Emissions Control for Lean Gasoline Engines

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Project Overview

Timeline

- Project began in FY12
- Project Ongoing

Barriers Addressed

- Barriers listed in VT Program Multi-Year Program Plan 2011-2015:
  - 2.3.1B: *Lack of cost-effective emission control*
  - 2.3.1C: *Lack of modeling capability for combustion and emission control*
  - 2.3.1.D: *Durability*

Budget

- FY14: $400k
- FY13: $500k
- FY12: $400k

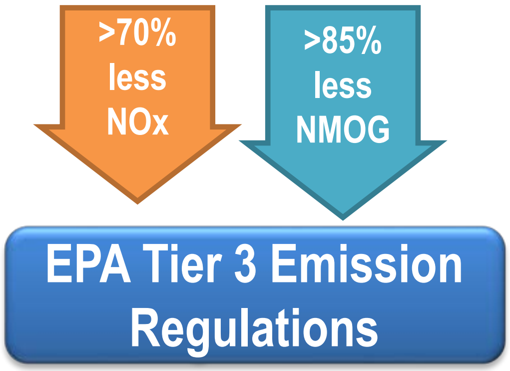
Collaborators & Partners

- Umicore
- General Motors
- University of South Carolina
- University of Wisconsin
- Cross-Cut Lean Exhaust Emissions Reduction Simulations (CLEERS)
- PNNL (platform for PM studies)

Objectives and Relevance

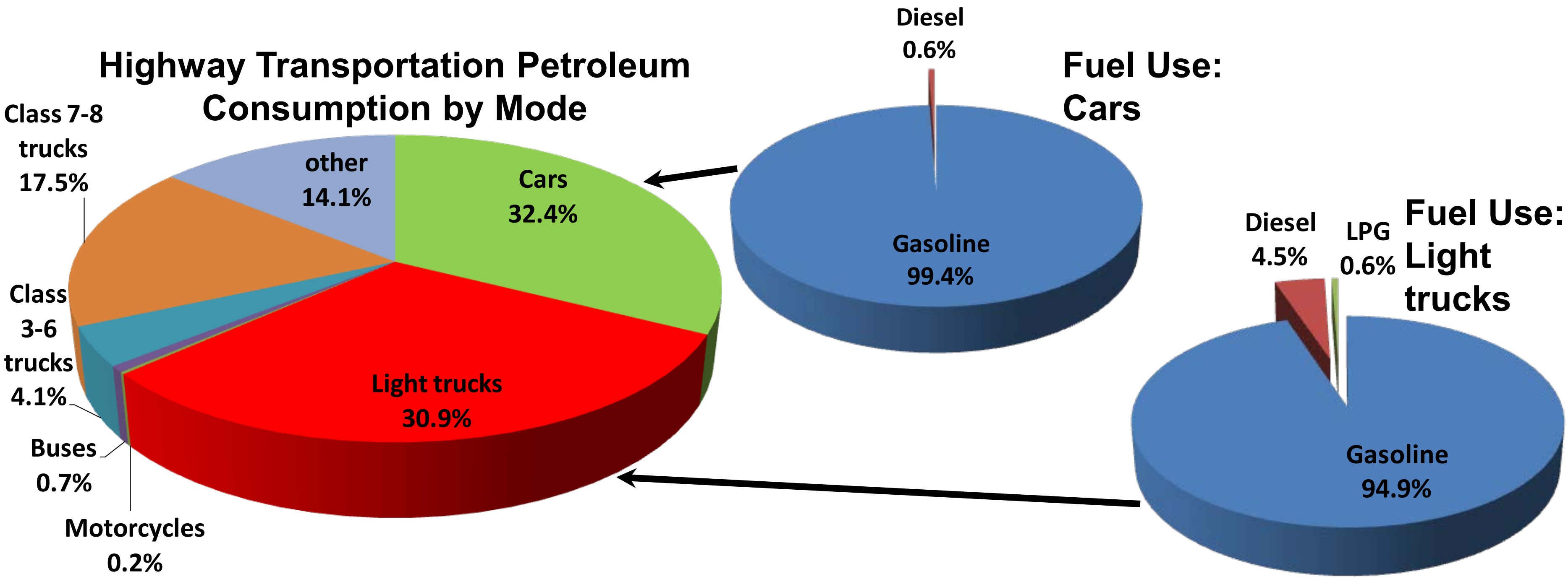
Enabling lean-gasoline vehicles to meet emissions regulations will achieve significant reduction in petroleum use

- Objective:
  - Demonstrate technical path to emission compliance that would allow the implementation of lean gasoline vehicles in the U.S. market.
    - Lean vehicles offer 5–15% increased efficiency over stoichiometric-operated gasoline vehicles.
    - Compliance: U.S. EPA Tier 3 standard (original goal Tier 2 Bin 2)
  - Investigate strategies to achieve cost-effective compliance
    - minimize precious metal content while maximizing fuel economy



- Relevance:
  - U.S. passenger car fleet is dominated by gasoline-fueled vehicles.
  - Enabling introduction of more efficient lean gasoline engines can provide significant reductions in overall petroleum use
    - thereby lowering dependence on foreign oil and reducing greenhouse gases

Relevance: small improvements in gasoline fuel economy <u>significantly</u> decreases fuel consumption



- US car and light-truck fleet dominated by gasoline engines
- 10% fuel economy benefit from base case of 23.0/17.1 mpg has significant impact
  - Saves 12.8 billion gallons gasoline annually
  - Or, save $47 billion/year (at $3.68/gallon 2012 US price)
- HOWEVER…emissions compliance needed!!!

Lean gasoline vehicles can decrease US gasoline consumption by <u>~12 billion gal/year</u>

References: Transportation Energy Data Book, Ed. 31 (2010 petroleum/fuel use data); www.eia.gov (2012 US gasoline price)

Milestones and Project Goals

- Complete — **FY2013:** Commission lean gasoline direct injection engine platform (Sept. 30, 2013).
- Complete — **FY2013:** Characterize the fuel efficiency and emission performance of a TWC+SCR system on the engine dynamometer platform as a function of the ratio of lean to rich periods (Sept. 30, 2013).
- Complete — **FY2014, Q1:** Measure transient NH_3 formed from TWC in an TWC+SCR approach on engine — Further studies ongoing
- Complete — **FY2014, Q2:** Characterize performance of Umicore prototype TWC catalysts for NH_3 production — Further studies ongoing
- On Track — **FY2014, Q3:** Present results at CLEERS Workshop
- On Track — **FY2014, Q4:** Define the potential impact of NOx storage components added to TWC formulations on NH_3 production for downstream NOx reduction over SCR catalysts

In addition to milestones, a set of project goals has been adopted to ensure progression towards goal of low-cost emissions control solution for fuel efficient lean-burn gasoline vehicles

	FY13	*FY14*	*FY15*	*FY16*	*FY17*
Fuel economy gain over stoichiometric	7%	10%	10%	12%	15%
Total emissions control devices Pt* (g/L_{engine})	8	7	6	5	4

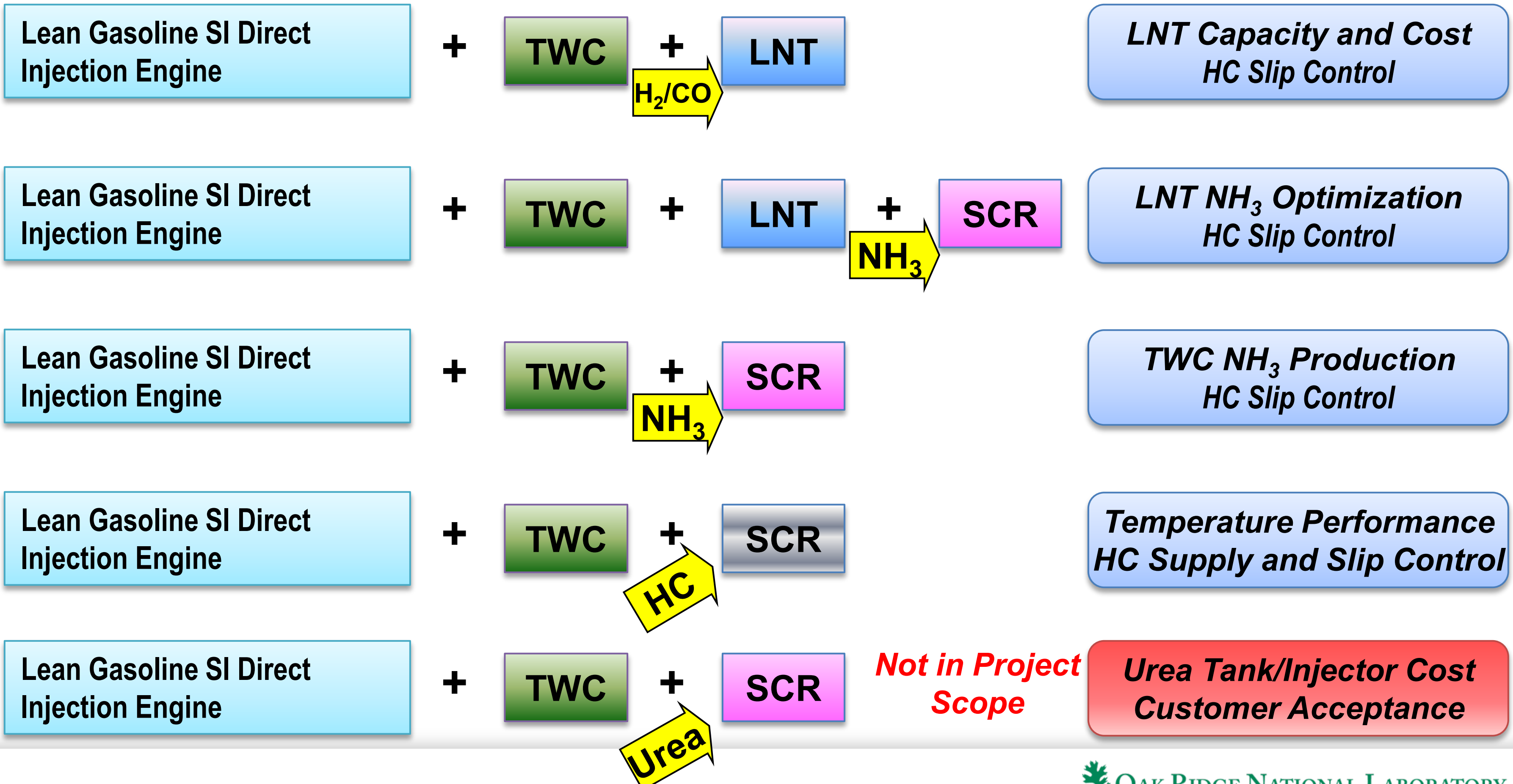
	5-year Average ($/troy oz.)	Pt-equivalent
Platinum	$ 1,504 /troy oz.	1.0
Palladium	$ 463 /troy oz.	0.3
Rhodium	$ 3,582 /troy oz.	2.4
Gold	$ 989 /troy oz.	0.7

