Economic Comparison of LNT Versus Urea SCR for Light Duty Diesel Vehicles in US Market

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Research & Advanced Engineering
Ford Motor Company

2004 DEER Conference
Coronado, California
Aug 29 – Sept. 2

Research and Advanced Engineering

Overview

- Future diesel systems require NOx catalysts
- Lean NOx trap (LNT) or urea selective catalytic reduction (SCR)
- If both work, what are the relative costs?
- Analysis based on published information
- LNT is much more expensive due to
  - Higher platinum group metal (PGM) use
  - Fuel economy degradation
  - CAFE compliance costs

Analysis Assumptions – Both Systems

1. Both LNT and SCR systems are capable of meeting Tier 2 Bin 5 emissions in 2010
2. U.S. Light duty market – passenger car and light truck
3. Only considers discrete LNT and SCR, not integrated systems
4. 2010 fuel price $1.50/gallon ($0.396/L)
5. 2010 urea price $1.50 per US gallon – high volume mature cost, no capital recovery considered.
6. 120k mile (193k km) vehicle useful life
7. Fast warmup strategy is required on the FTP cycle
8. NOx sensor used for OBD and control

Analysis Assumptions - LNT

1. DOC-LNT-DPF configuration
2. 5% fuel economy (FE) penalty from base due to rich operation for deNOx and deSOx, plus temperature support.

Analysis Assumptions - SCR

1. DOC-SCR-DPF configuration
2. No fuel economy (FE) penalty from base
3. Urea is used at 2% of fuel use

FE Effect of Aftertreatment

			% FE Cost				
Source	**Vehicle**	**Standards**	**DPF**	**SCR**	**DPF+LNT**	**LNT**	**Comment**
Johnson, SAE 2004-01-0070	13L HD	US 2007	0-0.5				
Johnson, SAE 2004-01-0070	13L HD	Euro 4		-(3 to 5.5)			
Johnson, SAE 2004-01-0070	2L car	Euro 5			2-4		
Johnson, SAE 2004-01-0070	4L LD truck	Bin 5			2-4		
TIAX EMA..pdf	Not def.	2010		-6		5	Assumes non-SCR would use high EGR at 6% FE penalty
Smyth, GM p42	mid size	Bin 5	3%	0	5-10		Hard to read values off chart, but about:
Mital et.al., SAE 2003-01-0041						7	
Schittler, DC DEER 2003			3	-6			
EPA draft offroad stds pV-22			1			1-2	
Palmqvist et al SAE 2004-01-1294	car	Euro 5		1			Fuel equivalent of urea
Lambert et al SAE 2004-01-1292 fig 4	Focus	Bin 5	3	1		5-10	

Our Estimate	***SCR***	***LNT***
% FE Cost	0	5

Components Compared

Item	LNT	Urea SCR
DOC	Yes	Yes
LNT	Yes	No
SCR	No	Yes
HC Injection System	Yes	No
Urea Injection System	No	Yes

Precious Metal Cost

- Input data:
  - PGM loading
  - Catalyst volume
  - Precious metal cost
- Estimate cost difference per vehicle
- Extend to fleet PGM cost by volume assumption

PGM Loading

LNT

Source	*Pt*		*Pd*	*Rh*		*Ba*	*Washcoat Load*	*Comment*
Unit	*g/ft3*	*wt%*	*g/ft3*	*g/ft3*	*%*	*wt%*	*g/L*	
2004-01-0578 Mizuno							75	DPNR
Appl Catal B **45**(2003) 147-159 James		0.5	0			99.5		Powder
Appl Catal B **45**(2003) 147-159 James		5	0			10		Powder
Appl Catal B **31**(2001) 27-38 Amberntsson						X	160	JMI sample monolith, undefined PGM
Appl Catal B **22** (1999) L241-L248 Engstrom	62		0	30		19	160	Model Monolith
Appl Catal B **46** (2003) 429-439 Amberntsson	50	1	0	0	0	13	122	Model cats; need Pt+Rh (low of range tested)
Appl Catal B **46** (2003) 429-439 Amberntsson	200	4	0	75	1.5	13	122	Model cats; need Pt+Rh (high of range tested)
2004-01-0080 Fridell	100	2	0	50	1	20		Model monoliths
2003-01-1158 Nakatsuji	100	2	0				300	Also unspecified storage compounds; 2 layers
2001-01-0510 Geckler	110		43	11				
Average	104	2	5	33	1	15	157	
min	50	1	0	0	0	10	75	
max	200	5	43	75	2	20	300	

