
Westport™
Here and Now.
METHANE – THE PERFORMANCE FUEL

U.S. Transportation Energy Insecurity

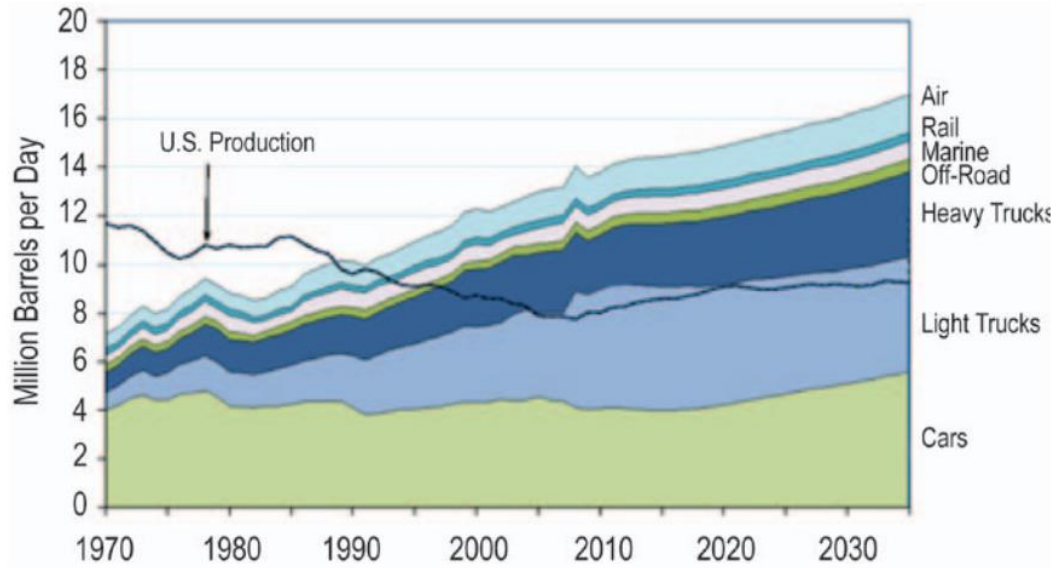
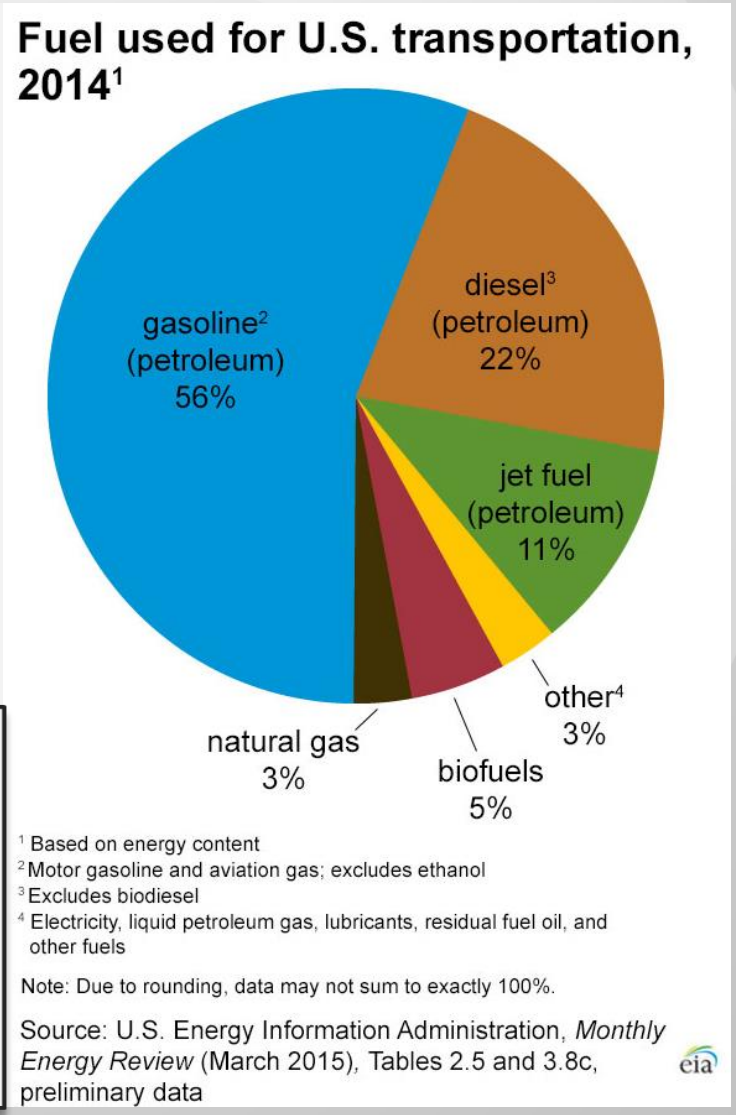


Figure 1.1-1. Transportation Energy Use by Mode, through 2035.

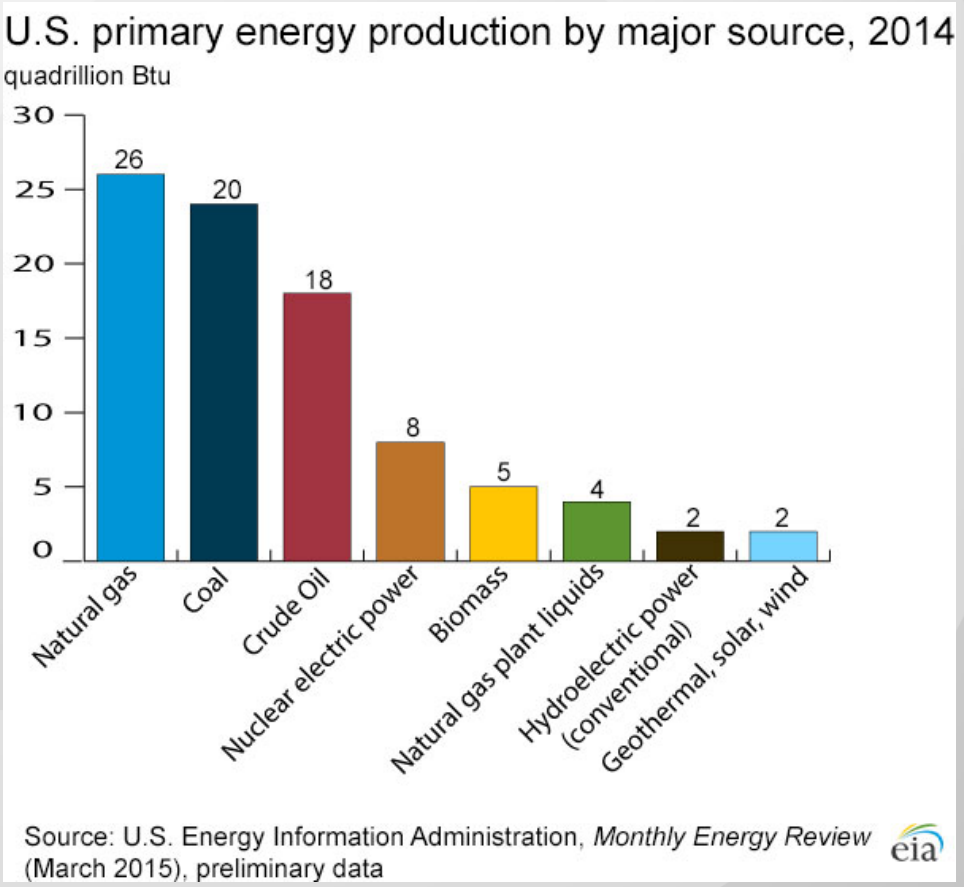
Sources: Historical information from Transportation Energy Databook 28, forecasts from the Energy Information Administration Annual Energy Outlook 2010.



- 92% of transportation powered by petroleum
- 60% of transportation fuel is finished motor gasoline (including ethanol), mainly used in cars and light trucks
- 3% of transportation powered by natural gas

NG is Most Abundant US Energy Source and Cleanest for Fuel for Transportation

- Natural gas is only viable fuel replacement for transportation petroleum that has required scale
- Renewable fuel pathway by substituting up to 100% biomethane
- Why have we surrendered 60% of the transportation sector reliant on gasoline?



Paradigm Shift Required for Light Duty

- ☑ Reduced fuel costs
- ☑ Reduced emissions
- ☒ Less performance than gasoline and diesel
- ☒ Lower efficiency
- ☒ Compromised utility
- ☒ Price premium

- ☑ Reduced fuel costs
- ☑ Reduced emissions
- ☑ More performance than gasoline and diesel
- ☑ High efficiency
- ☑ Same or better utility
- ☑ Price advantage

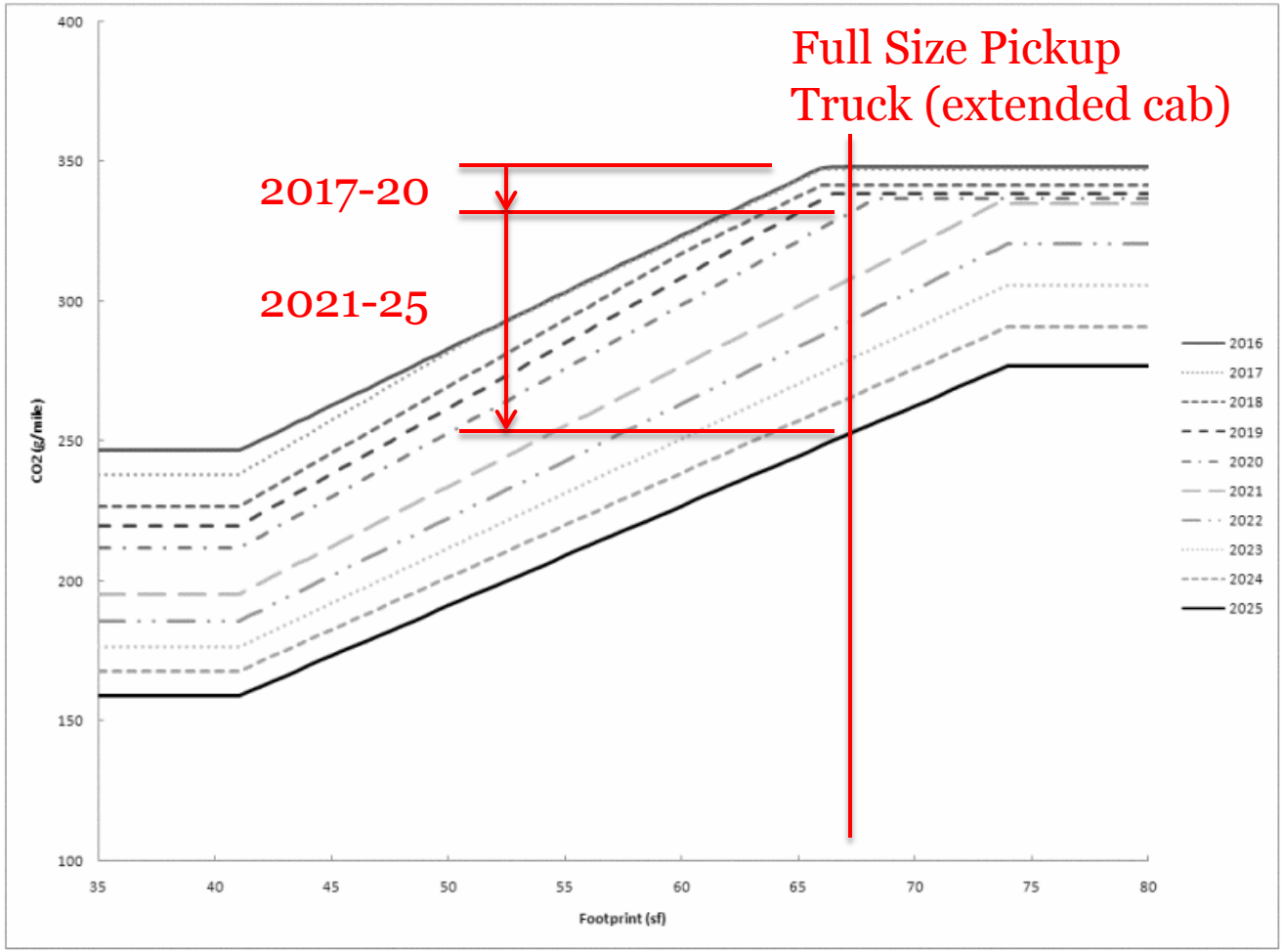
New Possibilities for Light Trucks & Cars Niche to Mainstream – How?