* - will use Pt equivalent to account for different costs of Pt, Pd and Rh; 5-year average value fixed at beginning of project

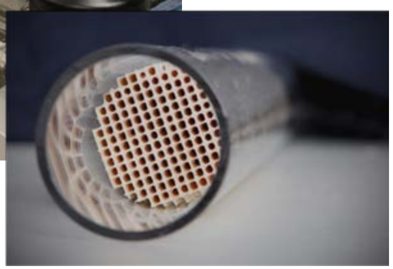
Approach: Emission Control Options and Critical Issues Related to Cost and Performance

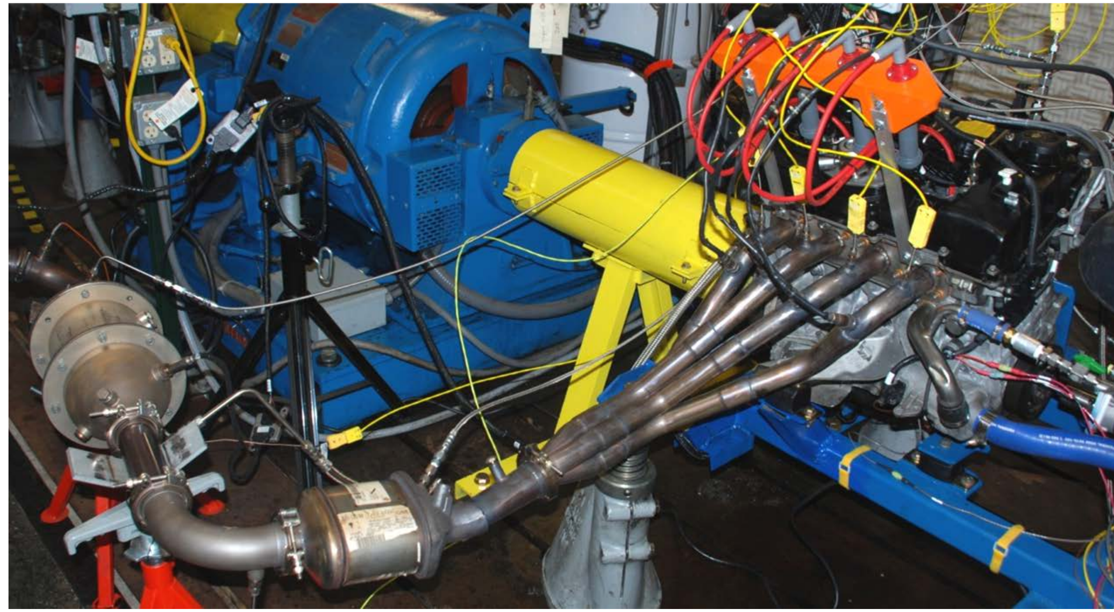
- **Goal: Enable Tier 3 (Tier 2 Bin 2) Emission Compliance for Lean Gasoline Engine Vehicle**
- Focus on NOx, CO, HC (PM may be issue for DI engines, but outside of project scope; new project starting)
- Technologies: **TWC** = Three-Way Catalyst
  LNT = Lean NOx Trap
  SCR = Selective Catalytic Reduction

Specific Key Issues:
Cost, Durability, Fuel Penalty, Operating Temp.,+…



Approach: Studies on Bench Reactor and Engine





- **Studies on BMW 120i lean gasoline engine platform with Drivven open controller**
  - Realistic exhaust conditions
  - Full control of rich AFR for catalyst regeneration and reductant production/control
  - Scope does not include lean combustion optimization

- **Studies on Bench Flow Reactor**
  - Commercial, prototype, and model catalysts
  - Study of chemistry and mechanisms under simulated exhaust conditions
  - Two reactors simulate two catalysts in close coupled and underfloor positions

Data supplied to modeling community via CLEERS

Collaborations and Partners

- **Umicore**
  - guidance (via monthly teleconferences) and catalysts for studies (both commercial and prototype formulations)
- **GM**
  - guidance and advice on lean gasoline systems via monthly teleconferences
- **University of South Carolina (Michael Amiridis)**
- **University of Wisconsin (Chris Rutland)**
  - Monthly teleconferences focused on sharing data for modeling of lean emission control systems (with Ph.D. candidate Jian Gong)
- **CLEERS**
  - Share results/data and identify research needs
- **PNNL**
  - Engine platform used for GDI PM study (see PNNL talk ACE023)

Related DOE VTO Projects of note:
ACE084; Thomas Wallner, ANL: High Efficiency GDI Engine Research, with Emphasis on Ignition Systems
FT007; Todd Toops, ORNL: Fuel Effects on Emissions Control Technologies

Response to FY13 reviewers' comments

- Approach:
  - Comments: *"using both bench and engine testing is a good approach, but should try to draw a better correlation between the two."… "including a catalyst supplier in this work is highly desirable to make sure the newest technologies are characterized."…" a well-balanced approach between the reactor and dyno work"…" the engine and laboratory bench studies are complementary to each other"*
  - Response: positive comments, bench and engine result correlations are developing as results to compare are obtained
- Technical Accomplishments:
  - Comments: *"system architectural level should include FTP testing and aging effects to"…" at some point PM should also be included because of its regulatory requirement"…" a tunable ammonia generator for passive SCR and noted that TWC was shown to be effective"…" the laboratory-scale results demonstrated more than 99% NOx conversion without using urea"…" great bench data so far and was looking forward to results from the engine"*

FY2013 AMR Review (5 Reviewers) [scores: 1 (min) to 4 (max)]

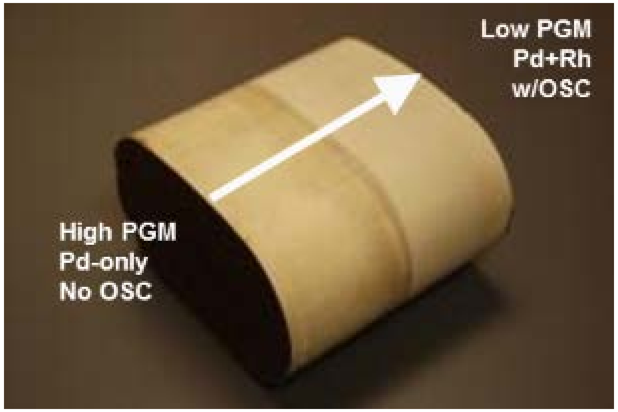
Weighted Average	3.48
Approach	3.80
Tech Accomplishments	3.40
Collaboration	3.40
Future Research	3.20