SCR

Source	PGM	*V*	*W*	*Base metal zeolite*	*Base Metal*	*Perovskite*	
2004-01-1291 Lambert	0	0	0	0			
2004-01-1294 Palmqvist	0				0	0	Unspecified materials
2003-01-0774 Scarnegie	0	0	0				Unspecified loading

DOC

Source	*Pt*	*Comment*
Unit	*g/ft3*	
932719 Fredholm et.al.	2.5-40	Loading study
1999-01-0471 Mogi et.al.	5.7-57	Loading study
98015 Uneo et.al.	14	Compared Pt to Pd
930130 Wyatt et.al.	40	Compared Pt to Pd
Average	27	
min	14	
max	40	

Note: rule of thumb 1% load ~ 50 gm/ft3 ~ 1.77 g/L

Our estimates				
LNT Pt Loading	50	g/ft3 =	1.77	g/L
LNT Rh Loading	10	g/ft3 =	0.35	g/L
SCR PGM Loading	0	g/ft3 =	0	g/L
DOC Pt Loading	20	g/ft3 =	0.71	g/L

PGM Loading Base Assumption

Loading, g/L	DOC	LNT	Urea SCR
Pt	0.71	1.77	0.00
Pd	0.00	0.00	0.00
Rh	0.00	0.35	0.00

Catalyst Volume (Displacement Ratio)

Source	DOC	LNT	4WC	SCR	DPF	Engine (L)	Stds	Notes
2004-01-1291 Lambert	0.9			2.0		1.8	ULEV	
2004-01-1791 McDonald	1.0		1.4			2.0		Veh A, Toyota DPNR
2004-01-1791 McDonald		2.0			1.3	1.9		Veh D, Audi A4/FEV
2004-01-1425 Herrmuth		1.4			2.1	1.2		AVL System 1
2004-01-1425 Herrmuth	1.0	1.4			2.1	1.2		AVL System 2
2004-01-1425 Herrmuth	1.0		2.1			1.2		AVL System 3
2004-01-1290 Hofman				2.8		12.0		SINOx system
2004-01-0153 Geering				2.0		10.0		
2004-01-0155 Blakeman	0.9			0.9		10.0		SCR size study
2004-01-0155 Blakeman	0.9			1.3		10.0		
2004-01-0155 Blakeman	0.9			1.7		10.0		
2004-01-1316 Abe	0.3					2.2	Eu-IV	HC-SCR = 1X Honda
2004-01-0585 Webb	0.7				2.6	6.6	Bin 5	SWRI dual leg (vols include both legs)
2004-01-1289 Blakeman	1.3			1.9	1.8	15.0	Tier II HD	JMI/Cummins - incl. Durability
2001-01-0510 Geckler		1.3				1.9		FEV deSOx study
2003-01-0774 Scarnagie				3.9	1.9	12.0		
2003-01-0041 Mital		1.8				5.9		Size study; larger did not help
2003-01-0041 Mital		1.8			1.5	1.7		also 0.7 SOx trap
Average	**0.9**	**1.6**	**1.7**	**2.0**	**1.9**	**5.9**		
Min	**0.3**	**1.3**	**1.4**	**0.9**	**1.3**	**1.2**		
Max	**1.3**	**2.0**	**2.1**	**3.9**	**2.6**	**15.0**		

Our estimates	*DOC*	*LNT*	*SCR*
Normalized Volume	0.5	1.5	1

Volume Base Assumption

DOC	LNT	Urea SCR
0.5	1.5	1

PGM Cost

Metal	Price, U.S. $ per gram
Pt	27.1
Rh	26.4

Data from Johnson Matthey's web site

http://www.platinum.matthey.com/

The price used was obtained by averaging the monthly average prices from January 2004 through August 2004

