Emissions from In-Use NG, Propane, and Diesel Fueled Heavy Duty Vehicles

2011 Directions in Engine-Efficiency and Emissions Research (DEER)

October 3-6, 2011

Presented By: Kent Johnson
Co-Authors: Thomas Durbin, J. Wayne Miller

University of California, Riverside
Bourns College of Engineering
Center for Environmental Research and Technology

Outline

- Motivation, background, methods
- Results and comparisons to previous studies
- Discuss formation mechanism and root cause
- Impact and discussions

Motivation and Background

- Alternate strategies exist to meet 2010 heavy duty emission standards such as natural gas (NG) and propane fuels

- University of Denver showed high ammonia NH_3 (1500 ppm) emissions from NG vehicles (Gary Bishop, CRC 2009)

- Ammonia (NH_3) can form ammonium nitrate particulate matter ($PM_{2.5}$) in the atmosphere

- What is the current in-use impact of NH_3 emissions between heavy duty fuel applications?

Test Methods: Vehicles

Type	Count	Mfg/Model	Disp	MY	Fuel	A/F	ATS	ID
School Bus	5	GM/8CLFH08	8.1	2008	LPG	SI stoich	TWC	LPG_st_TWC
Box Truck	1	GM/7CLFH08	8.1	2007	LPG	SI stoich	TWC	LPG_st_TWC
Shuttle Bus	2	GM/BCLFE06	6.0	2009	LPG	SI stoich	TWC	LPG_st_TWC
Transit Bus	1	CUM/ISL-G280	8.9	2009	CNG	SI stoich	TWC	CNG_st_TWC
Refuse Truck	1	CUM/CG-250	8.3	2001	CNG	SI lean	OC	CNG_ln_OC
Transit Bus	1	JD/6081H	8.1	2003	CNG	SI lean	OC	CNG_ln_OC
Class 8	2	CUM/ISL-G320	8.9	2008	LNG	SI stoich	TWC	LNG_st_TWC
Yard Tractor	2	CUM/CG-250	8.3	2005	LNG	SI lean	OC	LNG_ln_OC
Class 8	1	CUM/ISX450	15	2008	Diesel	CI	DOC/DPF	D_DPF
Class 8	1	DDC/S60	15	1998	Diesel	CI	CRT/SCR	D_CRT/SCR

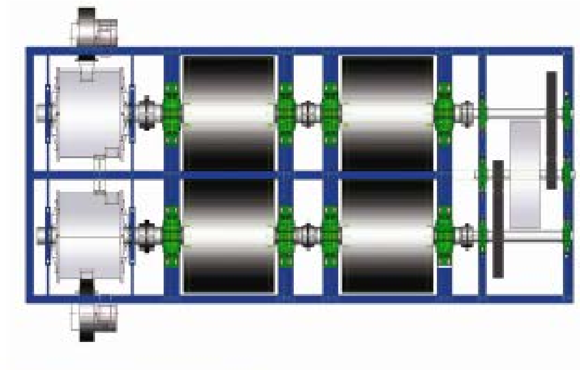
Disp - displacement liters, **MY** - model year, **A/F** - air-to-fuel ratio type, **ATS** - after treatment system

LPG - liquid propane gas, **CNG** - compressed natural gas, **LNG** - liquid natural gas

SI stoich - spark ignition stoichiometric combustion, **SI lean** - lean combustion, **CI** - compression ignition

TWC - three way catalyst, **OC** - oxidation catalyst, **DPF/SCR -** diesel particulate filter / selective catalytic reduction