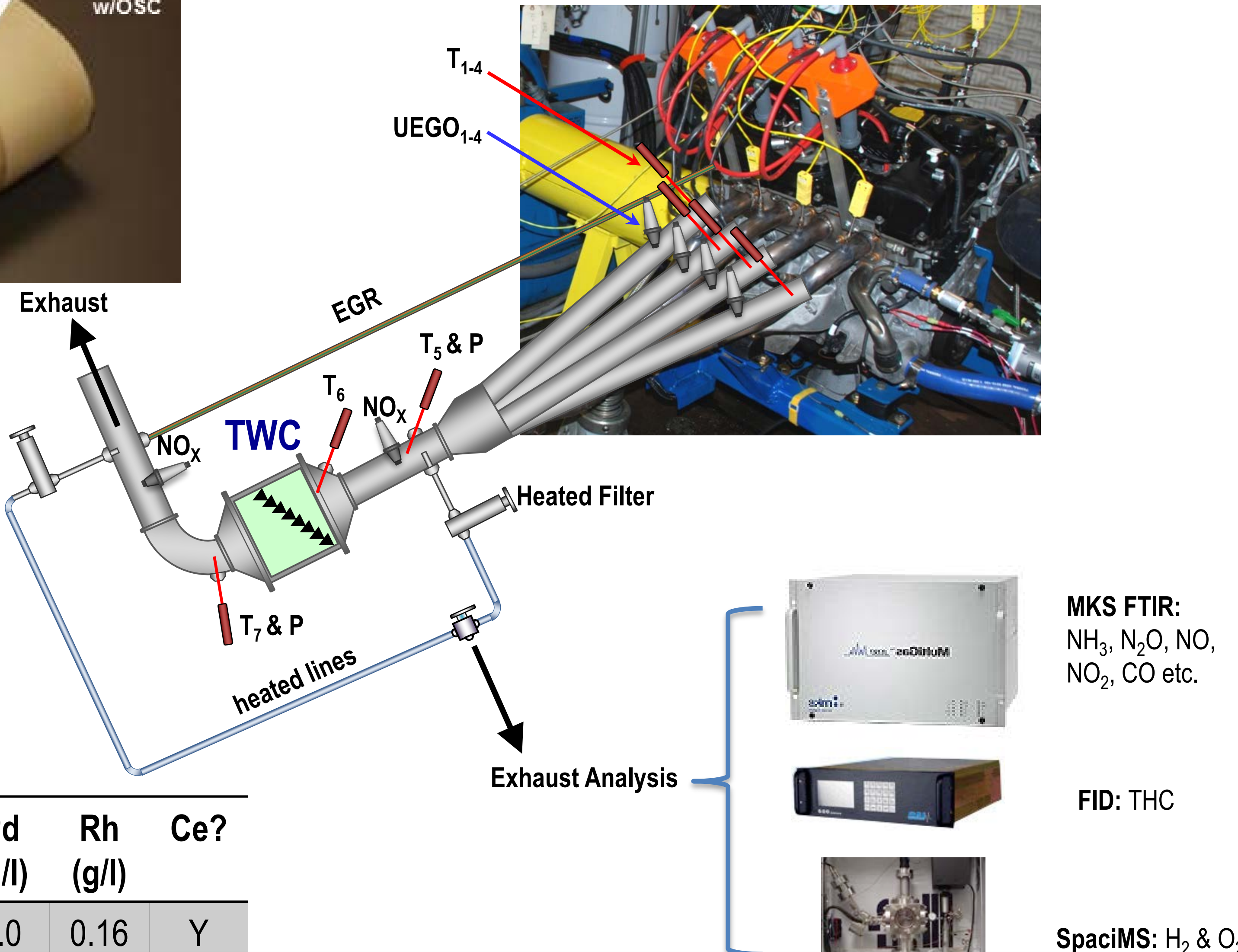
Notable Comment	Response
Liked bench+engine approach but want more correlation between them	Correlations now possible with both bench and engine results; will maintain such comparative analysis
Interest in transient/FTP studies and aging effects	Working that direction; modeling/analysis currently links to FTPs; more transient and aging experiments planned
Interest in PM emission studies	Resources limit ability to address; platform is serving community for PM studies

Summary of Technical Accomplishments

- **Measured combustion effects on NH_3 production from TWC on engine**
  - Results consistent with bench flow reactor studies
  - Fuel penalty for NH_3 production measured
  - Engine out NOx level a critical parameter for success (the higher the better)
  - H_2 measurements made – excess H_2 at TWC indicates potential for more NH_3 exists
- **Demonstrated >99% NOx Reduction Efficiency on engine with TWC+SCR**
  - Results consistent with bench flow reactor studies in general
  - NOx "puff" at transitions significant (relative to Tier 3 standard); investigations of cause ongoing
- **Analyzed potential for better fuel economy with transient drive cycle**
  - Direction toward project goals underline importance of engine-based studies
- **Characterized prototype TWC matrix supplied by Umicore (ongoing)**
  - Goals to improve catalyst design for best fuel economy gain
  - Of particular interest: addition of NOx storage component to TWC
  - First set of results obtained; research ongoing

Ammonia generation over TWC for passive SCR NO_x control on lean BMW 1-series engine (N43B20)



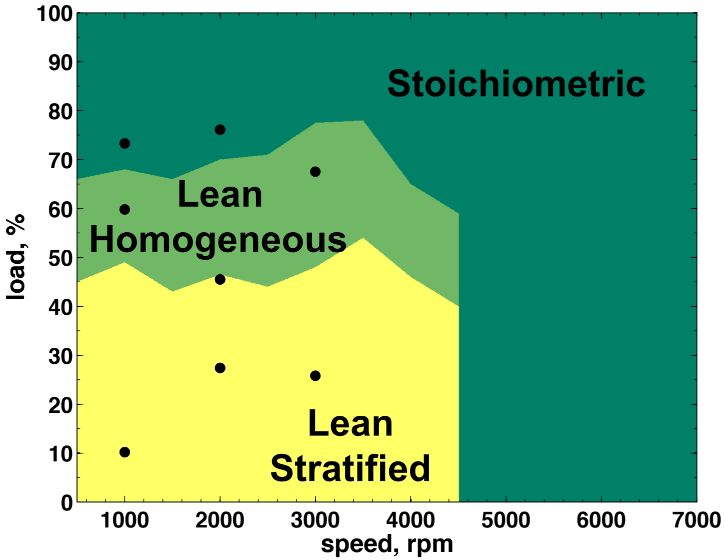


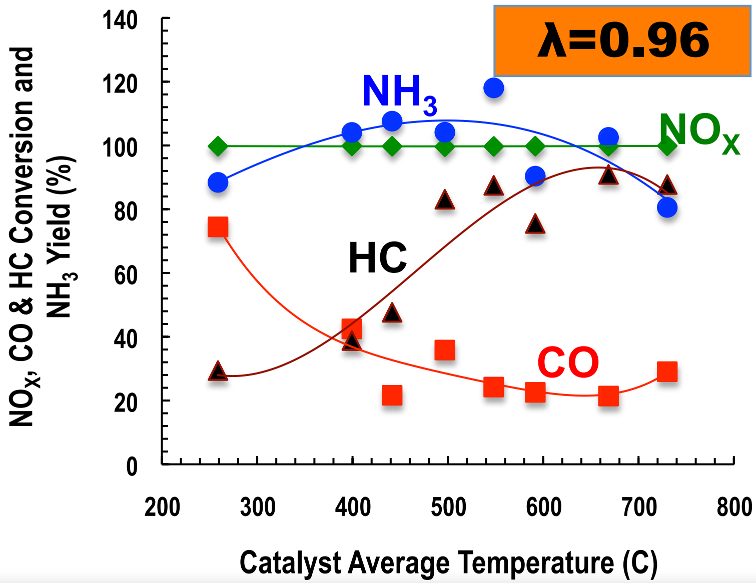
1.3 L TWC from PZEV 2009 Chevy Malibu

formulation	Pt (g/l)	Pd (g/l)	Rh (g/l)	Ce?
TWC combo	0	4.0	0.16	Y

High NH_3 yield is achieved at a wide range of engine conditions for λ=0.96

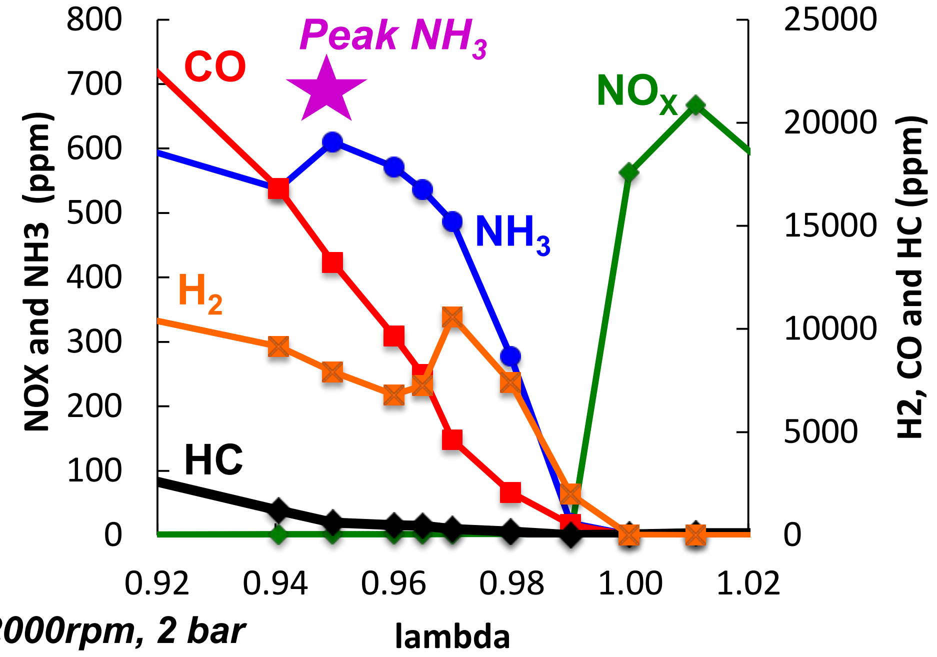
Speed	Load	OEM Mode
1000 rpm	1 bar	Lean Stratified
1000 rpm	5 bar	Lean Homogeneous
1000 rpm	6 bar	Stoichiometric
2000 rpm	2 bar	Lean Stratified
2000 rpm	4 bar	Lean Stratified
2000 rpm	6 bar	Lean Homogeneous
2000 rpm	8 bar	Stoichiometric
3000 rpm	2 bar	Lean Stratified
3000 rpm	7 bar	Lean Homogeneous