PGM Cost Difference per Vehicle

	2.0L Vehicle		6.5L Vehicle	
Catalyst	**LNT System**	**Urea SCR System**	**LNT System**	**Urea SCR System**
DOC	$19	$19	$62	$62
LNT	$172	$0	$558	$0
SCR	$0	$0	$0	$0
Total	**$191**	**$19**	**$621**	**$62**
Difference	**$172**		**$558**	

- Costs shown are PGM cost only
- Washcoat cost, canning, cones etc. not included
- Cross check:
  - 5.4 grams per vehicle in 2003 or ~$95
  - Smyth paper: 3-6 times PGM on LNTs, $300-600 per average car

Sales Volume Assumption

Source	Reference	Diesel Personal vehicles		Diesel Light comml veh		Total light vehicle	
		Sales %	units	Sales %	units	Sales %	units
JD Power	(18)	5.8	1877700	54.6	975000	14.7	3020000
Smyth	(9)			17			
NREL/TIAX	(14)						
	Pass car	0.9	6200		Personal	26	182200
(References EPA	LD truck	25.2	176000				
MOBILE 6 EPA420-	MD truck	14.2	99000		LCV	25	178000
R-01-047)	LHD	11.3	79000				
	HHD	48.4	338000				
	Total	100.0	698200				
					total light		360200
Ward's Auto.Com	(8)						
	2003 light truck diesel engine sales		315,767				
Our estimate	Assume JD Power penetration		5.8	% of vehicles			
	Assume constant industry volume		16600000				
	Diesel sales		962800				
	Round to		1	million units in 2010			

Fleet PGM Cost

Vehicle	Volume (000)	Unit Cost Difference	Fleet Cost Difference
Car	200	$172	$34,364,254
<8500 Truck	200	$558	$111,683,825
>8500 Truck	600	$558	$335,051,474
Total	**1000**		**$481,099,553**

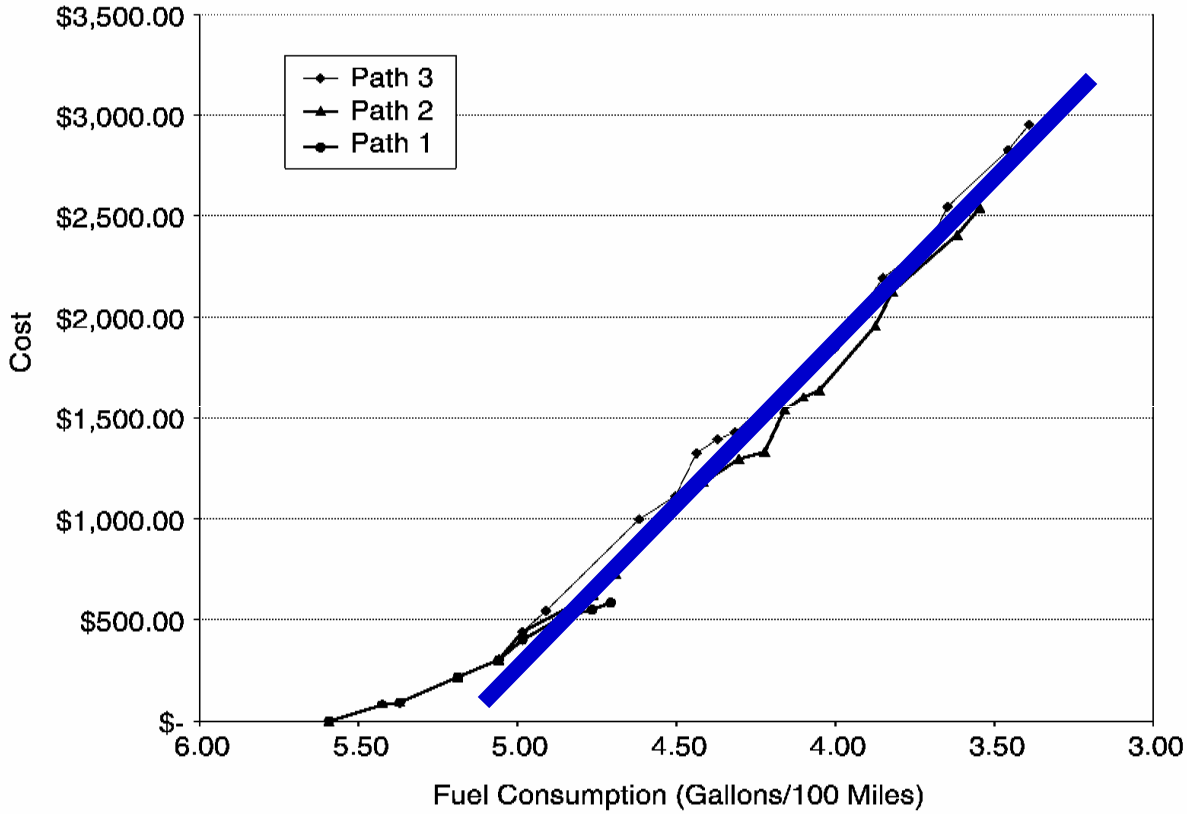
- Single year production cost (given assumptions)
- Will recur each year – or increase with volume