1. Advanced powertrains that fully exploit ultra high-octane low-carbon fuel properties of methane
   a. Not been done to-date – missed opportunity
   b. High efficiency and high performance at the same time – outperform gasoline and diesel
   c. >30% CO_2 reduction TTW* (up to 90% with biomethane WTW)
2. Conformable CNG tanks and low cost gas compression (e.g. ARPA-E MOVE Program)
3. Phase 2 EPA/NHTSA rules (2017-25)
   a. Become particularly challenging starting in 2021 for light trucks
   b. Conventional gasoline and diesel increasingly challenged
   c. Electrification is an option, but adds cost and may not be preferred approach for certain market segments

* Compared with advanced gasoline engines

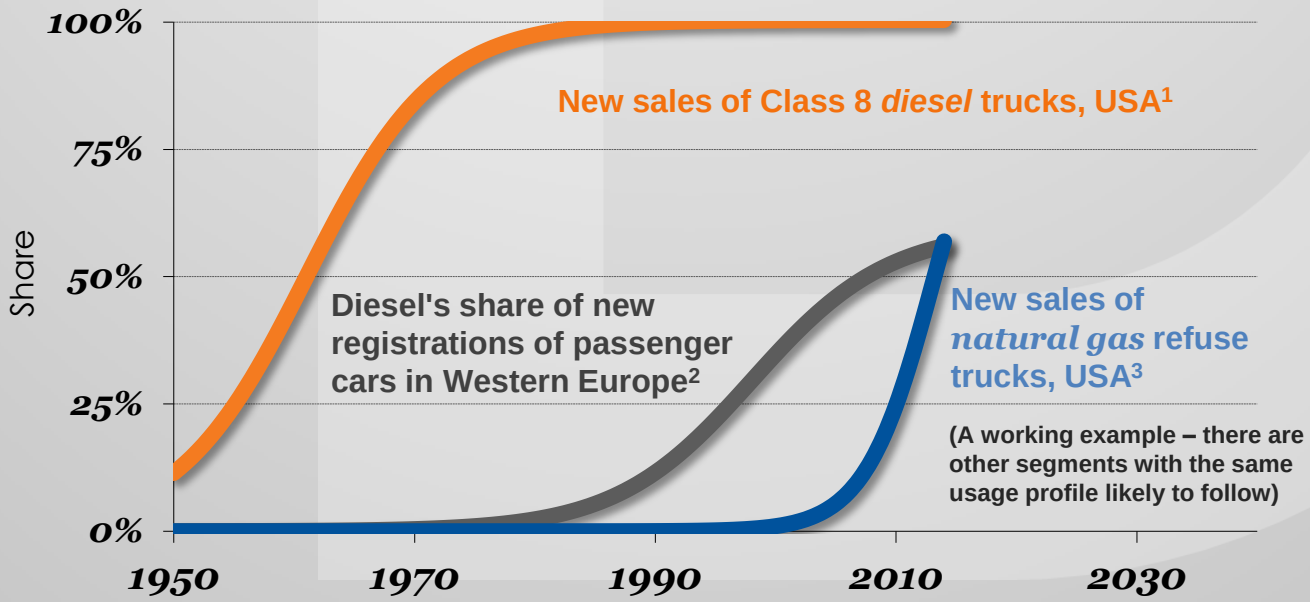
Deep CO2 Reductions Starting 2021

Figure I-4 CO2 (g/mile) Light-Truck Standard Curves



We Have Seen A Complete Market Shift Before

- In 1950 diesel powered trucks cost more and were heavier than gasoline trucks, yet the market shifted 100% to diesel within 2 decades. Why?
- A new paradigm of high productivity with low operating costs meant fleets needed to make the change or go out of business.
- The same 100% shift happened a decade earlier in locomotives; steam to diesel.
- Signs of a market shift to natural gas are appearing (e.g. refuse truck segment).



1. *MacKay & Co., & Wards Auto Group, a division of Penton Media, Inc.*
2. *ACEA*
3. *Westport*

Diesel Cars in Europe – Then and Now

Diesel cars in the 1980's

All about fuel cost savings
< 5% market share

Diesel cars today

All about performance with added benefit of low CO2 and fuel costs
> 50% market share

Consequences of VW's Actions

Volkswagen's falsification of pollution tests opens the door to a very different car industry

Sep 26th 2015 | The Economist From the print edition

"…Some fear that this may be the "death of diesel". So be it. There is still scope to improve the venerable petrol engine; and to switch to cleaner cars that run on methane, hydrogen and electricity, or are hybrids. A multi-billion-dollar race is already under way between these various technologies, with makers often betting on several of them as the way to meet emissions targets."

CNG Passenger Cars – Now and Future

CNG Cars Today

All about fuel cost savings
< 5% market share

Advanced Methane Cars Tomorrow

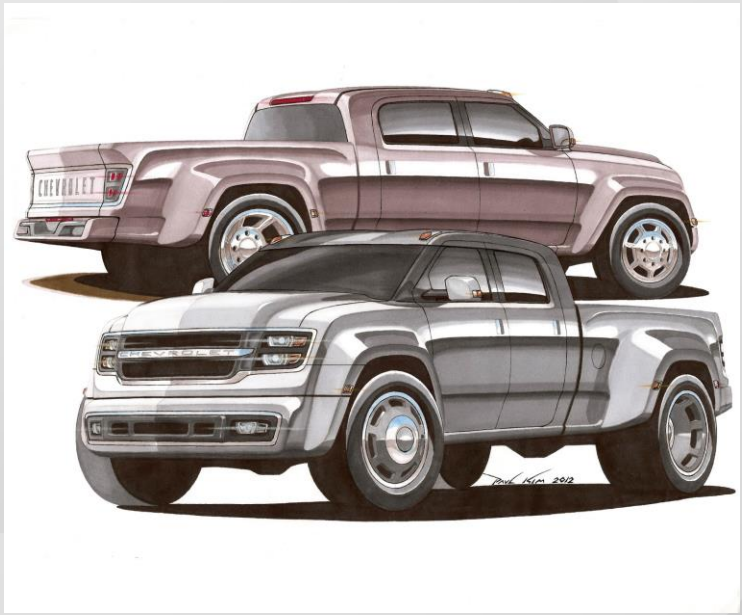
All about performance with added benefit of low CO_2 and fuel costs
> 50% market share

CNG Pickup Trucks – Now and Future

CNG Pickups Today

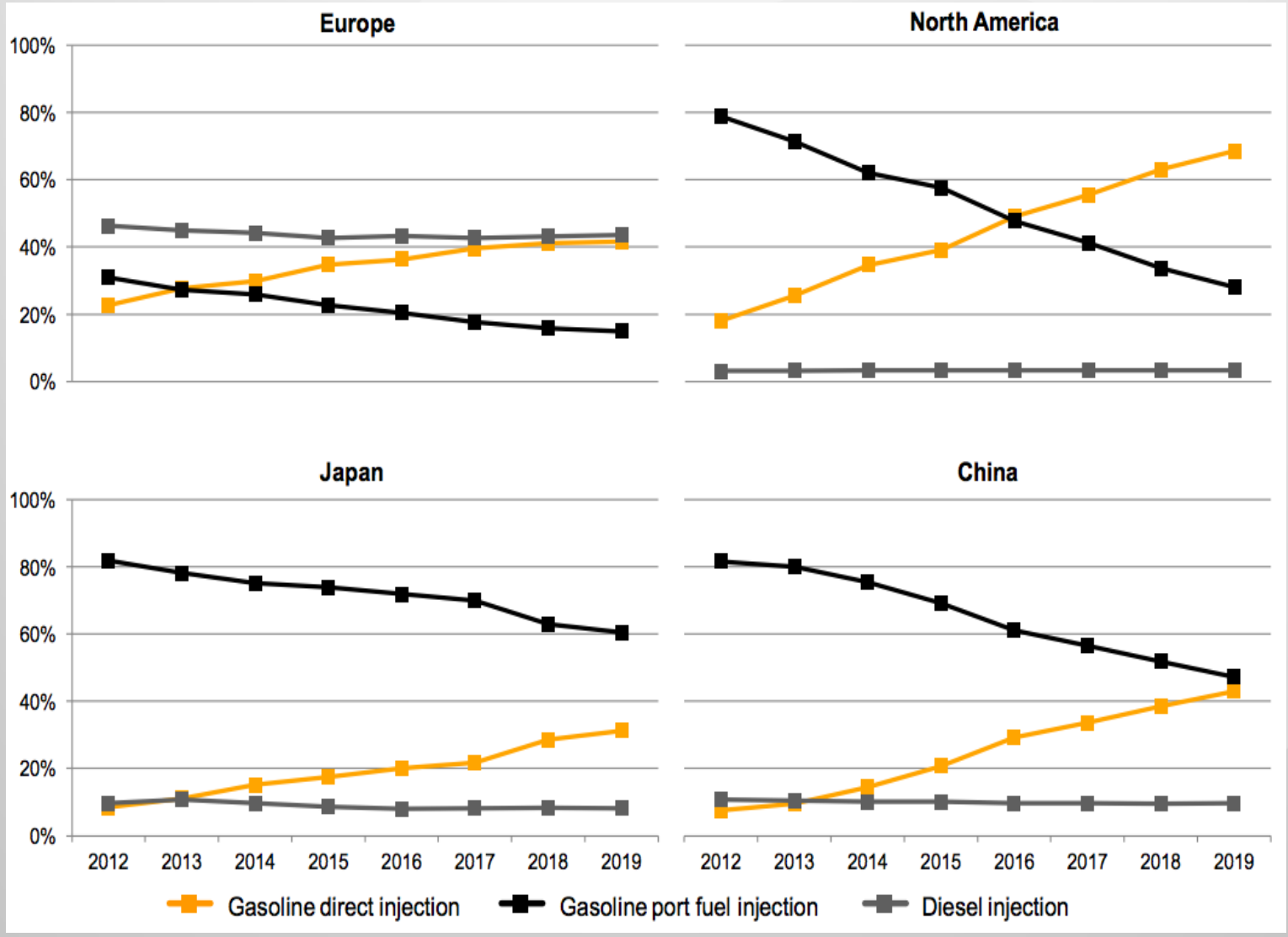
All about fuel cost savings
< 5% market share