- High NH_3 yield is achieved at a wide range of temperatures and space velocities at λ=0.96
- At high temperatures, O_2 is selectively reacting with HC compared to CO

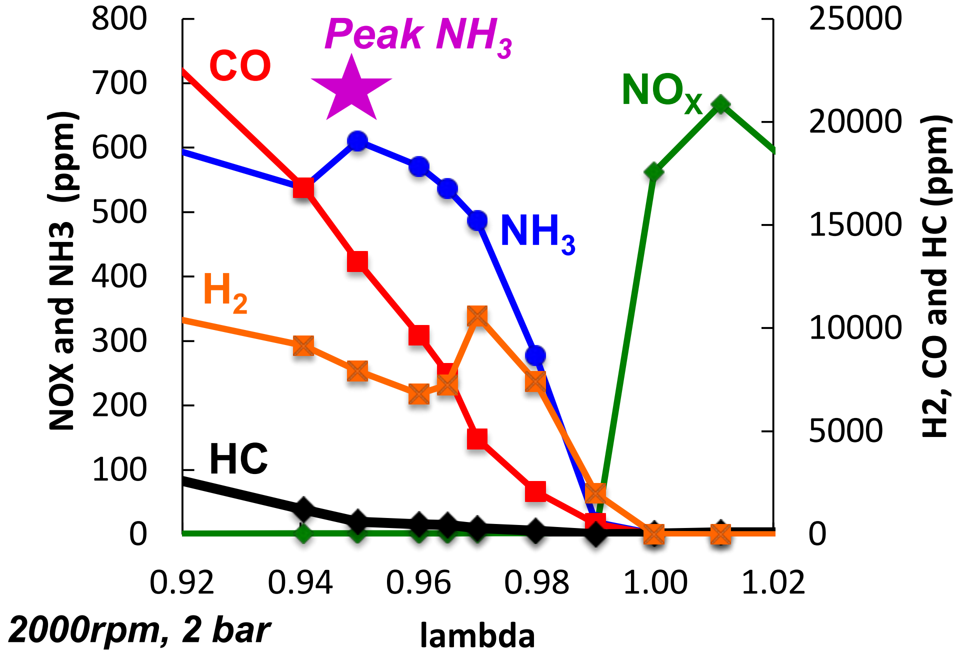
Complexity of NH_3 production on engine charted

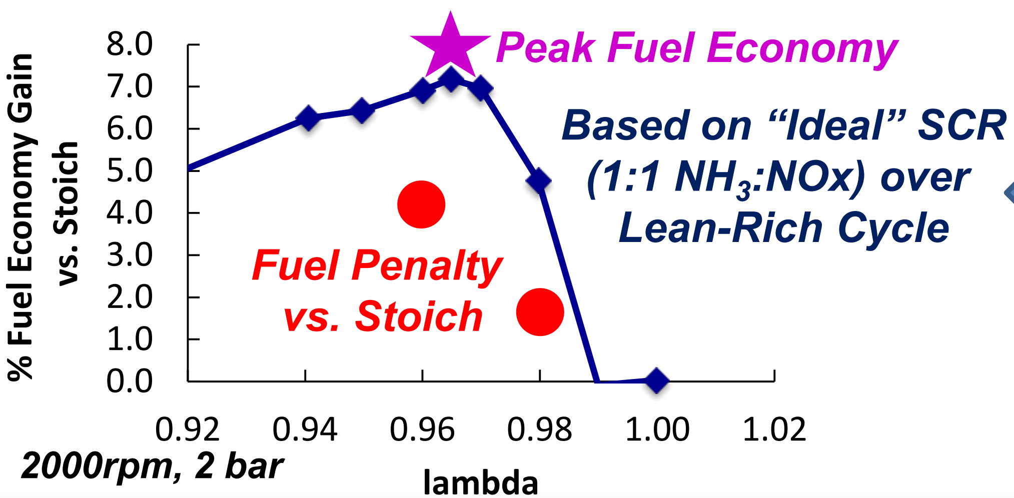


2000rpm, 2 bar

NH_3 vs. λ consistent with bench flow reactor results;
H_2 measured as well

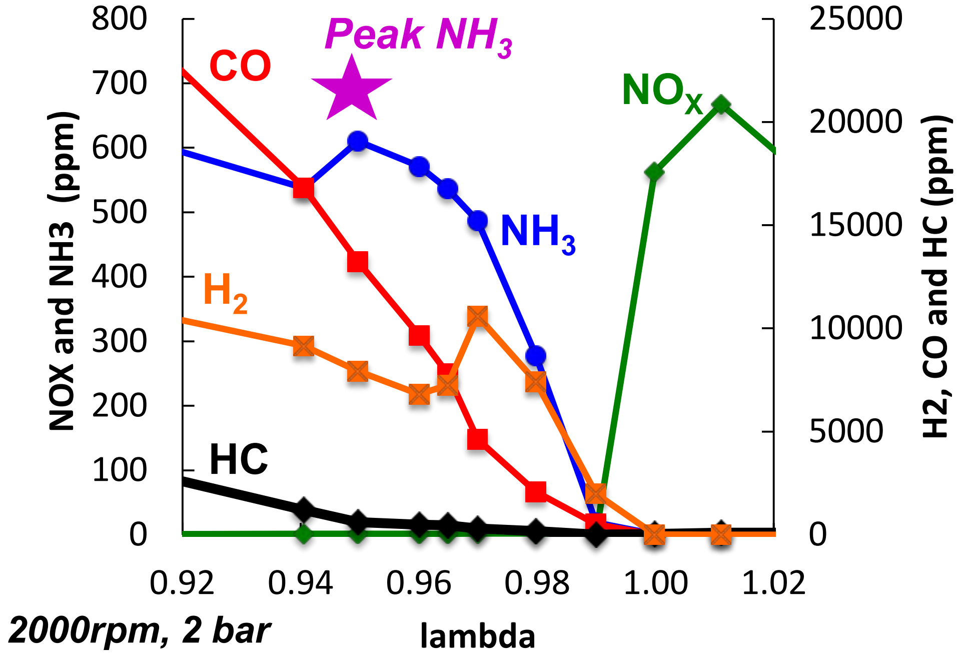
Complexity of NH_3 production on engine charted

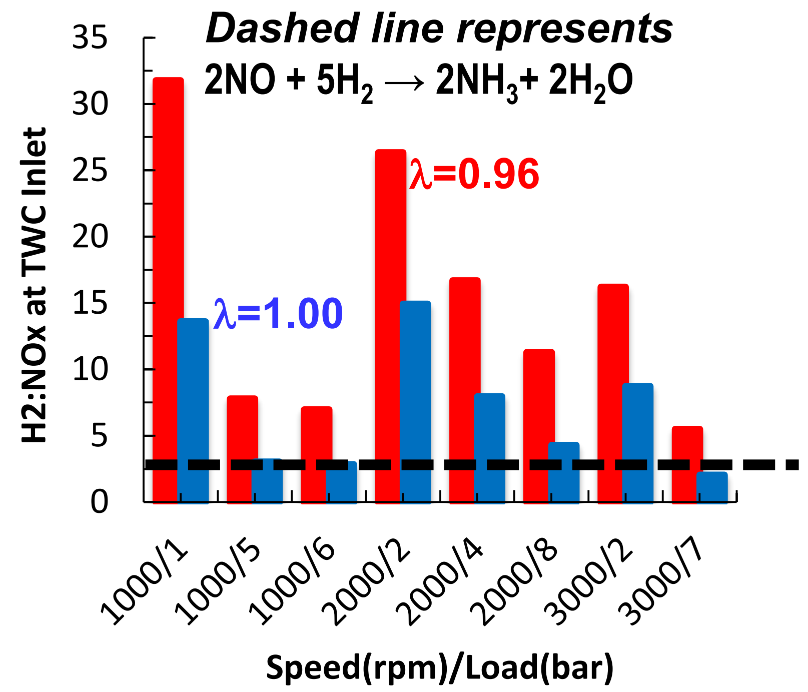




Peak NH_3 production is not necessarily optimal λ;
Fuel Economy gains depend on lean-rich cycle