CAFE Cost

Assumptions:

- 5% FE loss with LNT
- Volumes as above
- The manufacturer needs to hold CAFE
  - Thus, must take actions on other vehicles to increase FE
  - These actions cost the manufacturer

Cost to Improve Fleet FE



Transportation Research Board of the National Research Council. National Academy Press, ISBN 0-309-07601-3, **2002.** Also available at *http://books.nap.edu/books/0309076013/html/index.html*

Fleet CAFE Cost

Row	Item	Units	Compact Car	<8500 Truck
1	**Slope**	$ per gal/100 mi	$1,709	$1,667
2	**(Reference)**	$ per L/100 km	$724	$706
3	**Base FE**	L/100 km	8.1	10.5
4	**(Reference)**	mpg	28.9	22.4
5	**5% of Base FE**	L/100 km	0.41	0.53
6	**Cost per Vehicle**	$	$295	$371
7	**2010 Volume**	(000) units	200	200
8	**CAFE effect**	$	$58,960,500	$74,181,500
9	**Fleet Estimate**	$	**$133,142,000**	

- Single year production cost (given assumptions)
- Will recur each year – or increase with volume
- Might be less if the manufacturer is not CAFE constrained

Cost of Ownership

- LNT vehicles will use more fuel than SCR
- SCR vehicles will use urea
- Calculate cost difference over vehicle life based on
  - Base vehicle fuel consumption
  - Fuel and urea costs
  - Per vehicle, then for fleet

Vehicle Operating Cost

Vehicle Fuel Consumption	SCR Urea and Fuel	LNT Fuel	Difference
L/100 km	$	$	$/Vehicle Life
5.88	4572	4706	134
9.41	7315	7530	215

Fleet Lifetime Cost

Vehicle	Volume	Fuel Cost Difference	Fuel Cost Difference
	(000) units	$/Vehicle Life	$ for Fleet
Car	200	134	26,893,944
Truck	800	215	172,121,242
Total	**1,000**		**199,015,186**

- Assumes $1.50/gal fuel and urea cost
- Cost spread over 120k mile lifetime of vehicles
- Paid by customers at fuel/urea fill
- Repeats with each future model year

Urea Dosing System

- Consists of
  - Storage tank
  - Co-fueling refill system onboard components
  - Pump and metering system
  - Required sensors such as tank level
  - Heaters to prevent freezing
  - Controls integrated in powertrain control module
- No published cost estimates available
- We estimate $250 or less in high volume production

HC Dosing System

- Injects fuel into exhaust system
  - Enrichment in selected modes
  - Engine-only enrichment causes excessive oil dilution
- Consists of
  - Pressure regulator off existing fuel system
  - Metering nozzle
  - Controls integrated into powertrain control module
- No published cost estimates available
- We estimate $100 or less in high volume production

