US EPA 2010 and Euro 6 limits, with optimized fuel efficiency
- ✓ Synergy with SCR for NOx removal
- ✓ Achieve proposed CO_2 targets
- ✓ Licenses available from Clean Diesel directly or pass-through from authorized licensees