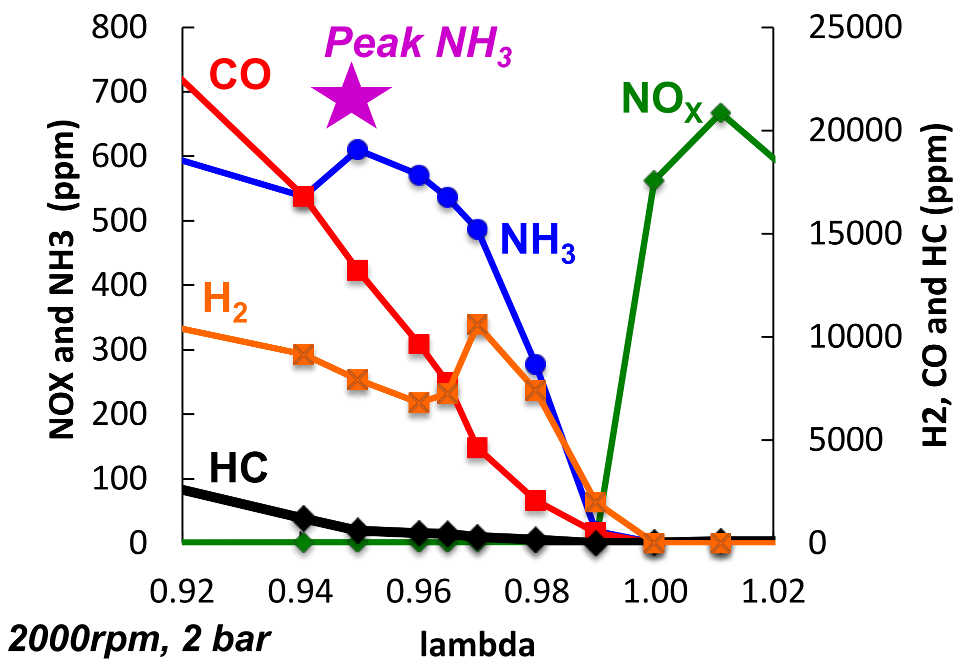
Complexity of NH_3 production on engine charted

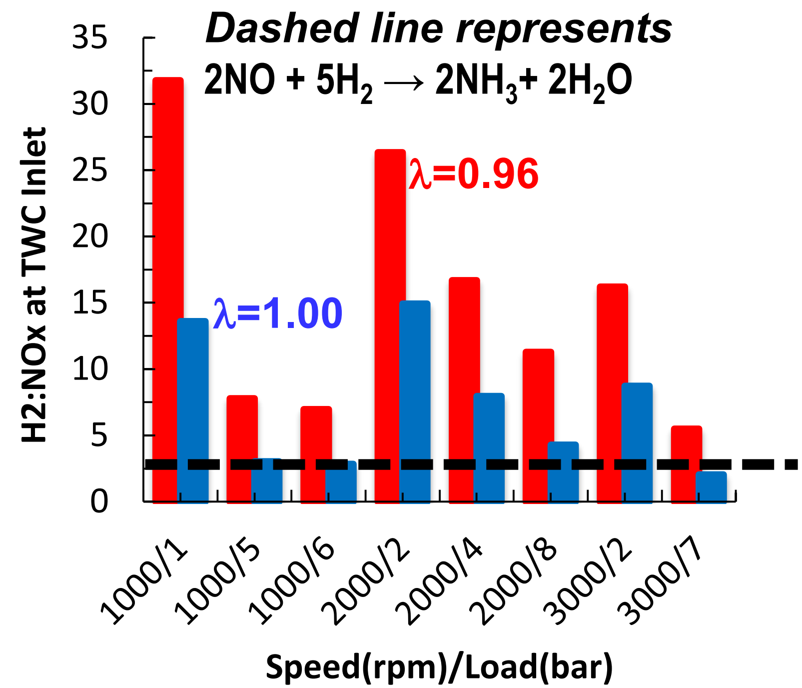




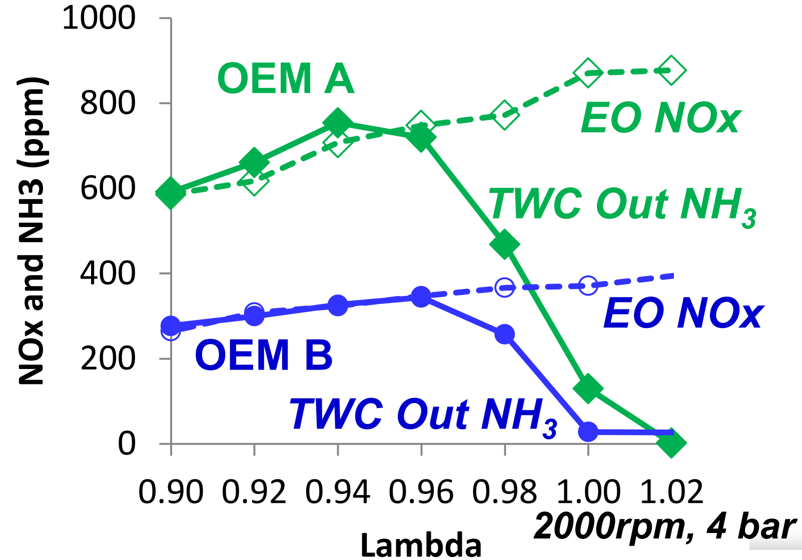
H_2 plentiful;
NH_3 not limited by H_2 supply
(engine out shown)

Complexity of NH_3 production on engine charted

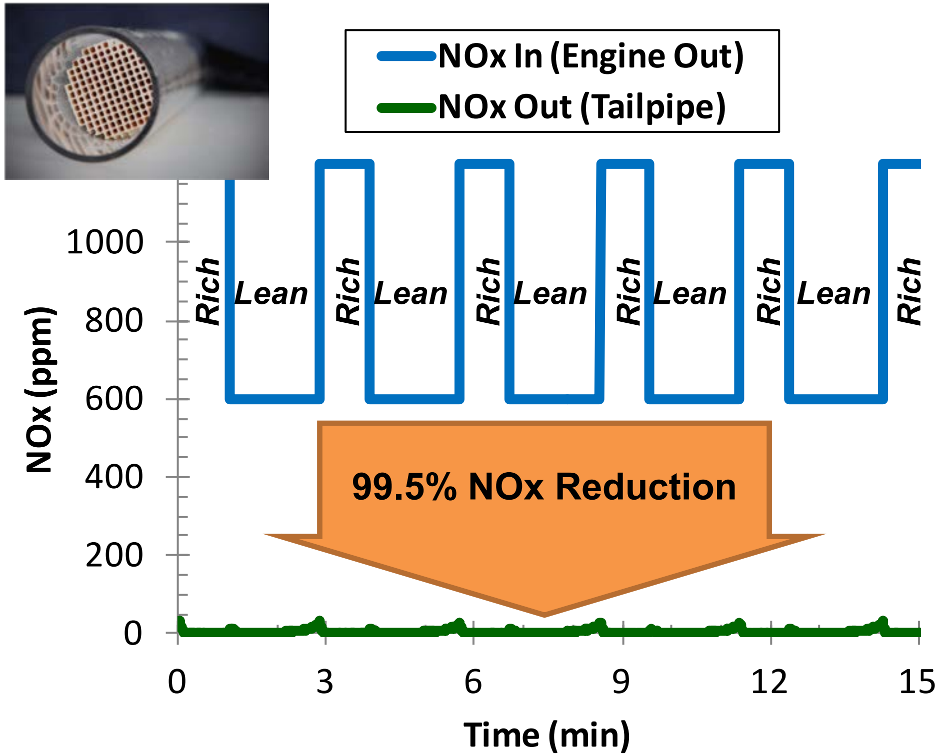




Since H_2 plentiful, Engine out NOx level has large impact on NH_3 production (the more the better)

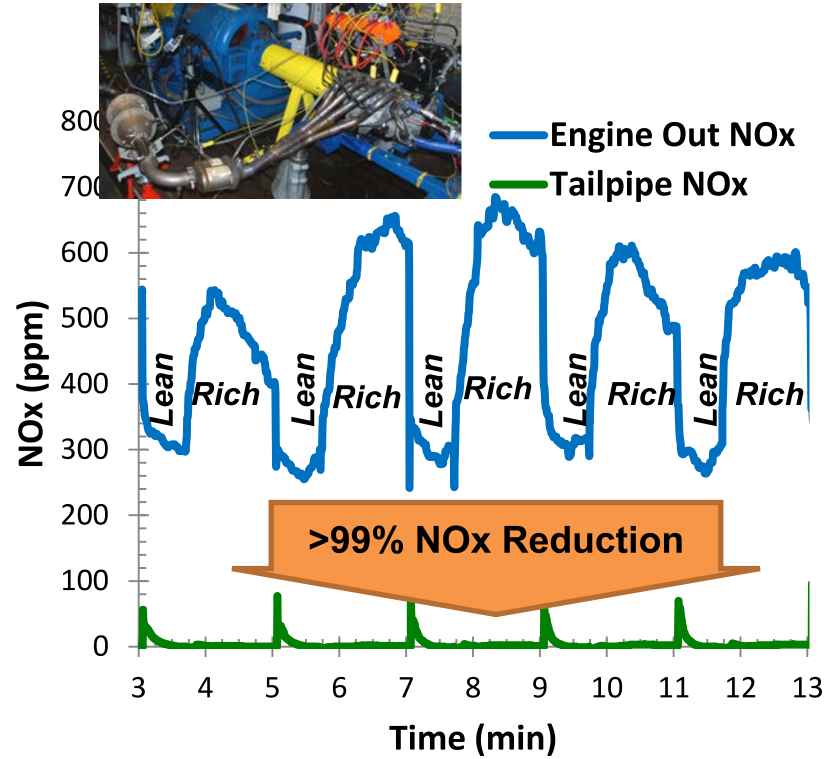


Bench reactor and engine-based passive-NH_3 SCR (TWC+SCR) experiments show consistent results



Bench Flow Reactor

Tailpipe	Avg (ppm)	Max (ppm)
NOx	4	31
NH_3	3	4
N_2O	2	32*
CO	*1200*	*3900*
HC	*0*	*0*