Vehicle Costs Summary

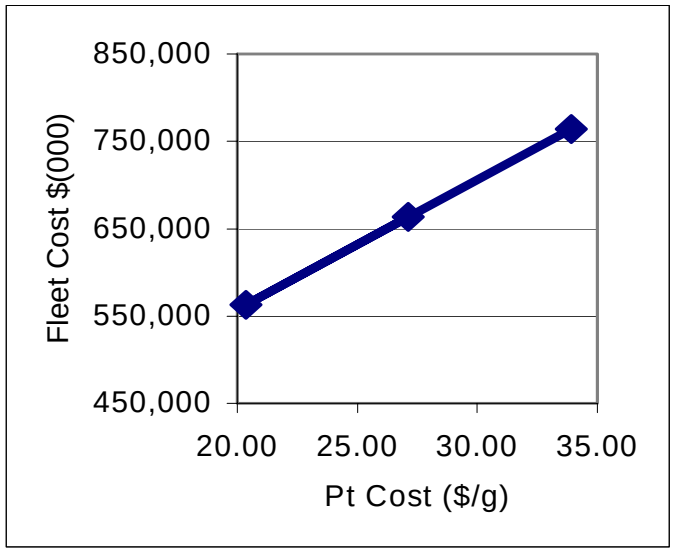
Cost Item	Fleet Cost Difference
	$(000)
Fuel/Urea Lifetime Usage	199,015
PGM Usage	481,100
CAFE Compliance	133,142
Urea Dosing System (SCR Only)	-250,000
HC Injection System (LNT Only)	100,000
Total	663,257

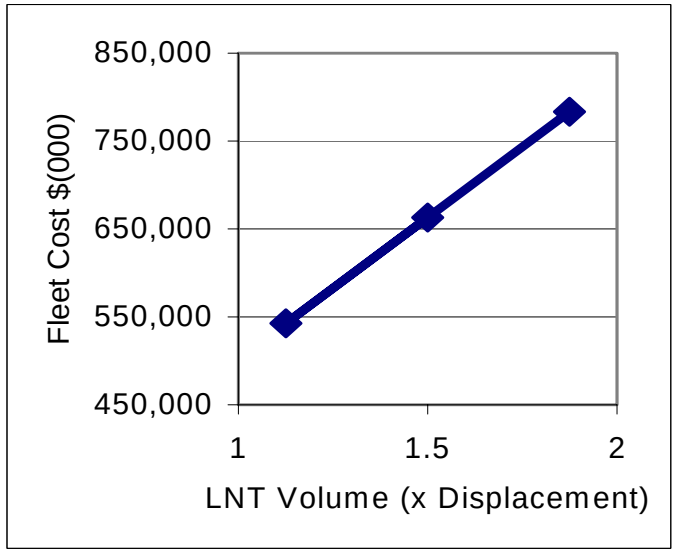
- Cost to the country (industry and consumers) more $0.6 billion *per year* for LNT over SCR