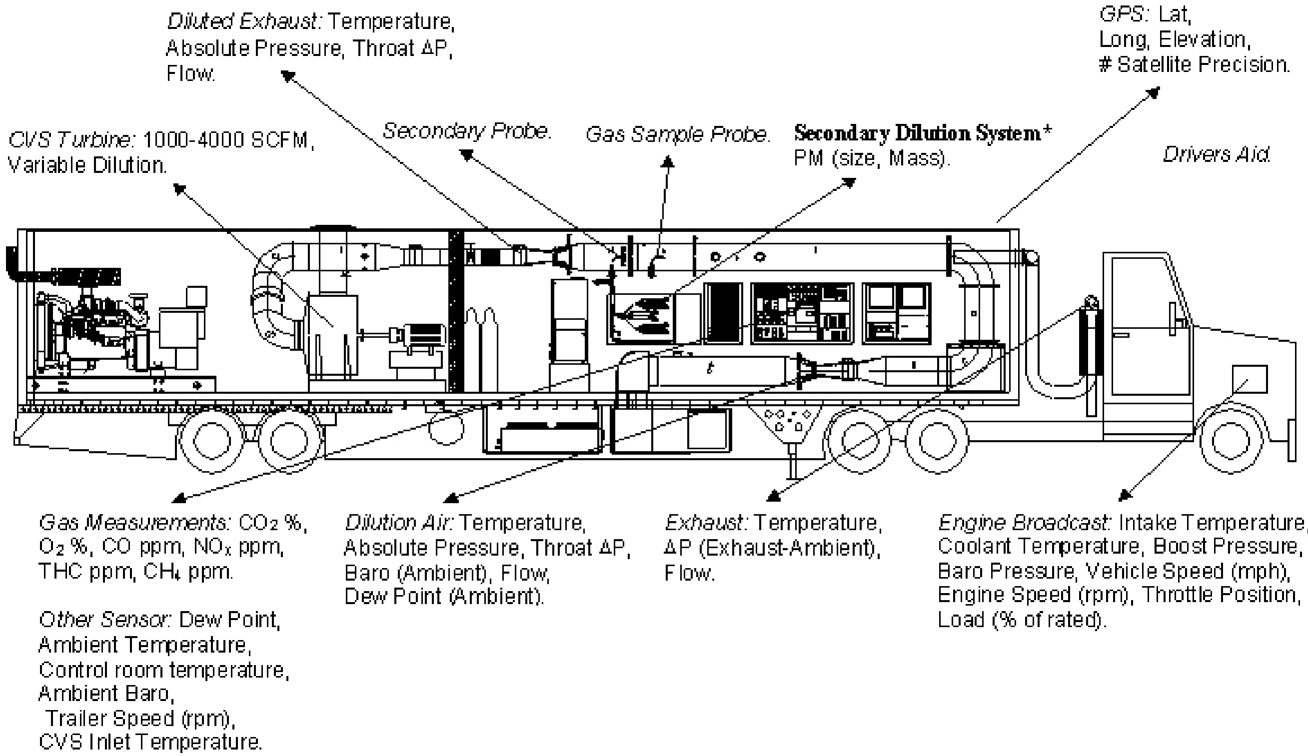
Test Methods: Test Repeatability Controlled with UCR's Chassis Dyno



- Performance
  - 5,000 lb 0-15 mph
  - 600 hp 45-80 mph
  - 200 hp 15 mph
- Acceleration 6 mph/sec
- Inertia Simulation
  - 10 lb increments
  - 10,000 lb – 80,000 lb range
  - 45,000 lb base inertia
- Speed accuracy +/- 0.01 mph
- Acceleration accuracy +/- 0.02 mph/sec
- Response time 44 to 100 ms

(durbin 2010 CRC)

Test Methods: Laboratory Measurements Used



- Mobile emissions laboratory (MEL) established (CO, CO2, THC, CH4, NMHC, PM2.5, NOx) (Cocker 2004 Part I ES&T, Johnson AE 2009, and Johnson ES&T 2010)
- NH_3: Integrated tunable diode laser (TDL) spectroscopy (Johnson 2009 CRC)
- Carbonyls: DNPH (Cocker 2004 Part II ES&T)
- Particle size distribution: SMPS (Shaw 2005 ES&T)

Outline

- Motivation, background, methods
- Results and comparisons to previous studies
- Discuss formation mechanism and root cause
- Impact and discussions