Engine

+5.5% Fuel Economy (vs. Stoich)

at 2000rpm, 2 bar

Tailpipe	Avg (ppm)	Max (ppm)
NOx	5	126
NH_3	2	5
N_2O	1	10
CO	*1782*	*4658*
NMOG	*<1*	*16*

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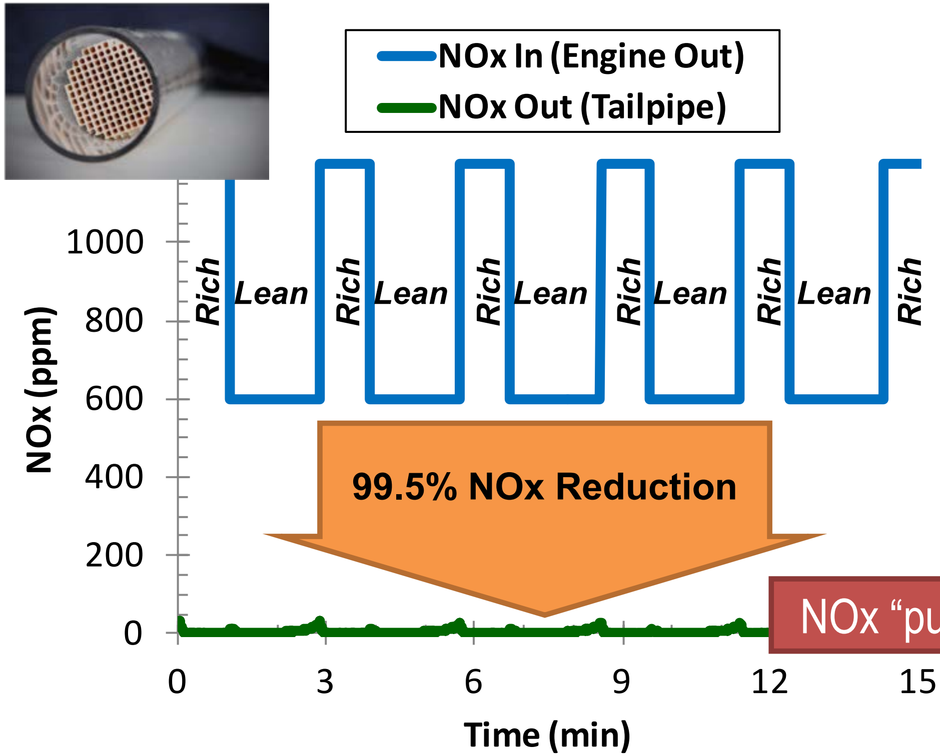

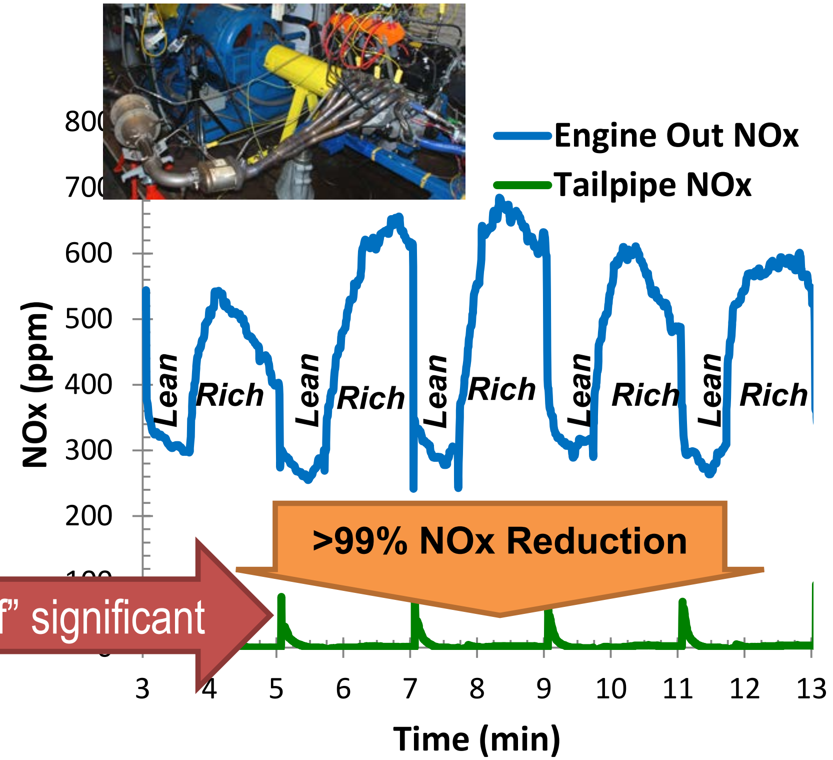

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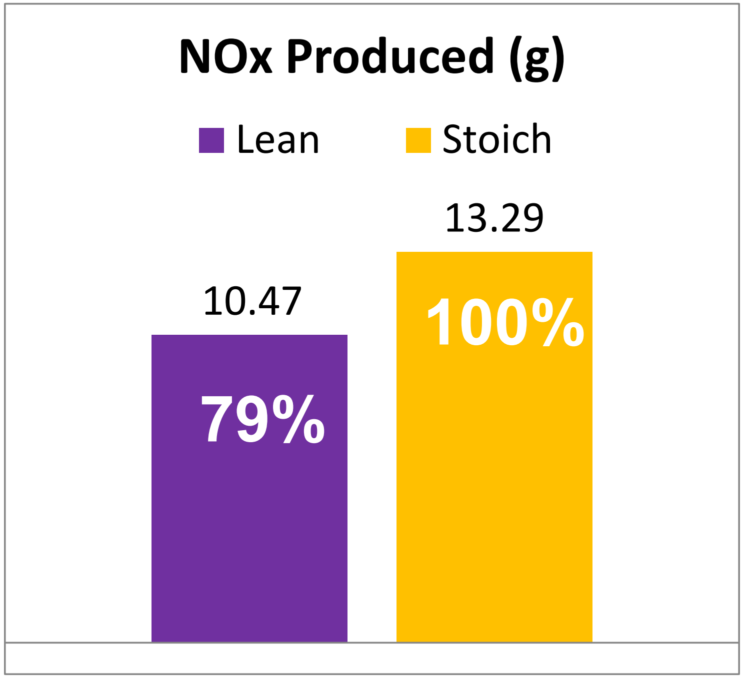
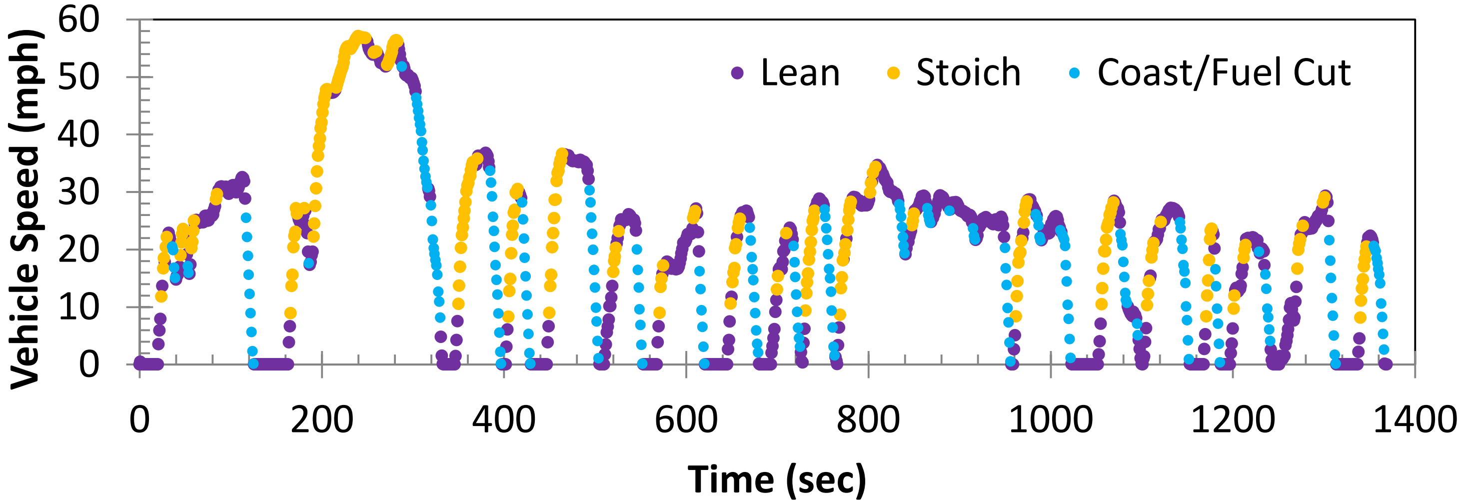
Transient drive cycle may enable better fuel economy gain

- Acceleration during transient drive cycle creates opportunity for high Engine Out NOx, and thereby, high TWC Out NH_3
- Modeled results shown based on steady-state engine map and FTP drive cycle
- Over entire cycle, more NOx created during stoichiometric operation; thus, efficient NOx to NH_3 catalysis can enable greater vehicle fuel economy
- **Estimated transient fuel economy gain = 10.8% (vs. ~5-6% observed for steady-state operation)**