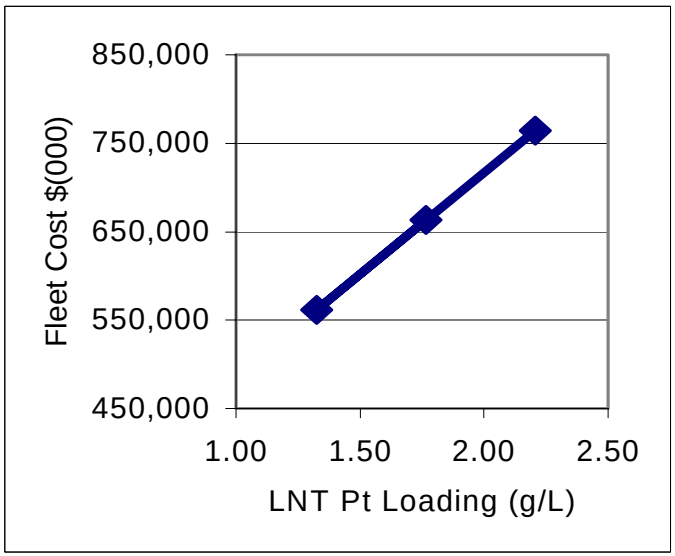
Sensitivity

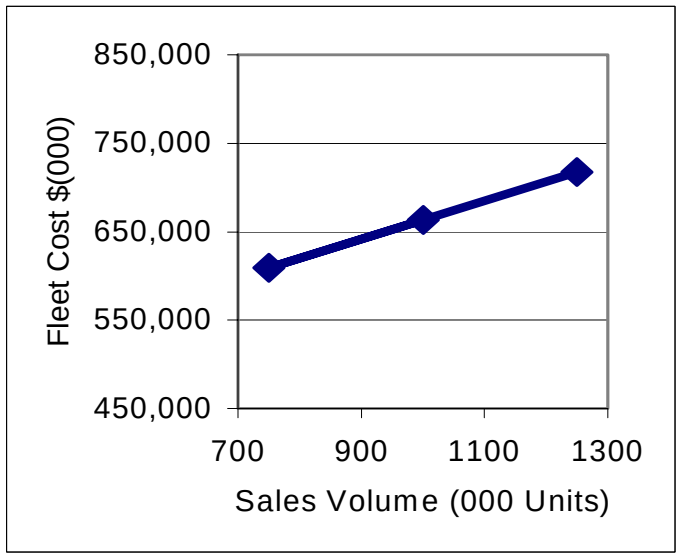
- Many assumptions were made in this analysis
- Is the answer robust to those assumptions?
- Varied each assumption +/- 25%

Sensitivity









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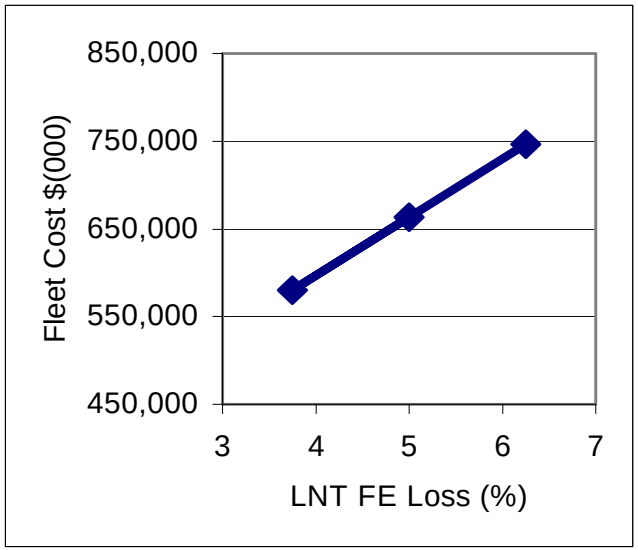