Advanced Methane Pickups Tomorrow



All about performance with added benefit of low CO_2 and fuel costs
> 50% market share

Industry Megatrend: PFI to Turbo GDI Global Passenger Cars and Light Trucks



(Source: Continental Fact Book 2014)

Fuel Economy & Performance are Driving the Global Shift to Turbo GDI

2015 Chevrolet Silverado C15 2WD	2015 Ford F150 Pickup 2WD	2015 Ram 1500 2WD
Gasoline Vehicle	Gasoline Vehicle	Diesel Vehicle
		
5.3 L, 8 cyl, Automatic 6-spd	2.7 L, 6 cyl, Automatic (S6), Turbo	3.0 L, 6 cyl, Automatic 8-spd, Turbo
MSRP: $26,105 - $47,875	MSRP: $25,800 - $51,650	MSRP: $25,660 - $49,980
Regular Gasoline	**Regular Gasoline**	**Diesel**
19 combined city/highway MPG 16 city 23 highway 5.3 gal/100mi	**22** combined city/highway MPG 19 city 26 highway 4.5 gal/100mi	**23** combined city/highway MPG 20 city 28 highway 4.3 gal/100mi
Gasoline	Gasoline	Diesel
494 miles Total Range	506 - 792 miles Total Range	598 - 736 miles Total Range

Source: U.S. DOE and EPA http://www.fueleconomy.gov/

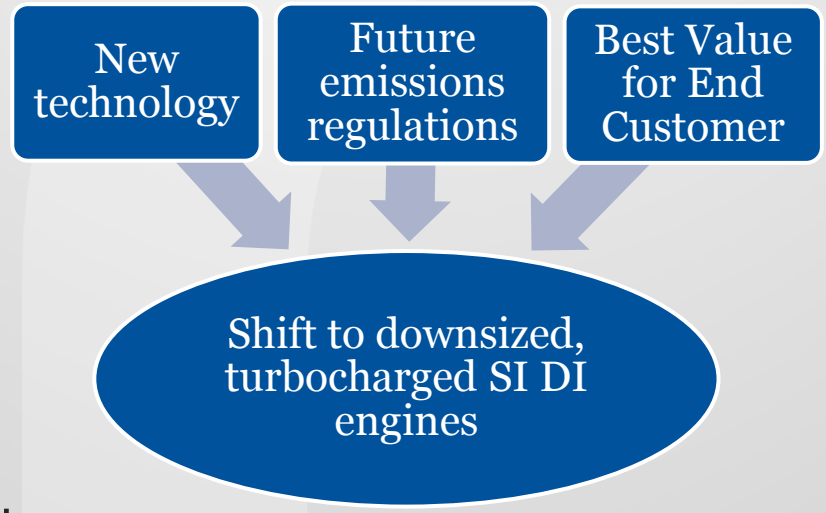
Fuel Economy & Performance are Driving the Global Shift to Turbo GDI

Jan 30, 2015	2015 Chevrolet Silverado 1500 LTZ Z71	2015 Ford F-150 Lariat 4x4	2014 Ram 1500 Outdoorsman EcoDiesel 4x4
POWERTRAIN/CHASSIS			
DRIVETRAIN LAYOUT	Front-engine, 4WD	Front-engine, 4WD	Front-engine, 4WD
ENGINE TYPE	90-deg V-8, aluminum block/heads	Twin-turbo 60-deg V-6, iron block/alum heads	Turbodiesel 60-deg V-6, iron block/alum heads
VALVETRAIN	OHV, 2 valves/cyl	DOHC, 4 valves/cyl	DOHC, 4 valves/cyl
DISPLACEMENT	325.1 cu in/5,328 cc	164.4 cu in/2,694 cc	182.3 cu in/2,988 cc
COMPRESSION RATIO	11.0:1	10.0:1	16.5:1
POWER (SAE NET)	355 hp @ 5,600 rpm*	325 hp @ 5,750 rpm	240 hp @ 3,600 rpm
TORQUE (SAE NET)	383 lb-ft @ 4,100 rpm*	375 lb-ft @ 3,000 rpm	420 lb-ft @ 2,000 rpm
TEST DATA			
ACCELERATION TO MPH, UNLADEN; TOWING 7,000-LB TRAILER			
0-30	2.3; 5.7 sec	2.4; 5.0 sec	2.6; 5.2 sec
0-40	3.5; 8.9	3.5; 7.5	4.3; 9.0
0-50	5.2; 13.6	4.9; 11.5	6.3; 14.5
0-60	6.9; 19.5	6.5; 16.2	8.8; 23.9
0-70	9.4; -	8.6; 22.2	11.8; -
0-80	12.2; -	11.2; -	16.0; -
0-90	15.5; -	14.2; -	20.8; -
PASSING, 45-65 MPH	3.6; 15.5	3.2; 9.4	5.1; 21.2
QUARTER MILE	15.4 sec @ 89.8 mph; 22.0 sec @ 62.3 mph	15.1 sec @ 92.8 mph; 20.7 sec @ 68.0 mph	16.6 sec @ 81.5 mph; 22.2 sec @ 58.7 mph
DAVIS DAM "FRUSTRATION"**	7.6 sec, 665 ft	6.0 sec, 524 ft	9.0 sec, 812 ft

Source: Motor Trend http://www.motortrend.com/roadtests/trucks/

Technology MegaTrend Enables Methane – The Performance Fuel

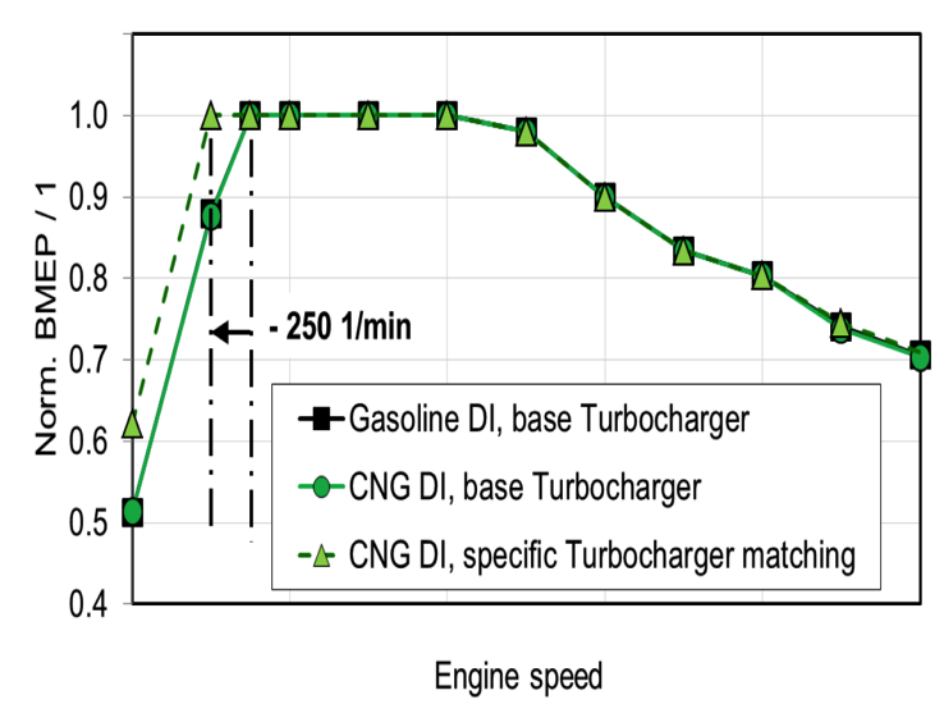
Global Passenger Car / Light Truck Market

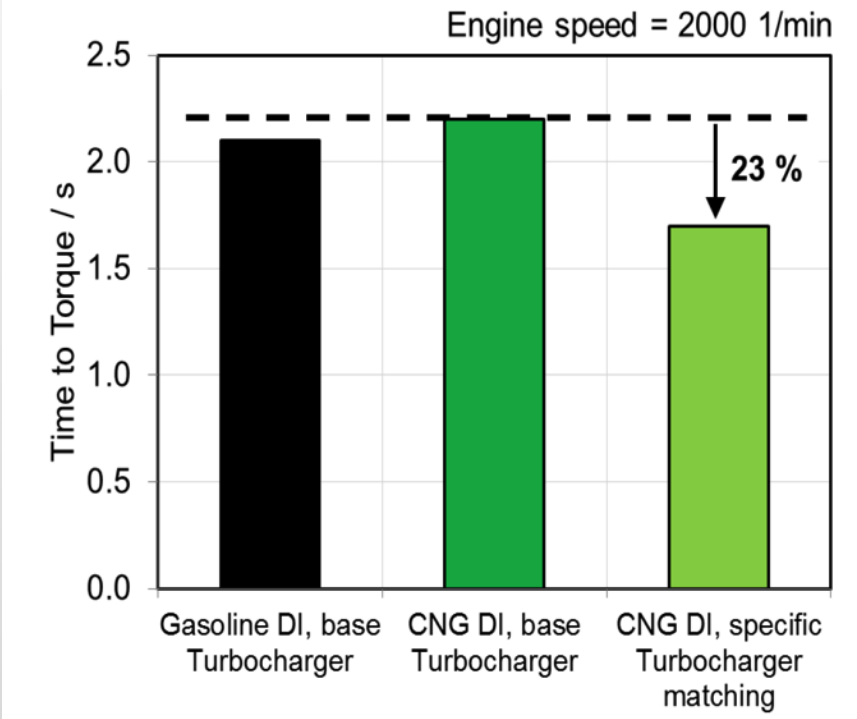


Impact for NGV Industry:

- Future NGVs will increasingly be based on turbo GDI platforms that must:
  a. operate without damaging GDI fuel system (i.e. when using PFI natural gas) or
  b. replace GDI fuel system with CNG DI – can exceed performance of gasoline
- Turbo GDI have limitations in fully exploiting methane's fuel properties