Results Averaged over Cycles and Vehicles

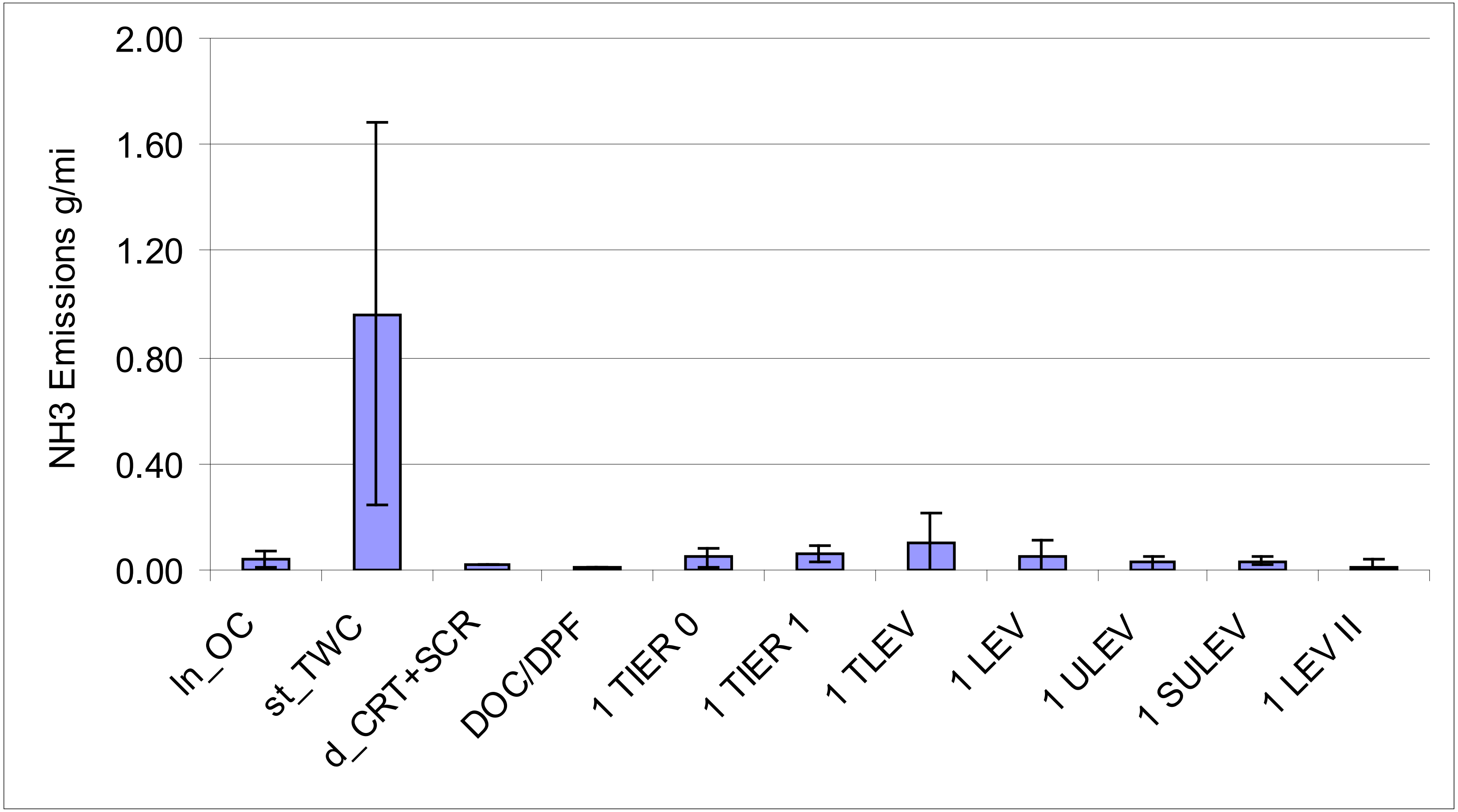
ID [1]		Emissions g/hp-h				Conc
n/a	NMHC	CO	NOx	NH3	PM	NH3
NG_ln_OC	0.002	0.113	9.530	0.007	0.001	2.4
LPG_ln_OC	0.004	0.029	3.932	0.007	0.001	2.0
NG_st_TWC	0.001	4.042	0.051	0.397	0.001	151.6
LPG_st_TWC	0.001	1.462	0.051	0.135	0.004	97.1
CRT+SCR	0.034	0.261	1.488	0.005	0.004	1.2
DOC/DPF	0.015	0.030	1.590	0.002	0.001	0.5