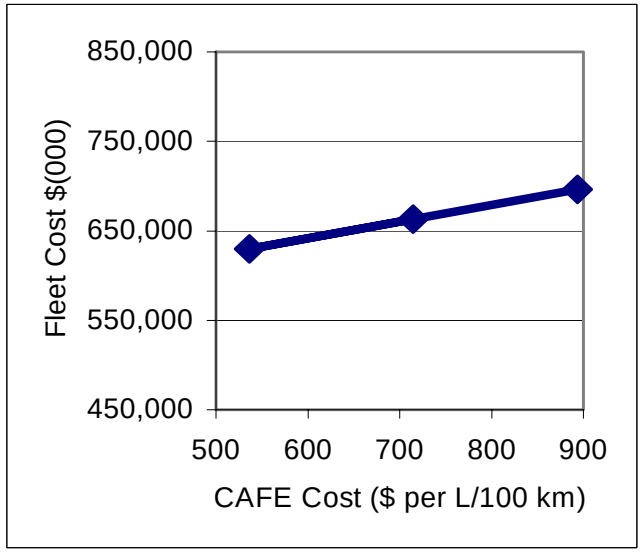

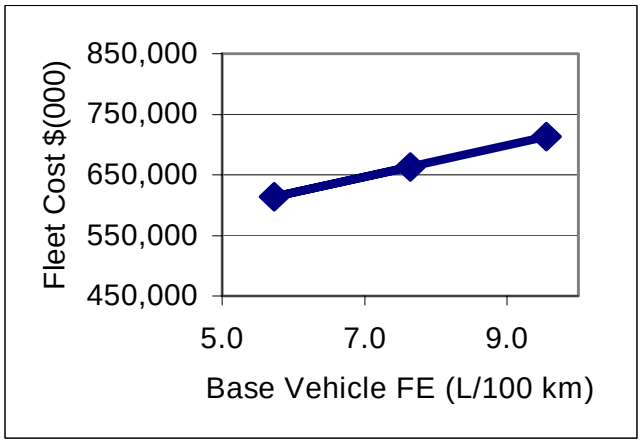

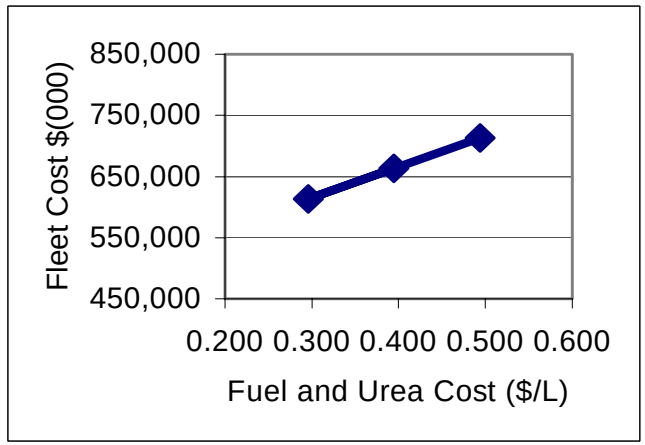

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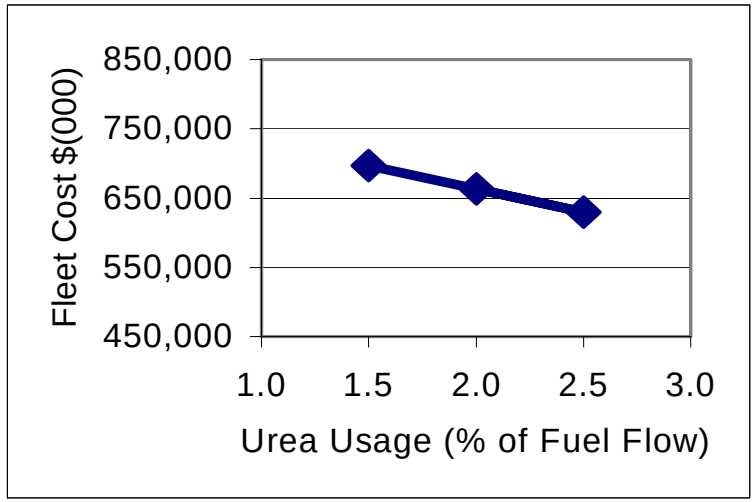