CNG DI can exceed GDI Base Engine Performance

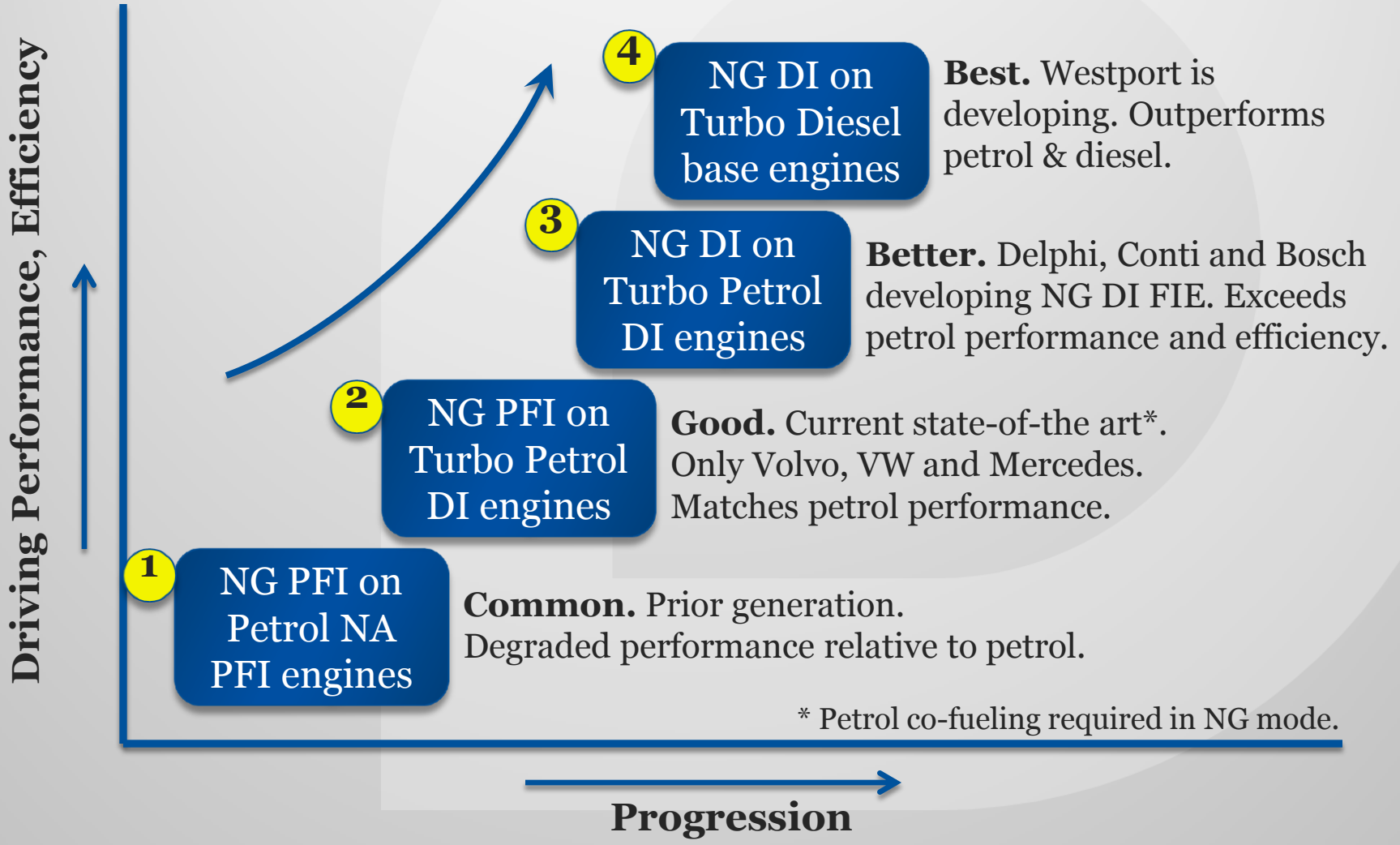




Engine full load performance with and without CNG DI optimized turbocharger and resulting time-to-torque comparison for Ford EcoBoost 1.0L engine using CNG DI system

(Source: CNG Specific Downsizing – Potentials and Challenges, Internationales Wiener Motorensymposium 2015, Ford Werke GmbH, Köln, FEV GmbH, Aachen)

Progression of Methane Powertrain Technology - Outperform Petrol, Diesel



Technology Trend
Convergence b/w Gasoline & Diesel

- New gasoline & diesel engine families designed with common elements for high boosting with 0.5 l per cylinder with common block, bore, stroke, bore centers, etc. and shared machining & assembly lines:
  - BMW's new modular Efficient Dynamics at Hams Hall, UK

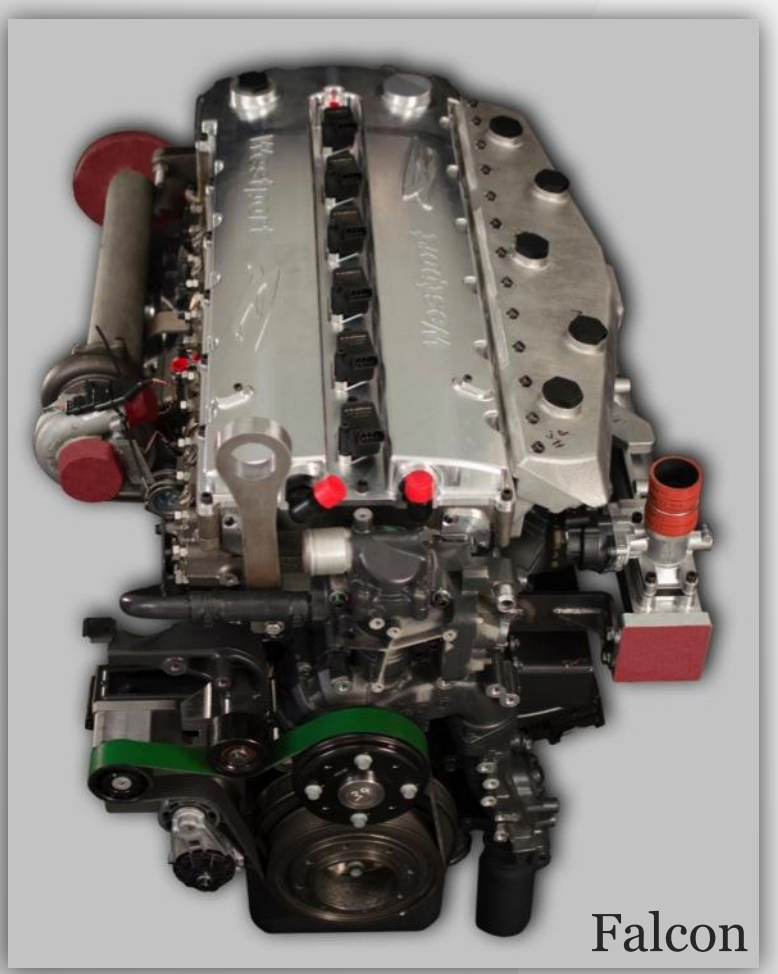
    https://www.press.bmwgroup.com/usa/download.html?textId=161119&textAttachmentId=198820
  - Volvo's Drive-E engine family at Skövde, Sweden

    https://www.media.volvocars.com/uk/en-gb/media/pressreleases/138421/volvo-cars-new-drive-e-powertrains-efficient-driving-pleasure-with-world-first-technologies9
  - Jaguar Land Rover's new Ingenium engine family at Wolverhampton, UK

    http://newsroom.jaguarlandrover.com/en-in/jlr-corp/news/2014/07/jlr_ingenium_engine_release_090714/

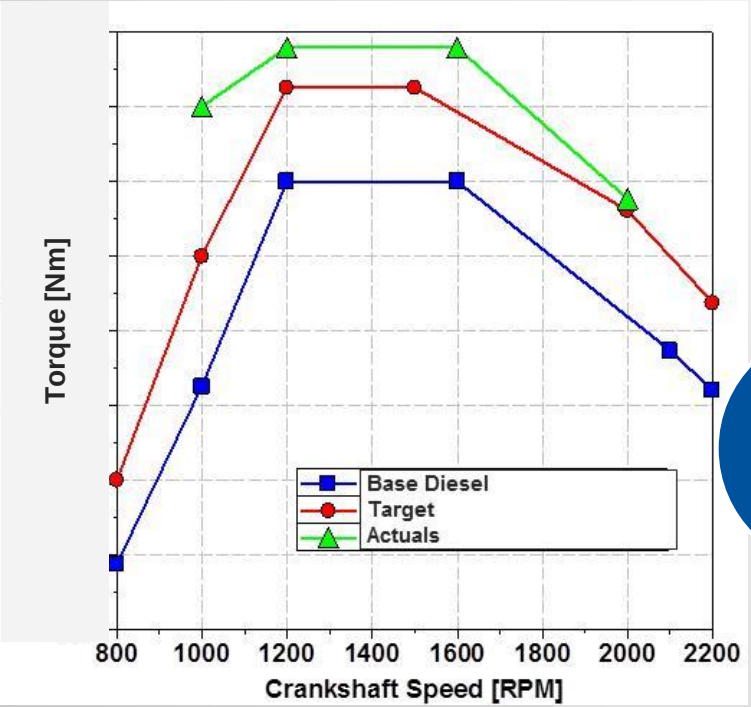
- Convergence trend ideal for fully exploiting ultra-high octane performance fuel properties of methane
- Higher cylinder pressure capability of diesel bottom end needed due to higher compression ratio and advanced combustion phasing with methane
- Gasoline engine elements such as cam phasing, ignition system, etc needed for Otto cycle combustion