[1] refer to previous table for description of ID's

[2] draft data

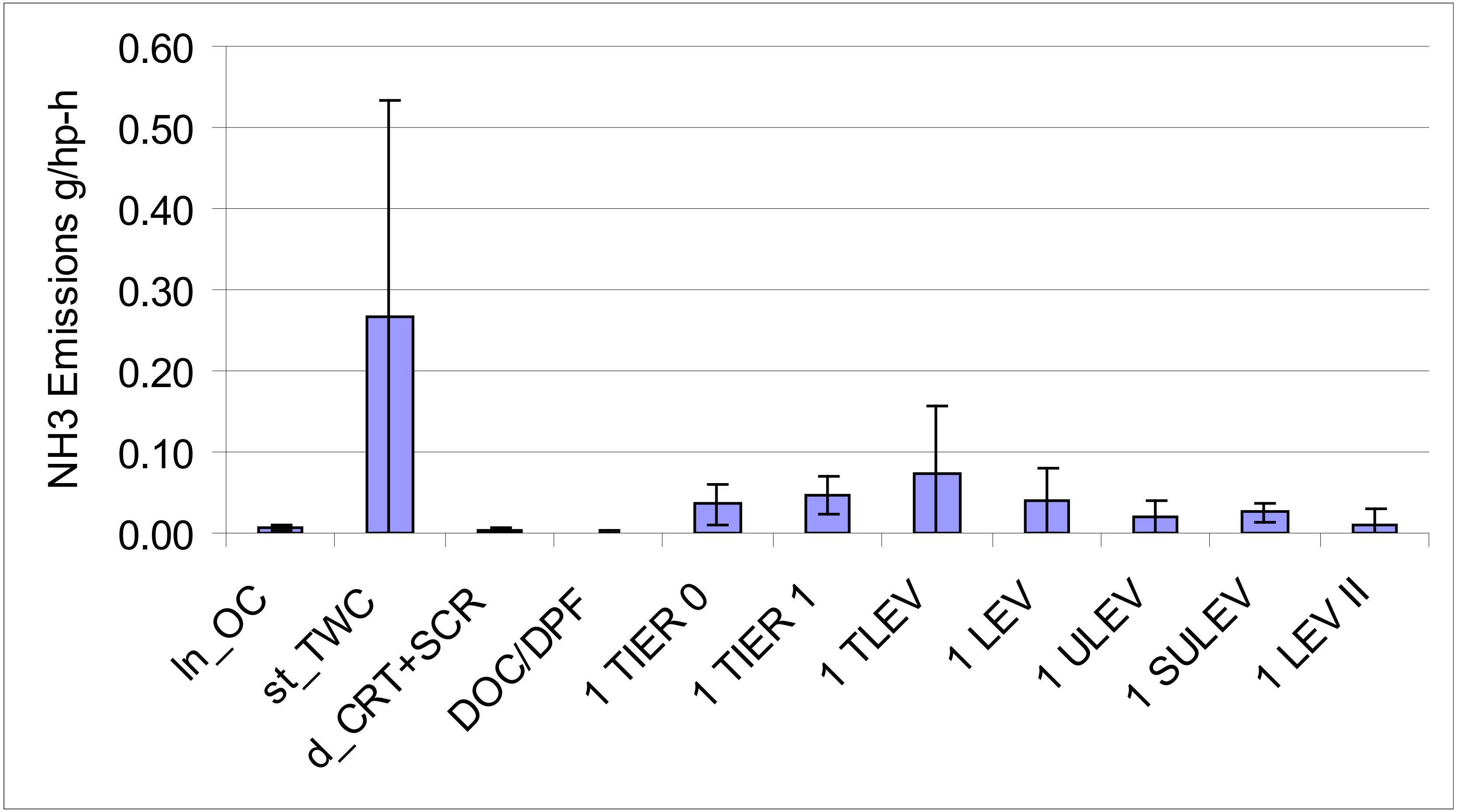
- Each data row represents the average of all vehicles and cycles (UDDS, CBD and Cruise) to highlight ATS affects
- Differences due to vehicles was relatively low