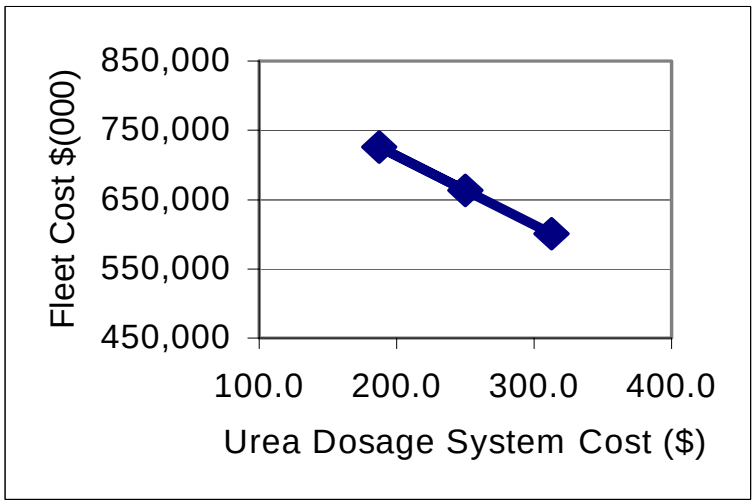

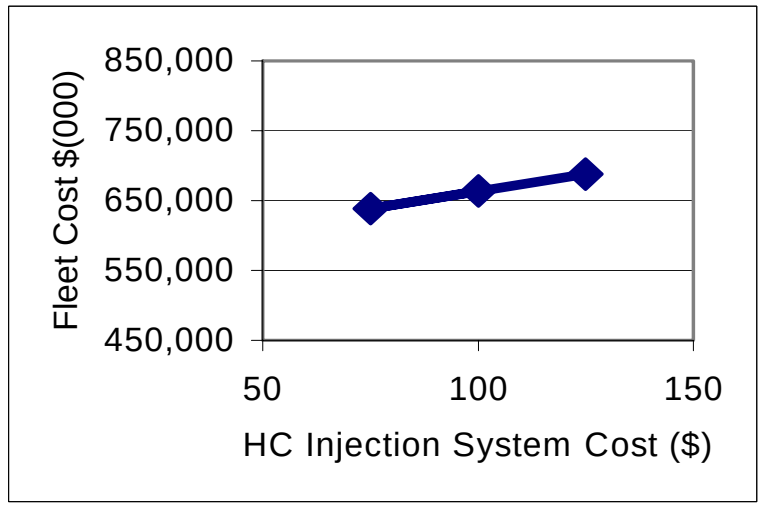

Urea Infrastructure Cost

- Assume co-fueling
- Initially, investment cost outweighs urea cost
- More analysis in accompanying paper
- Here, two methods used to estimate investment cost
  - One based on TIAX study data
  - One based on our own estimate

TIAX Study

- Study of urea infrastructure for Class 7 and 8 trucks
- Most diesel fuel sold by small number of stations
- Larger number of stations that sell smaller quantities
- Study assumes stand alone urea dispensers, not co-fueling
- $25K to $200K per station
  - Depends on size of station, number of pumps
  - Various distribution and dispensing methods
- Use their capital cost to estimate total cost

TIAX LLC, “SCR-Urea Infrastructure Implementation Study Final Report”, TIAX reference number D5197, July 30, 2003.

Estimate from TIAX Data

No. Stations	Fraction Sales	$(000) per station	Cost $(000)
2,200	77	200	440,000
3,500	20	100	350,000
25,000	3	25	625,000
Total			**1,415,000**

- About $1.4 billion to cover stations selling 85% of diesel fuel
- Remember, data is for Class 7 & 8 trucks!

Authors' Estimate

- Input data:
  - Number of fuel stations
  - Fraction of stations selling diesel
  - Assume $25K per pump to convert an existing diesel dispenser to a co-fueling pump
    - Modified dispenser, hoses, nozzle
    - Urea tank
    - Heaters to prevent freezing
    - Possible electrical power upgrade, etc.
  - Average two pumps per station
    - TIAX stated that larger stations have 5, smaller stations one pump

Authors' Estimate

Item	Value	Source
No. Stations	195,455	NPN Market Facts: 120, July 15, 2000
Fraction selling diesel	13.7%	NPN Market Facts: 91(8) 121, July 15, 1999
Diesel Stations	26,777	
Average No. Pumps	2	TIAX: 5 truck stops, 1 small
Cost per pump (assumed)	$25,000	Author's estimate of capital cost
Total capital cost	**$1,338,866,750**	

- About $1.3 billion to cover stations selling diesel fuel
- Based on loose estimates!

Discussion

- Estimates of LNT cost over SCR were made
  - Based on published information
  - Effect of added costs on sales volume not included
  - Over $0.6 billion higher cost for LNT
- Estimates of urea infrastructure cost
  - Range $1-2 billion
  - More data in another paper (Hammerle et.al.) in this conference
- Although co-fueling infrastructure cost is large, it would repay in a few years, with large net savings after that
- Less capital intensive urea infrastructures pay back faster

Conclusions

- Urea SCR systems are expected to be significantly lower cost than LNT systems
  - Over $600 million
- Urea infrastructure and means to assure an onboard urea supply are required