Enhanced Spark Ignited Technology

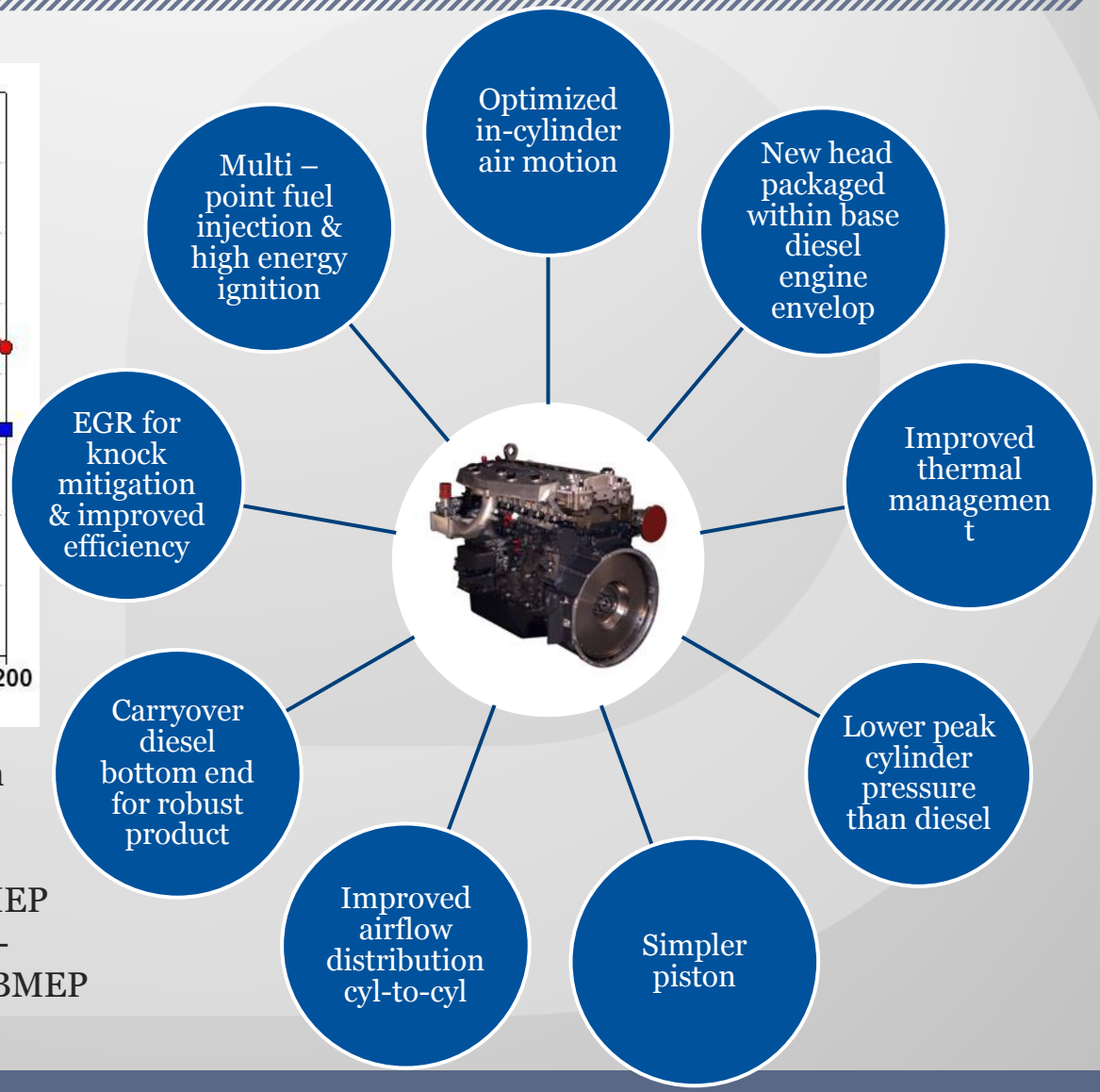


- September 2014, Westport unveiled its proprietary enhanced spark ignited engine technology
- First time SI NG engine exceeds diesel engine performance
- Redesign, optimization and downsizing provide significant fuel economy improvements
- Stoichiometric operation with EGR and simple 3-way catalyst
- ~ 15% engine + aftertreatment product costs savings vs diesel

Enhanced Spark Ignited Technology
System Elements

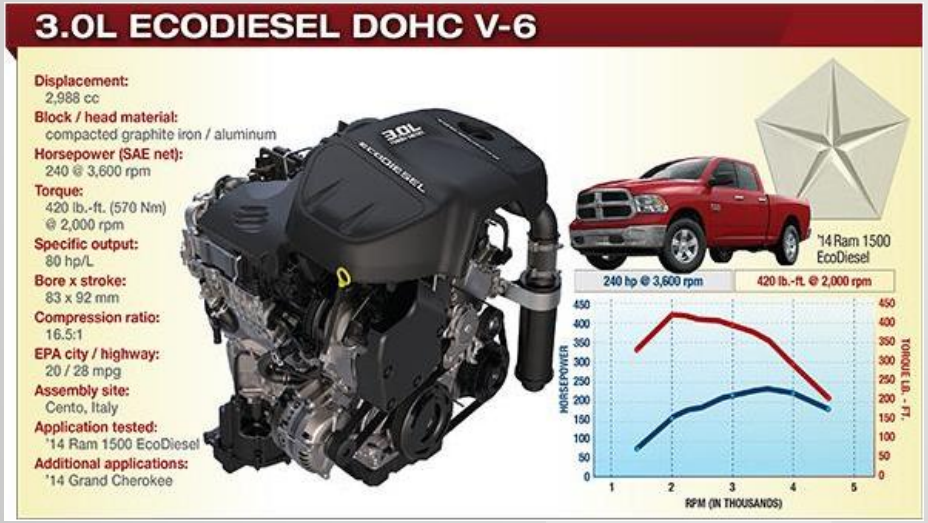


*Westport engine test data from a modern Brand X 7.XL diesel donor engine
Base diesel peak output @ 23 bar BMEP
Enhanced SI NG peak output > 25 bar BMEP
Current production state-of-the-art diesel-derived on-road NG SI engines 19-21 bar BMEP



Enhanced SI Performance Potential

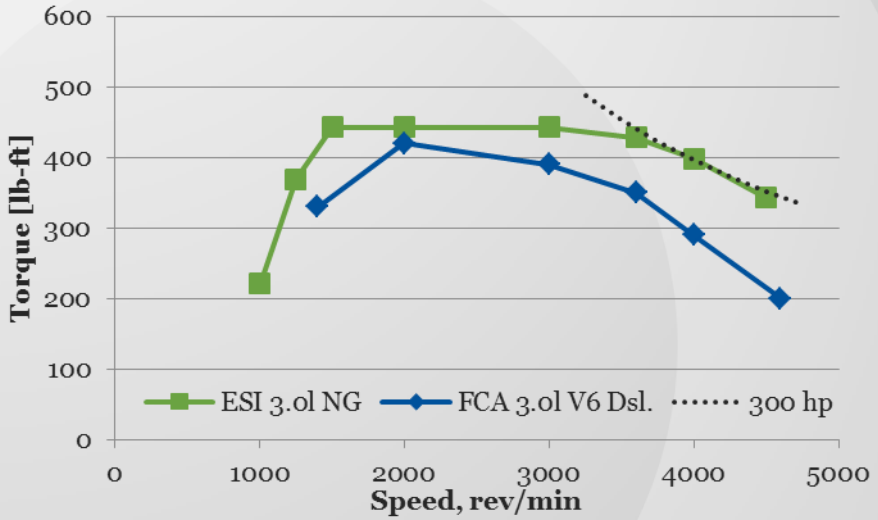
Example: Ram 1500

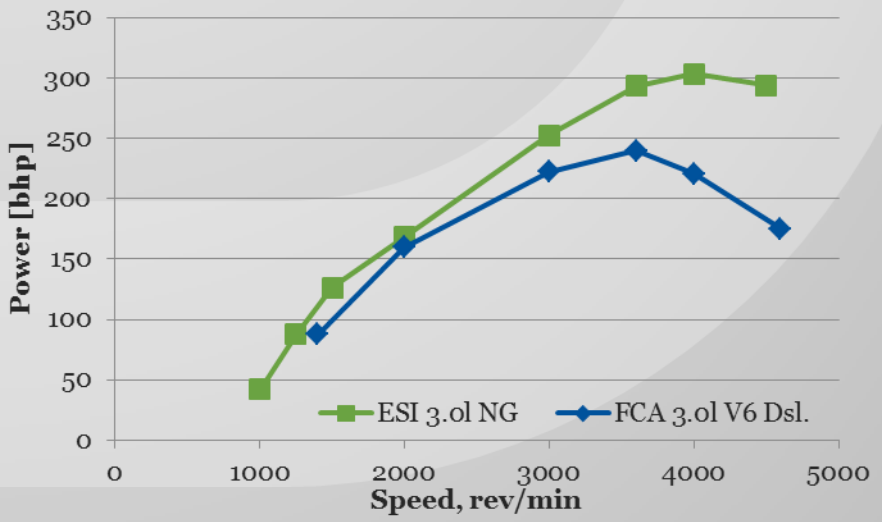


Source: Ward's Auto

ESI NG engines avoids expensive diesel:

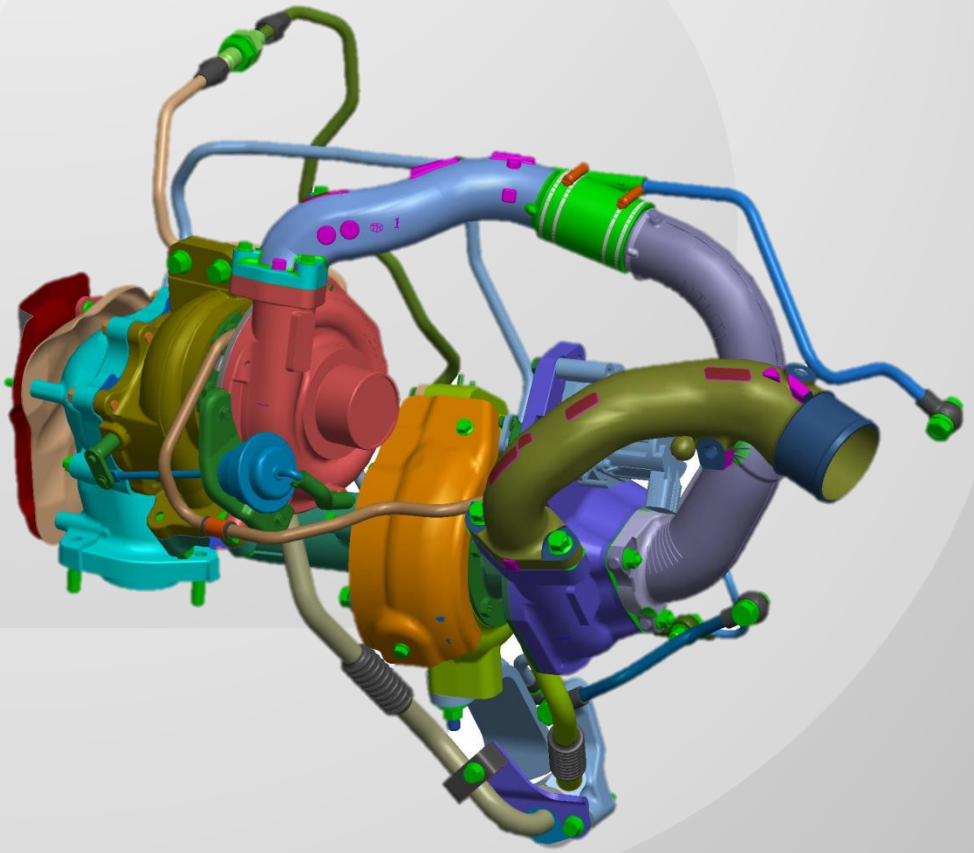
1. Aftertreatment (DPF and SCR)
2. Fuel injection equipment
3. Multi-stage variable geometry turbo-charging