Heavy Duty > Light Duty NH_3 Emissions on Mile Basis



[1] light duty data souce from Livingston et al 2009 AE

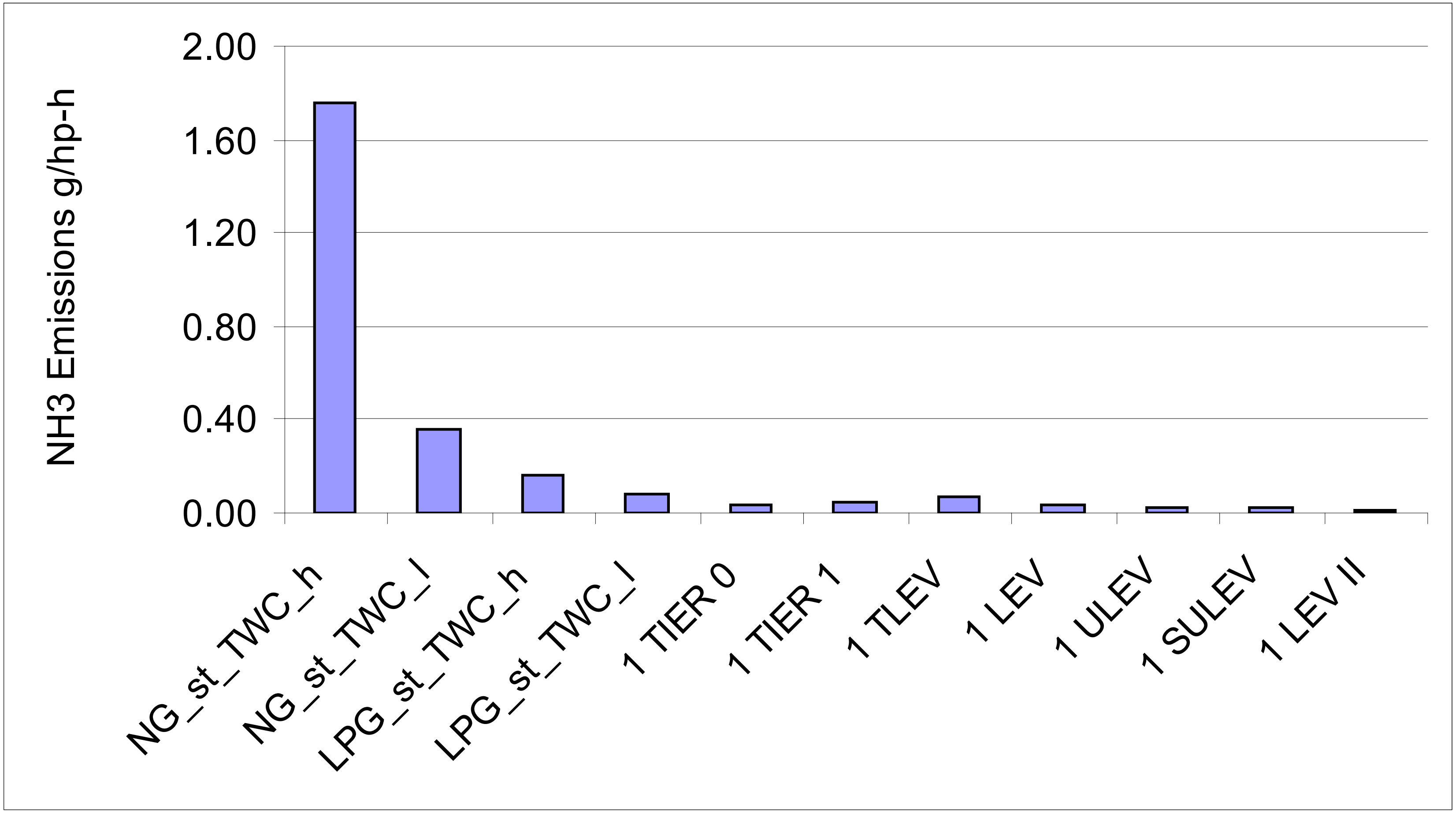
Heavy Duty NH_3 Emissions Similar to LD on g/hp-h basis