Note: analysis based on steady-state engine data

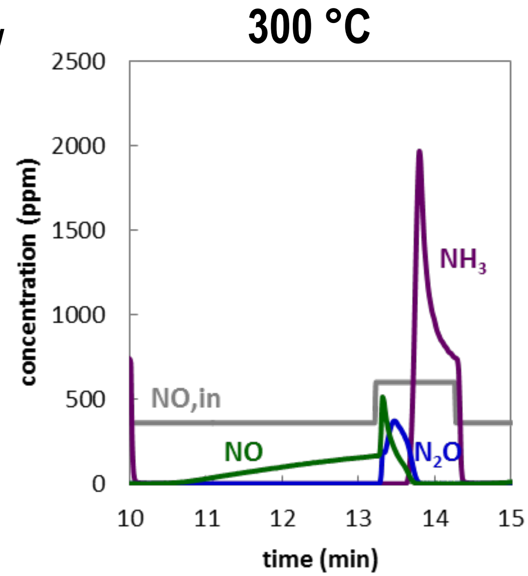
Studying matrix of TWC prototype formulations (from Umicore)

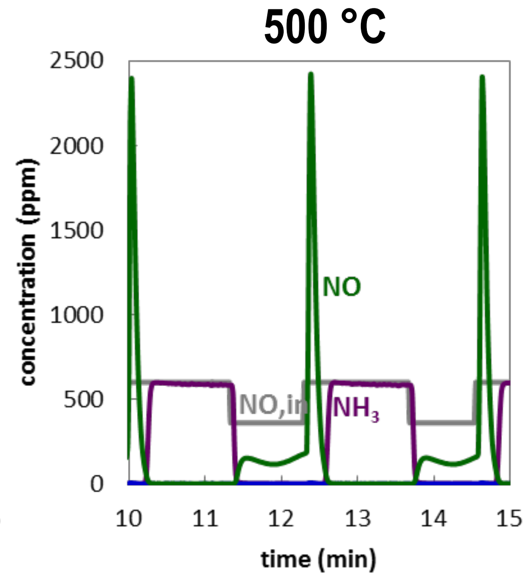
- New matrix of samples furthers FY13 focus of Pd with and without OSC
- NOx Storage Component (NSC)

sample ID	description	Pt g/l	Pd g/l	Rh g/l	OSC	NSC
ORNL-2	Pd + Rh	0	6.36	0.14	N	N
ORNL-6	Pd	0	6.50	0	N	N
ORNL-5	Pd + OSC high	0	6.50	0	H	N
ORNL-4	Pd + OSC med	0	4.06	0	M	N
ORNL-3	Pd + OSC low	0	1.41	0	L	N
ORNL-1	PGM + NSC	2.47	4.17	0.05	Y	Y

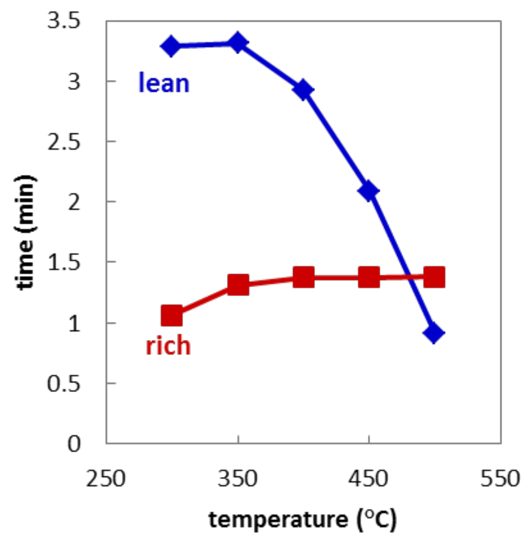
TWC NOx storage component improves lean time and fuel economy (but not at high temperatures)

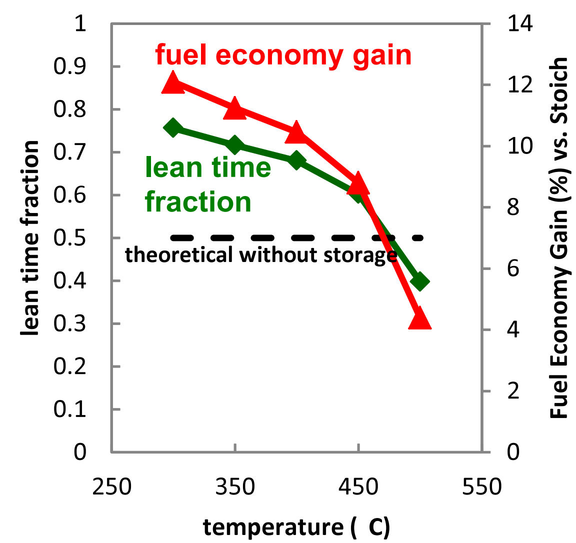
- Cycled TWC w/NOx storage on flow reactor in synthetic exhaust modeled after BMW 120i engine
  - feedback controlled cycles based on real time integration
  - NH_3 produced during rich = NOx slipped over entire cycle
  - theoretically operates equal times lean and rich w/o storage





- NOx storage component enables longer lean operating times at low TWC temperatures (and better fuel economy):
  - storage/reduction of lean NOx allows longer lean times
  - NH_3 produced from stored NOx allows shorter rich times
  - Delay in NH_3 onset a concern





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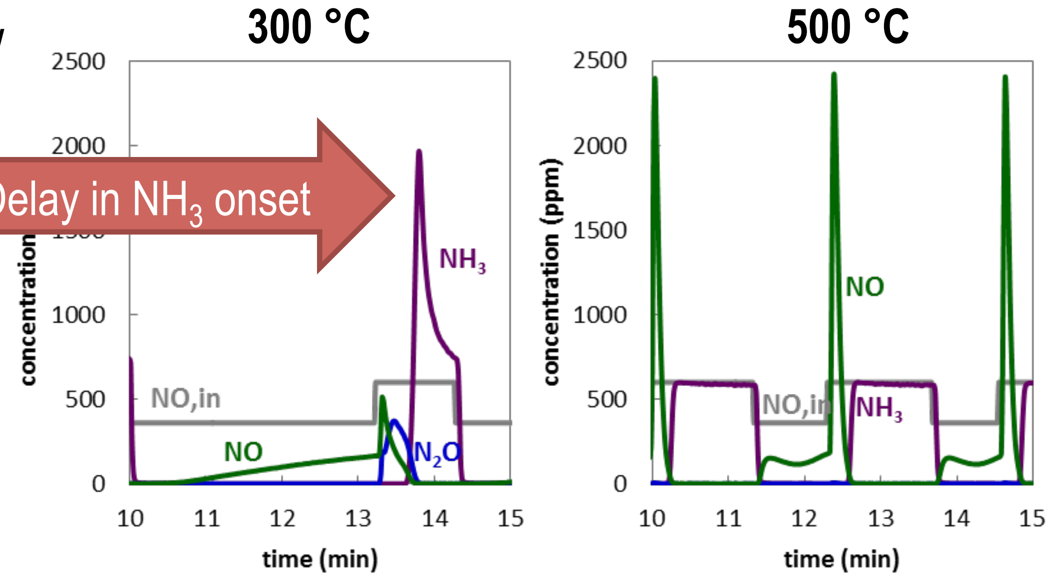