Enhanced Spark Ignited Technology
Boosting System Example

- 2 stage turbocharger system (VGT & WG) on diesel can be replaced with single WG turbocharger



Turbo for Current Diesel Engine

Example Concept Study:
new medium duty diesel

Enhanced Spark Ignited Technology
Boosting System Example

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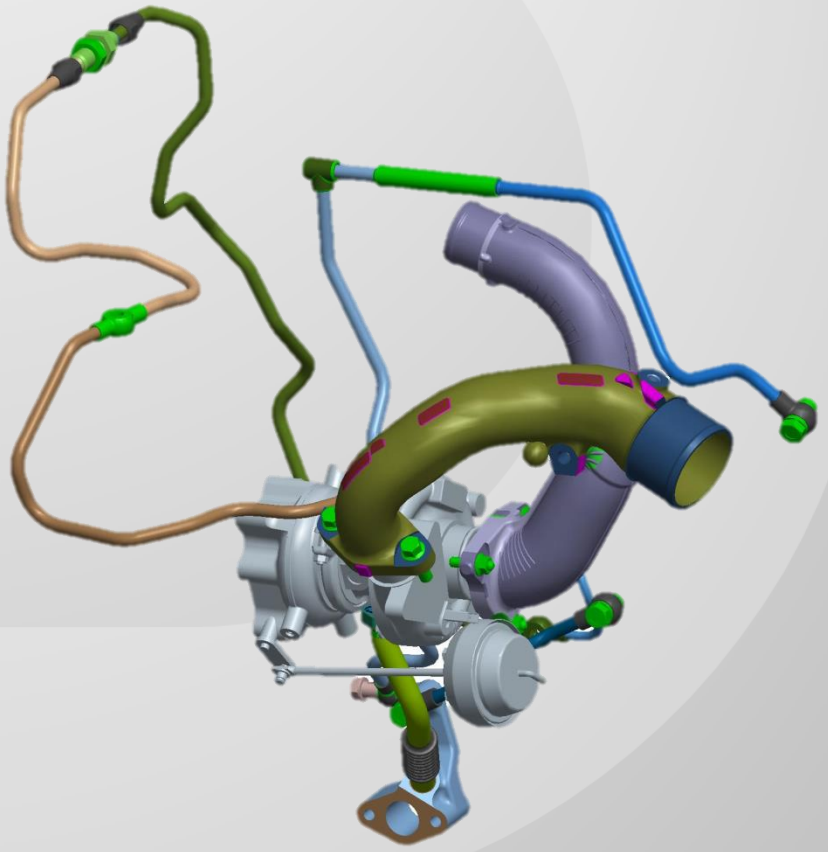
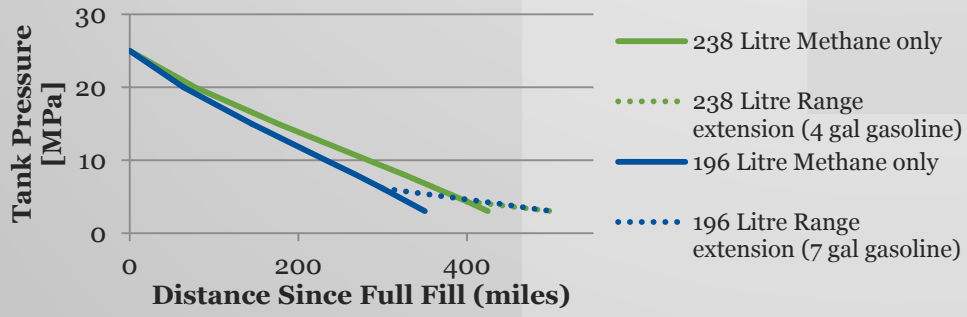


Example Concept Study:
new medium duty diesel

Turbo for NG Enhanced SI Solution

Optional Range Extension Mode

- Methane DI combined with petrol PFI offers knock tolerance / octane enhancement
- Reserve some methane for operation in range extension mode with majority of operation and fuel burned being gasoline (e.g. 75% gasoline / 25% methane)
- Gasoline tank in the 4-7 gallon range (similar size to DEF tank)



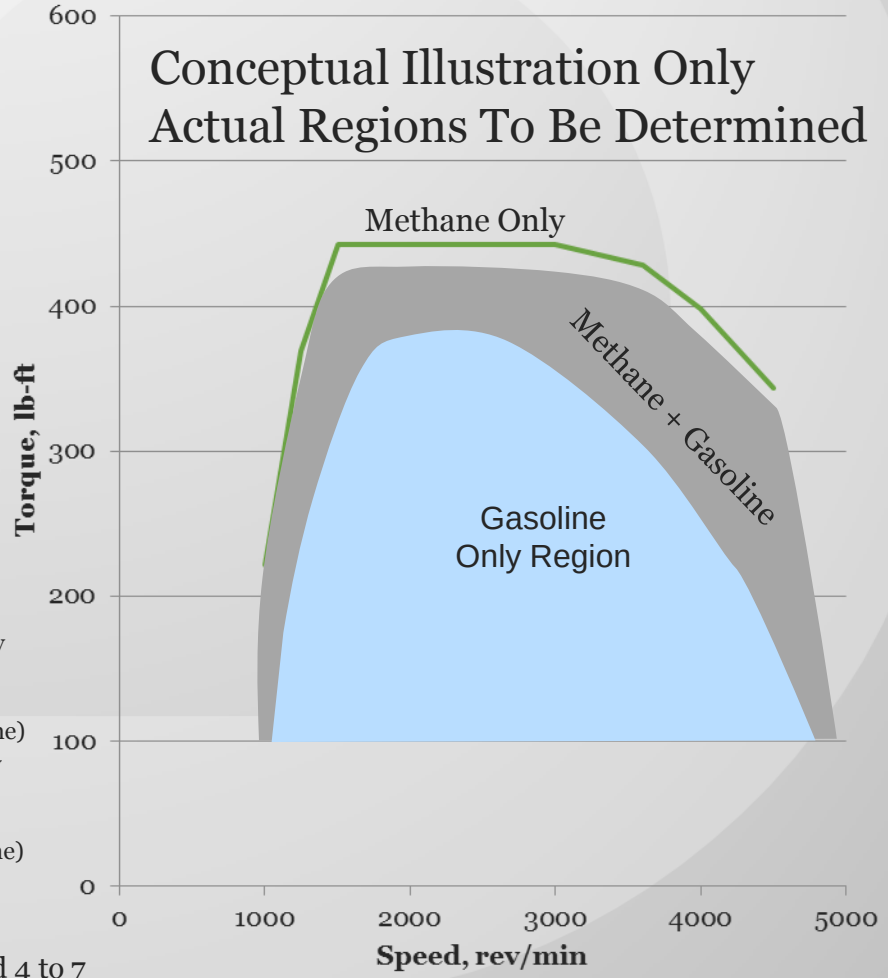


Illustration based on 26.5mpg, 75% gasoline usage in range extension, and 4 to 7 USgal gasoline tank. May need to limit 196 litre range to 450 miles due to Phase 2 EPA/NHTSA rules.

Methane Opportunities for Vehicular Energy

MOVE

Dane Boysen, Ph.D. Program Director
Jason Rugolo, Ph.D. Program Director

Sven Mumme, MBA Tech-to-Market Advisor
Mark Pouy, Ph.D. Technical Consultant

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Advanced Research Projects Agency • ENERGY

Improving Performance: Advances in Pumps, Fill, and Range
North American Natural Gas Vehicle Conference and Expo
Denver, CO | September 16th, 2015

About arpa.e

if it works…
will it matter?

"if it works"

1. make science into technology
2. take risks industry won't
3. identify new opportunities

"matter"

1. reduce energy imports
2. improve energy efficiency
3. reduce energy emissions

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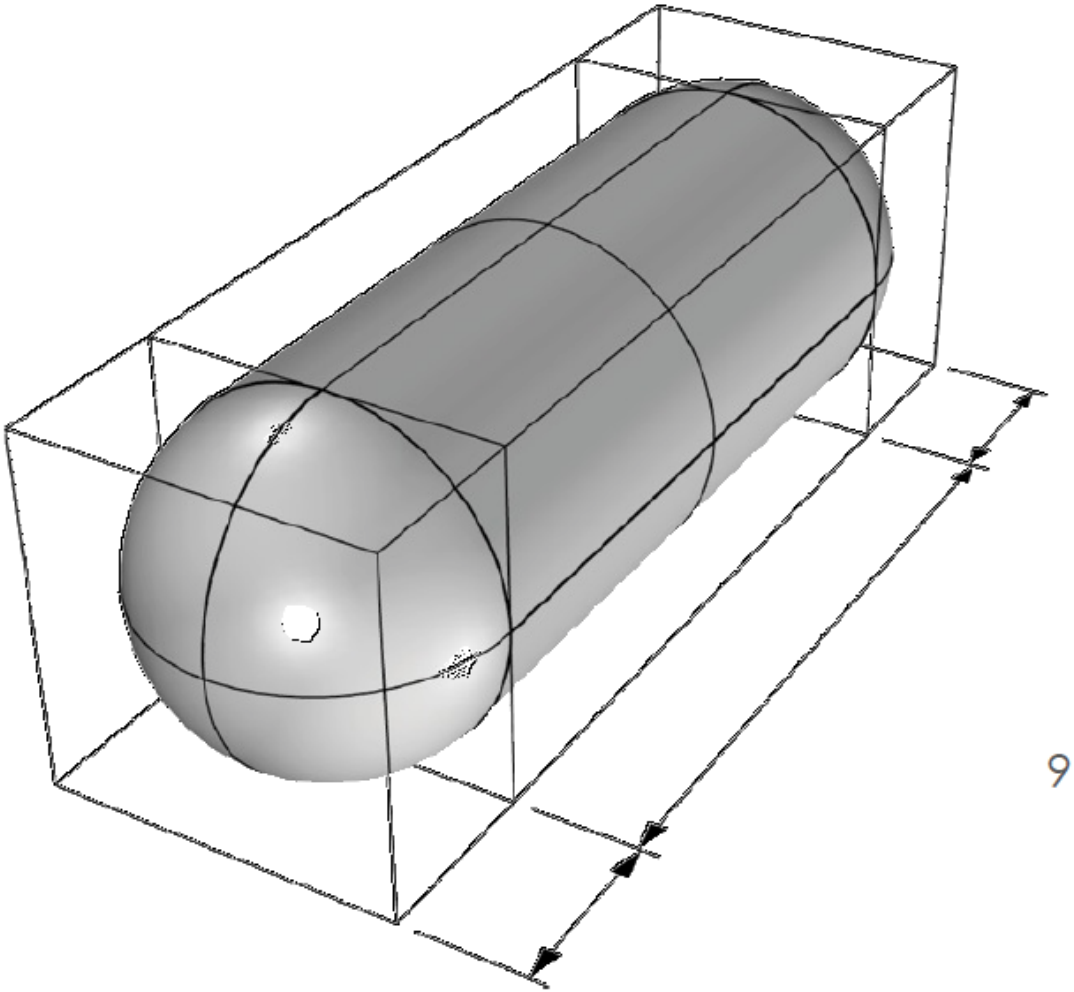
	Now	Need	How
Home Refueler	$ 5000	$ 1500	—
compressor	1500	500	MOVE
system balance	2500	750	volume
installation	1000	250	volume
Vehicle	$ 8000	$ 2500	—
onboard storage	2500	1500	MOVE
system balance	4000	750	volume
certification	2500	250	regulation
Total	$ 13000	$ 4000	—
Payback	15 y	5 y	—