[1] light duty data souce from Livingston et al 2009 AE

[2] light duty brake specific data estimated from FTP length, time and nominal 30 hp load

Heavy Duty NG NH_3 Emissions is Higher than LPG



[1] light duty data souce from Livingston et al 2009 AE

[2] light duty brake specific data estimated from FTP length, time and nominal 30 hp load

Outline

- Motivation, background, methods
- Results and comparisons to previous studies
- Discuss formation mechanism and root cause
- Impact and discussions

Why is NH_3 High for the Alt Fueled Vehicles?

- Research suggest that NH_3 is formed from the water-gas shift reaction (Bradow, 1977 SAE and Cadle et al 1979 SAE)

$$CO + H_2O \rightarrow CO_2 + H_2$$

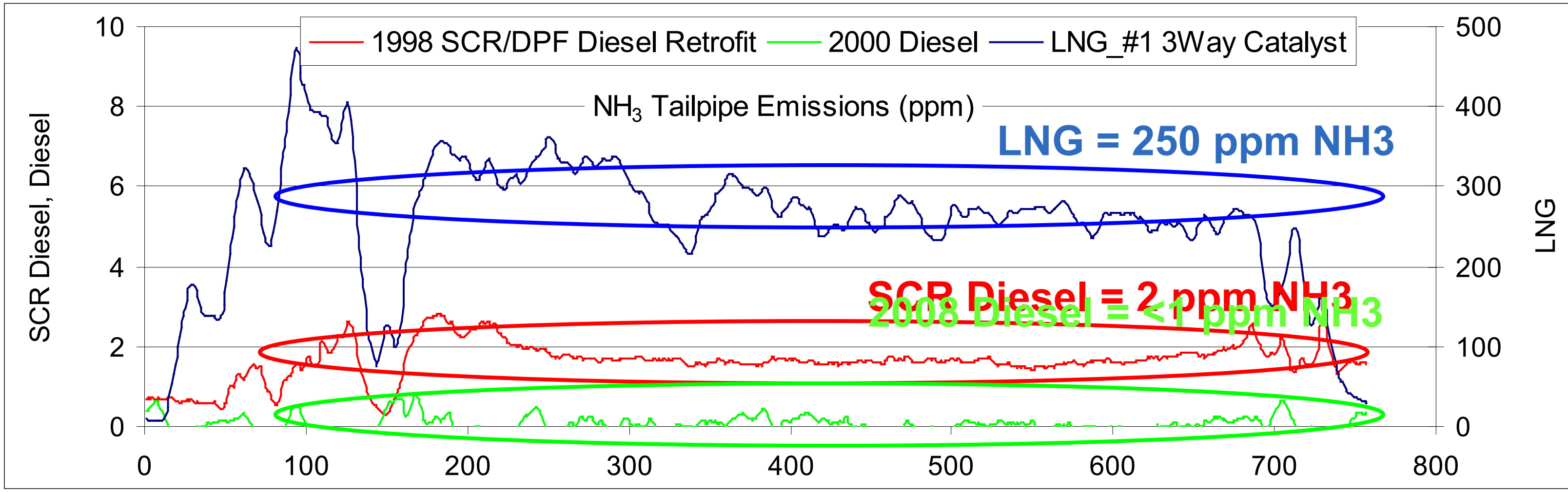
$$2NO + 2CO \rightarrow 2NH_3 + 2CO_2$$

$$2NO + 5H_2 \rightarrow 2NH_3 + 2H_2O$$

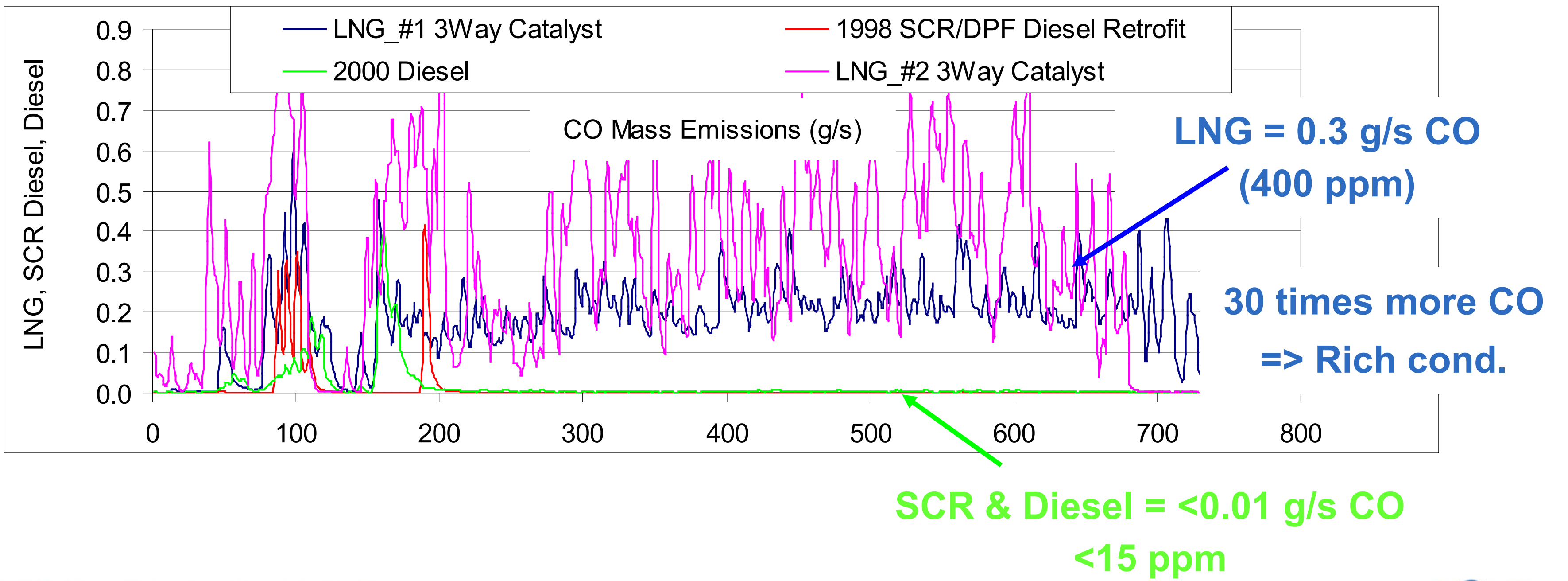
- Several researchers reported that NH_3 emissions were present on light duty gasoline vehicles equipped with TWC under rich conditions (Durbin et al, 2000 ES&T and Huai et al, 2003 ES&T)
- GM research suggested controlling NO_x emissions using NH_3 formation over the catalyst (Viola et al, 2010 DEER)