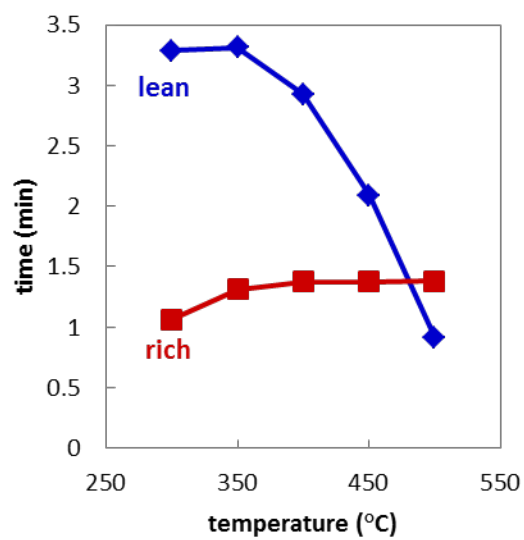

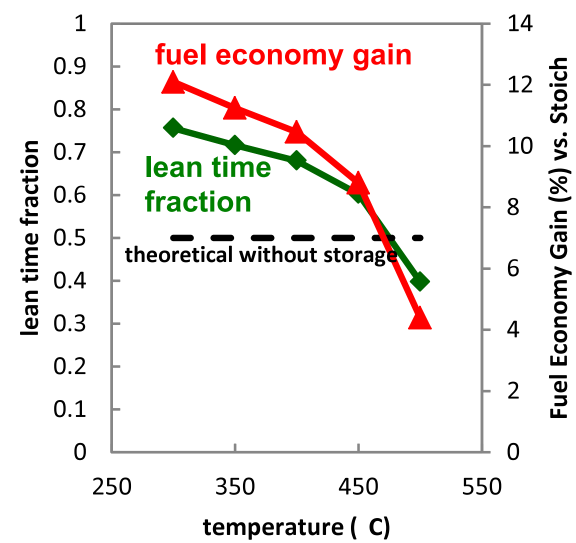

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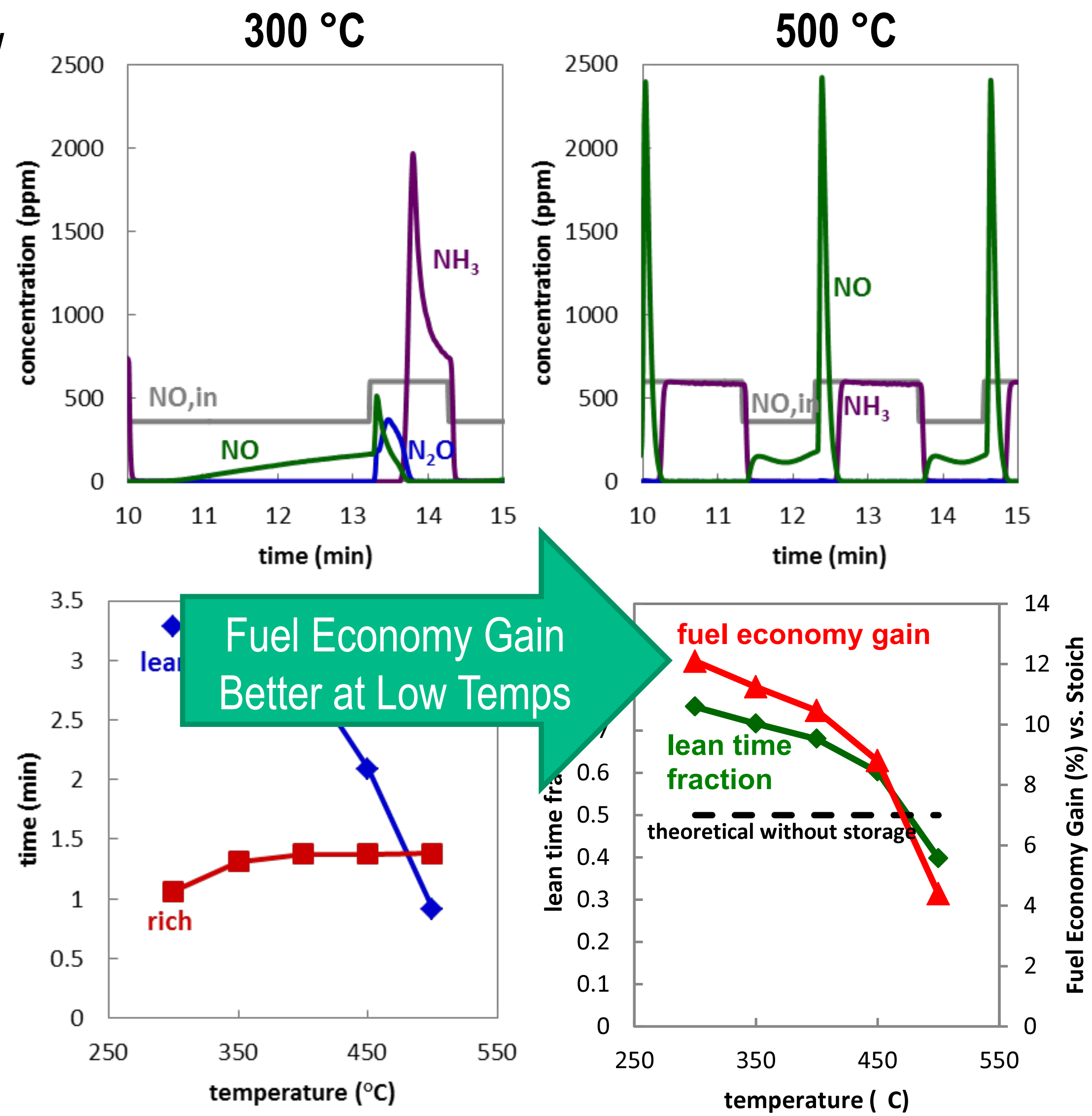
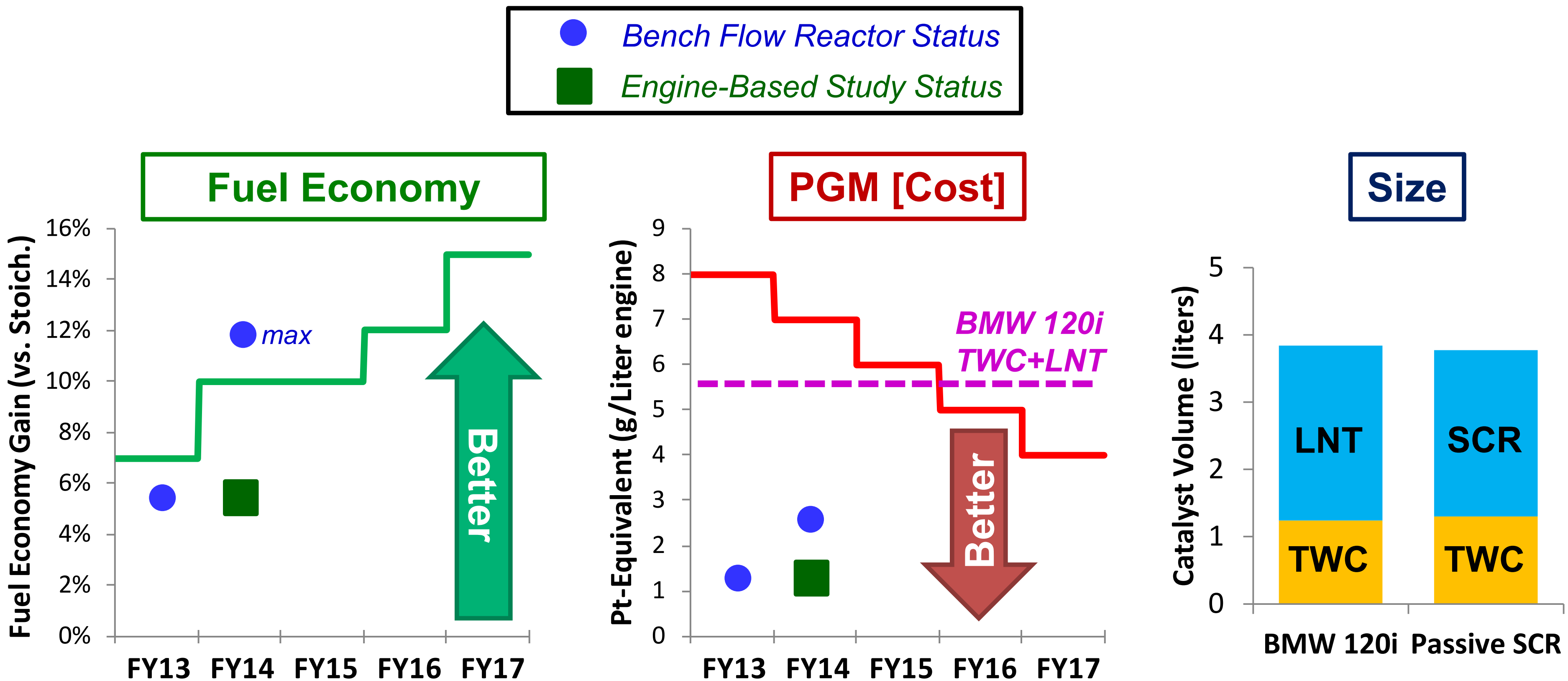


Remaining Challenges

- Improve system level fuel economy (reduce NH_3 production fuel penalty)
- Optimize catalyst performance during transients and rich-lean transitions
- Characterize and assess effect of S and aging on TWC NH_3 production



Future Work: Addressing Remaining Challenges

- Improve system level fuel economy (reduce NH_3 production fuel penalty)
  - Study two approaches identified in FY14 for improved fuel economy:
    - (1) utilization of acceleration load/speed during transient operation for higher NH_3 production
    - (2) addition of NOx storage component to TWC for increasing lean:rich ratio (extend bench flow reactor studies further and onto engine)
- Optimize catalyst performance during transients and rich-lean transitions
  - Further investigate NOx emissions during rich-lean transitions on engine
  - Predict effects of transient operation on drive cycle fuel economy gains
- Characterize and assess effect of S and aging on TWC NH_3 production
  - Add S to TWC formulations to determine effect of S on NH_3 production
  - Perform rapid thermal aging of TWC formulations and determine effect on NH_3 production and CO and HC slip

Summary

- **Relevance**:
  - Enabling lean gasoline vehicles will significantly impact US petroleum use
- **Approach**:
  - Evaluate catalyst formulations and system geometries on bench flow reactor for cost-effective emissions control (focus on non-urea systems)
  - Study fuel penalty and realistic performance on lean gasoline engine dynamometer research platform
- **Collaborations**:
  - Industry: GM and catalyst supplier Umicore
  - Universities: University of South Carolina and the University of Wisconsin
  - National Labs: PNNL (platform supported PM study)
- **Technical Accomplishments**:
  - Demonstrated >99% NOx reduction efficiency with TWC+SCR approach on engine; results consistent with bench flow reactor results obtained previously
  - Defined key emissions on the engine platform including: NOx pulse at lean-rich transitions, H_2 during rich operation, effect of engine out NOx on NH_3 supply-demand over lean-rich cycle
  - Characterized prototype TWC with NOx storage component (further studies ongoing)
- **Future Work**:
  - Improve system level fuel economy (reduce NH_3 production fuel penalty)
  - Study effects of sulfur and aging on NH_3 production and CO/HC oxidation