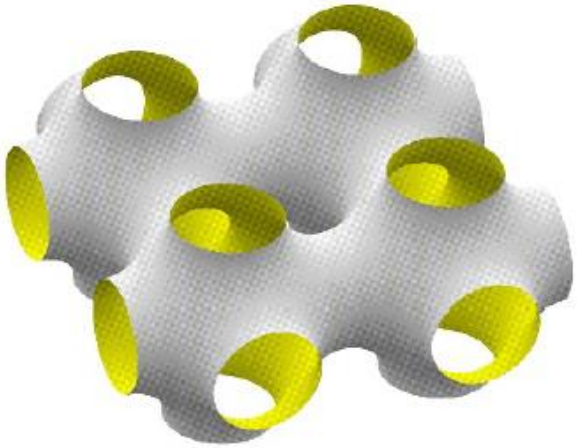

2010 Honda Civic GX – Natural Gas

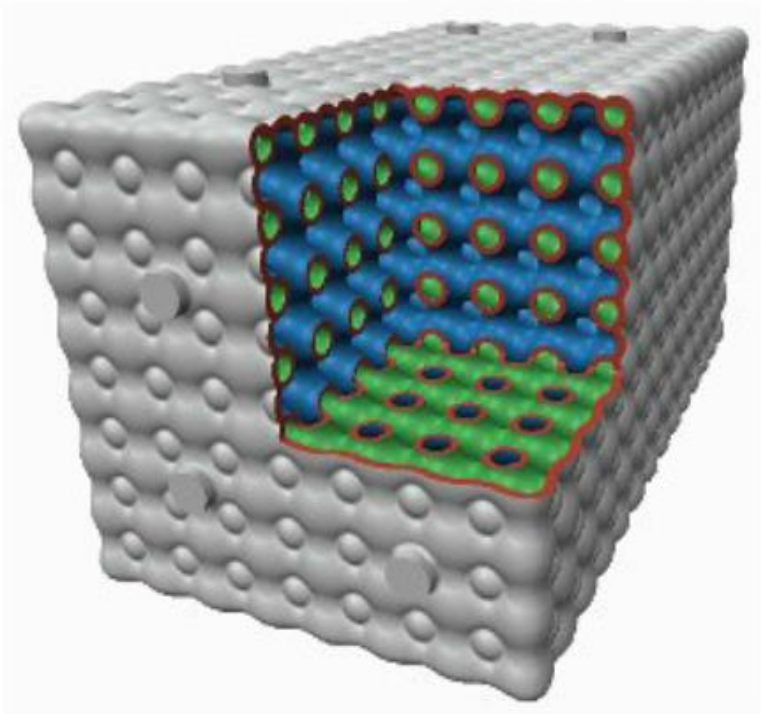


63% of volume wasted

9.3 MJ/L at 3600 psi
-> 5.8 MJ/L

REL, Inc.





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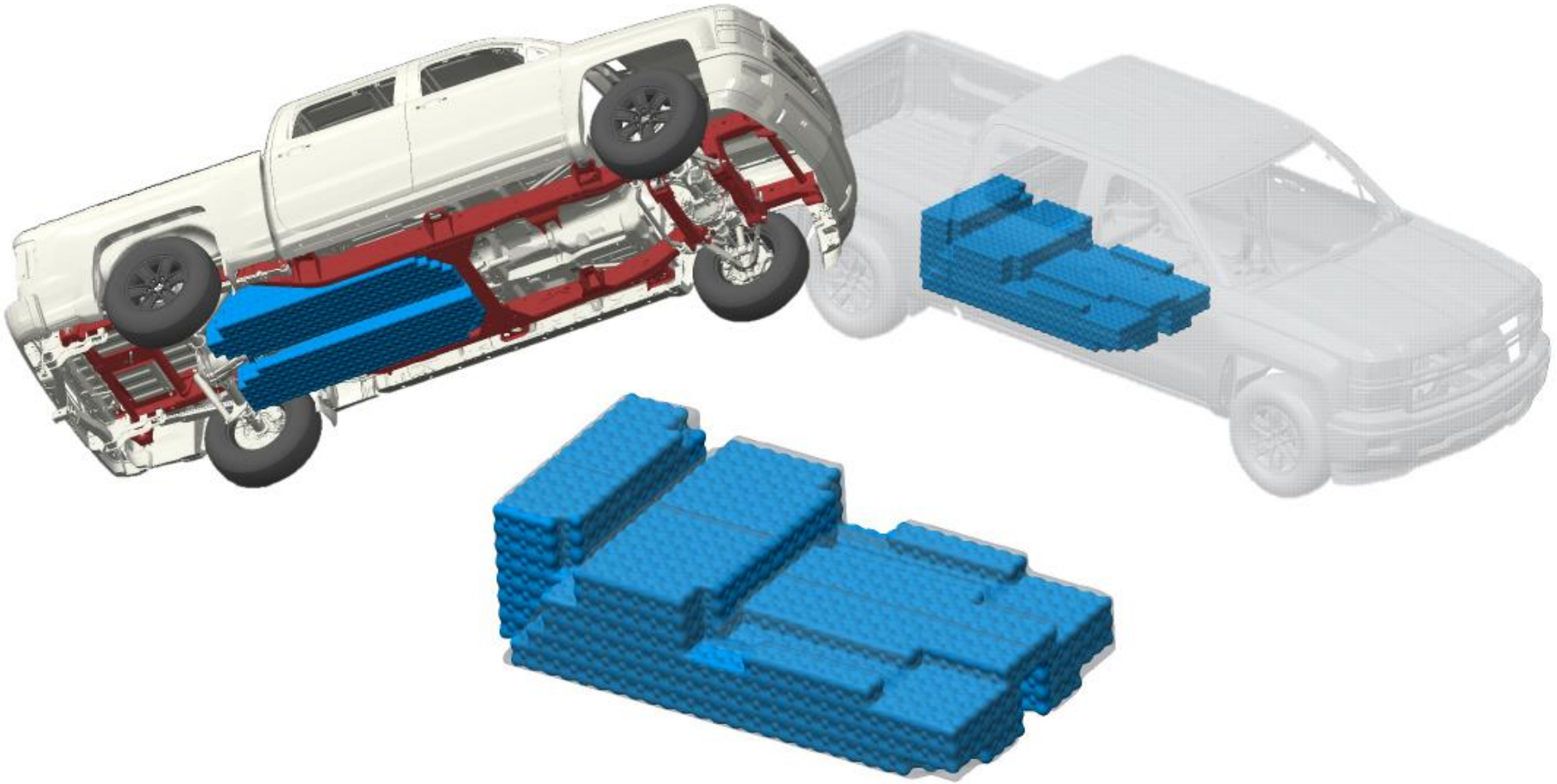
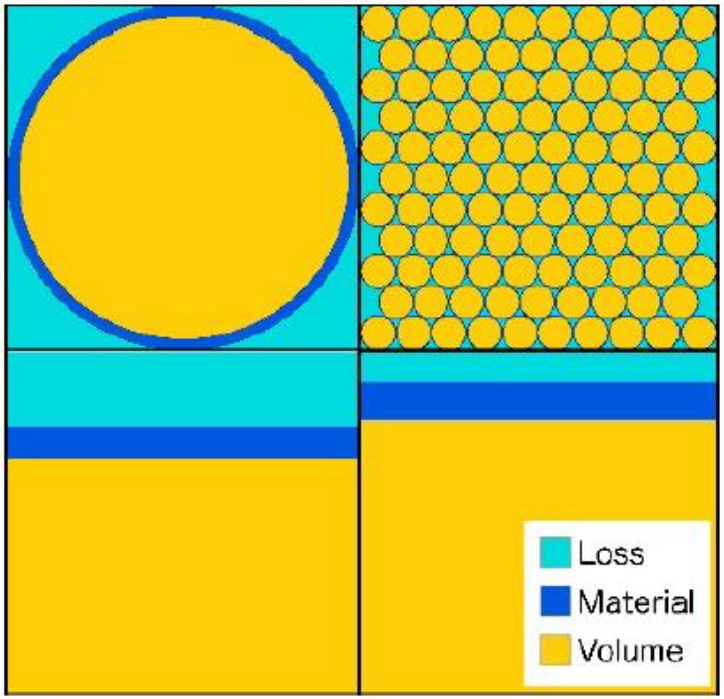