NG Vehicles Show High NH_3 and CO During Cruise

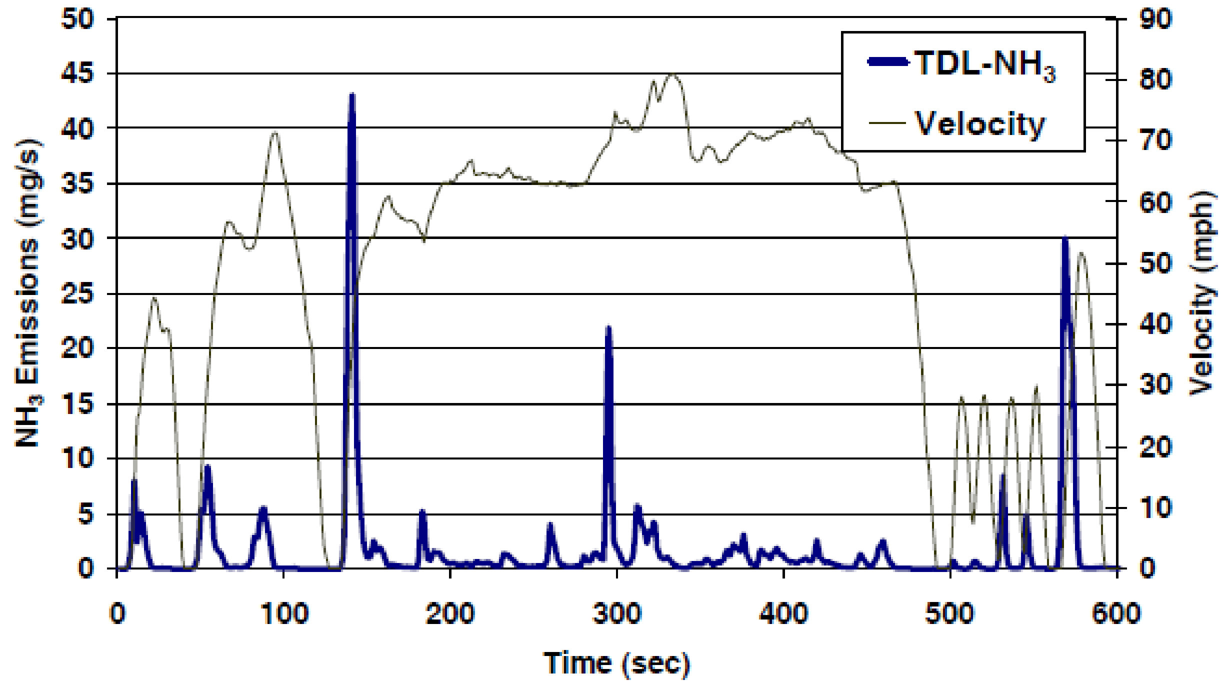
NH_3



CO



Light Duty High NH_3 Spikes Occurs at Tip-In



(AE, Durbin 2004)

- NH_3 emissions in real time show issue occurs during transients accels (US06 cycle 5 times > than FTP: ULEV light-duty gasoline truck)
- Once the vehicle A/F is controlled NH_3 is minimal
- Advanced air-fuel ratio controls for SULEV's show minimal NH_3 spikes (Kitagawa et al, 2000)

Outline

- Motivation, background, methods
- Results and comparisons to previous studies
- Discuss formation mechanism and root cause
- Impact and discussions

Why Does it Matter to Have High NH_3 Emissions?

- Urban areas have high congestion and sufficient NO

$$NO + O_3 \rightarrow NO_2$$

$$NO_2 + OH \rightarrow HNO_3$$

$$NO_3 + HNO_3 \rightarrow NO_2$$

$$NH_3 + HNO_3 \Leftrightarrow NH_4NO_{3(s)}$$

Conclusions

- NG and propane vehicles, with SI stoichiometric control, can produce high NH_3 emissions over a TWC
- Heavy duty NG NH_3 emissions are significantly higher on a g/mi basis, but closer on a g/hp-h basis compared to light duty vehicles
- Propane vehicles produced less NH_3 emissions than NG, but still slightly more than LD vehicles
- High NH_3 release is associated with high CO

Future Work

Engine/Technology	Number of Vehicle				Total Test
	Transit	Sch. Bus	Refuse	Goods Movement	
I. 8.9L 0.2g Natural gas engine with 3-way cat.	1	-	1	3	11
II. 15L 0.8g HPDI engine with EGR and DPF				3	6
III. 15L 0.2g HPDI engine with EGR and SCR/DPF				2	4
IV. Diesel engine at 1.2 g NOx	-	-	1	3	10
V. Propane and diesel school bus	-	2	-	-	2
VI. Diesel engine above 0.2 g NOx w/o SCR	-	-	2	2	12
VII. Diesel engine at or below 0.2 g NOx w/SCR	-	-	2	3	14
VII. Natural gas engine w/3-way catalyst + AFD	1*		1*	1*	7
Total	1	2	6	16	66

- WVU and UCR working together
- 3 more propane and 6 more diesel added to matrix
- Total vehicles 34