Otherlab/Volute



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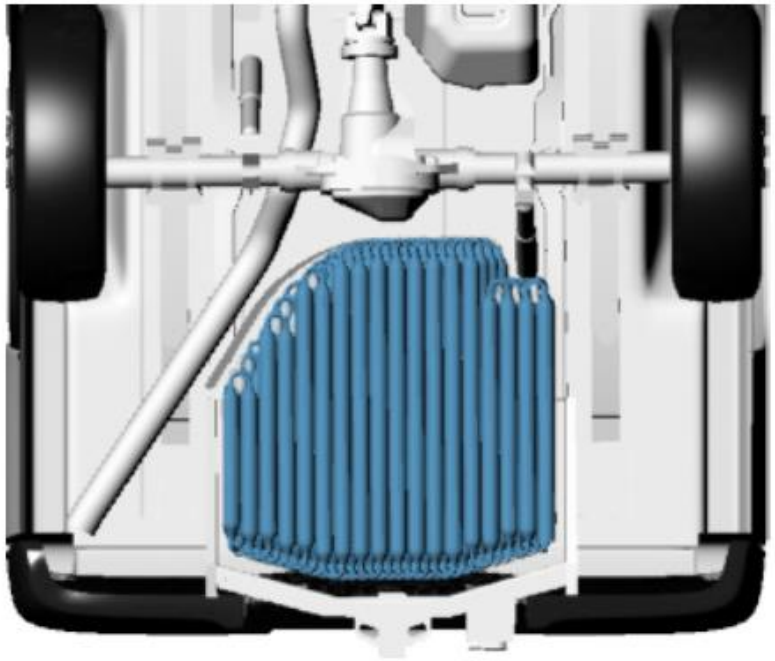
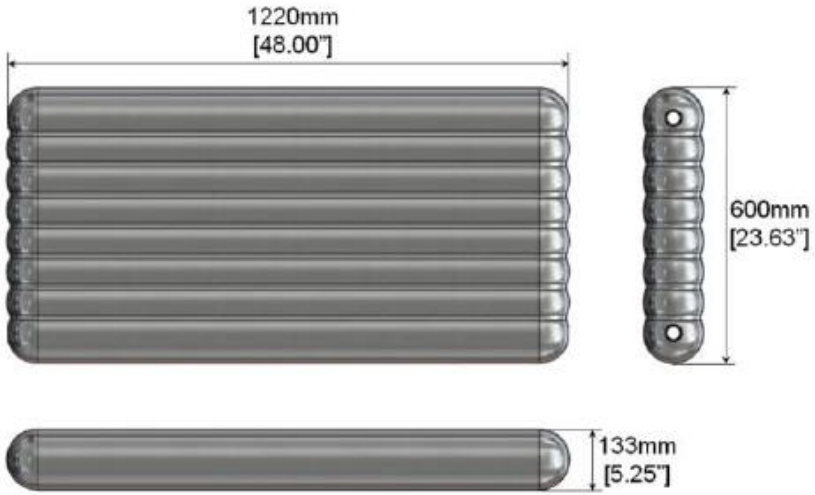
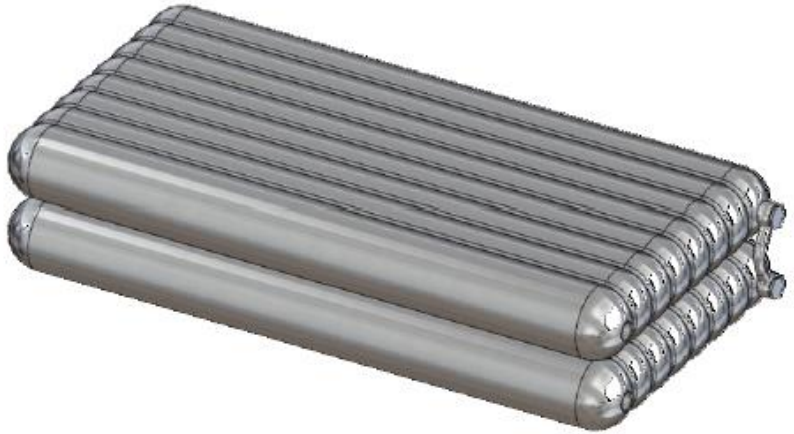


United Technologies Research Center





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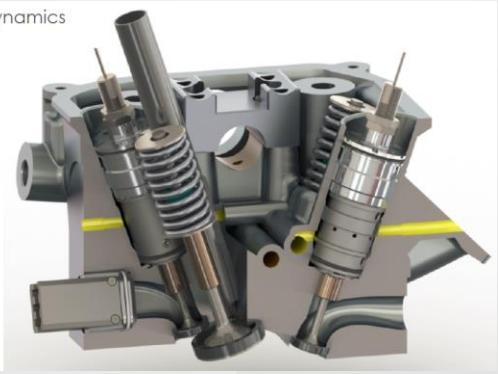
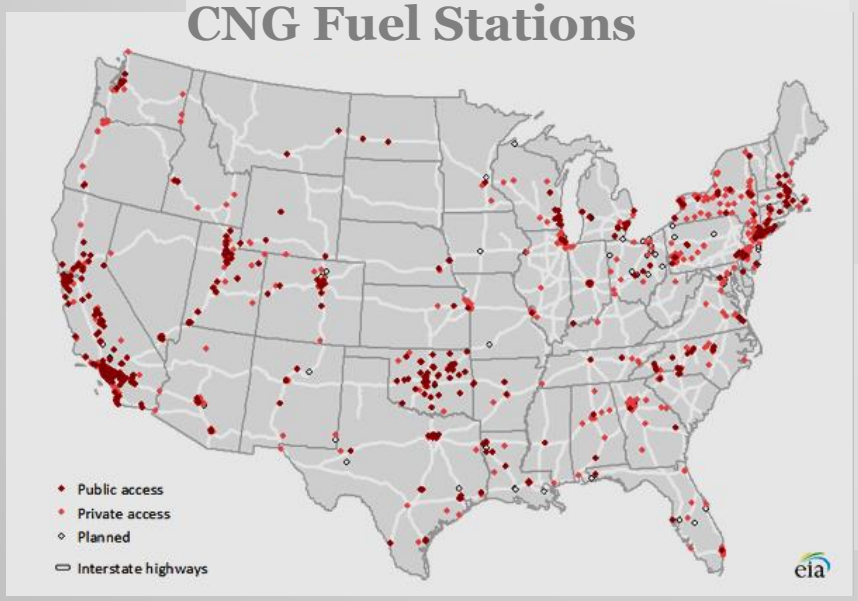
Democratize Re-fueling



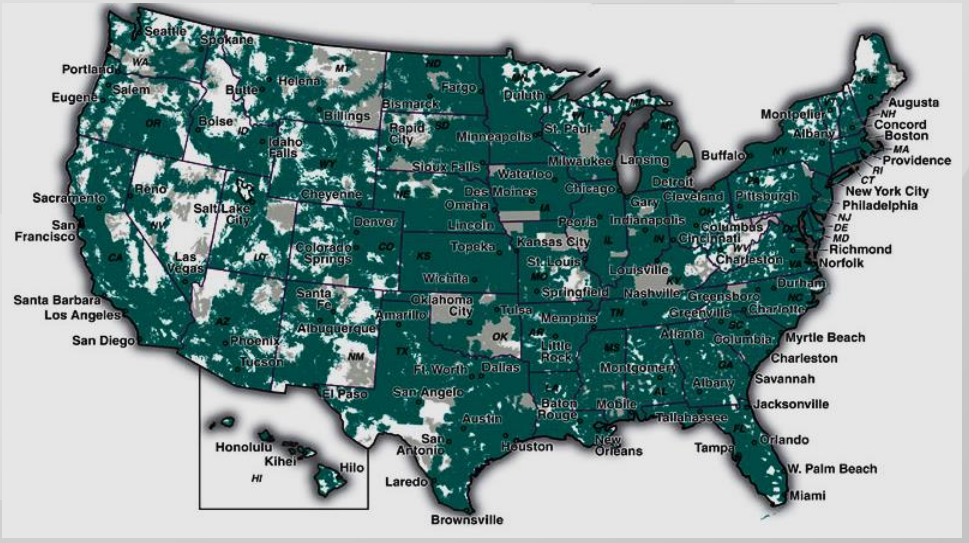
From ~ 1,500 stations to…

64 million potential fueling locations.

CNG Fuel Stations

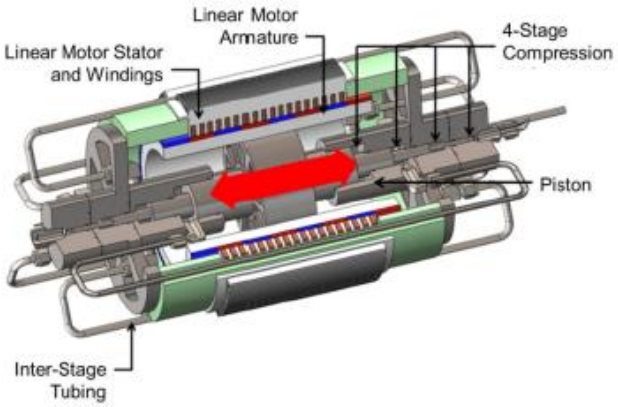


Natural Gas Meter Locations

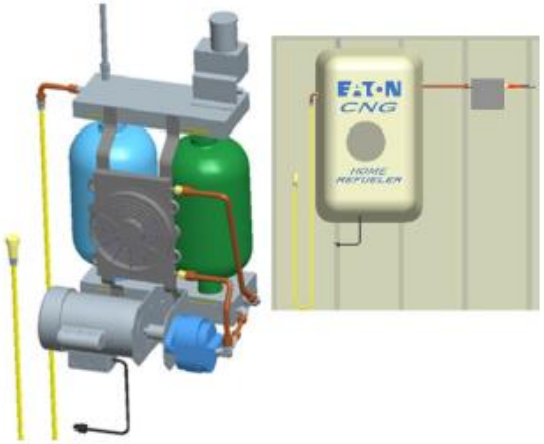


vs ~180,000 gasoline station

UT-CEM



Eaton



BlackPak Inc.

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Over 20 M€ in Gov't Funding in Europe for Advanced Methane Powertrains

- GAS-ON Project (European funding of 17 M€ , total budget 23 M€, 2015-2018)
  - Innovative injection, ignition and boosting system concepts
  - Advanced exhaust gas aftertreatment system
  - Detecting the gas-quality and its composition
  - Fiat (CRF), Ford, VW, Renault, Delphi, Conti + 13 others
- Bosch led consortium with Daimler (German Gov't funding of 3.8 M€, 2015-2017)

Bosch-led Consortium Explores CNG's "Greater Potential" as Vehicle Fuel

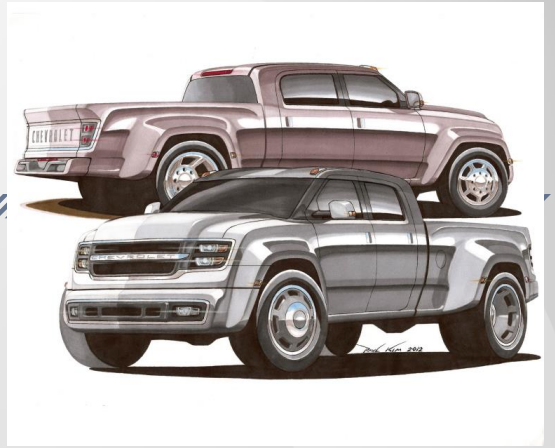
Direct injection for CNG engines: more efficiency, more driving enjoyment

In Germany, a consortium of automotive suppliers and automakers led by Robert Bosch GmbH is striving to develop a new fuel system for Compressed Natural Gas (CNG) that may well be a gamechanger for the industry. The design concept takes the principle of direct injection, normally associated with diesel and gasoline engines, and applies it to natural gas, thereby making the already lower-emission natural gas vehicle (NGV) even more economical and eco-friendly.

DOE VTO SuperTruck Project

- $115M of funding from DOE (3 projects)
- Projects started in 2010
- Goal was to improve freight efficiency by 50%

Proposed SuperPickupTruck Project ($50M from DOE?)



Stream 1: nearer term, lower risk

1. Low cost home refuelling
2. Lower cost, lighter conformable CNG tanks (3600 psi)
3. High efficiency, high performance powertrains

Stream 2: longer term, higher risk, but higher reward

1. Self-refueling vehicles (designed into engine)
2. Adsorbed NG (reduce pressures for above to be more viable)
3. Conformable lower pressure tanks to contain the ANG
4. High efficiency, high performance powertrains

Innovation is a delicate thing. Stop nurturing too early and it will die. Avoid the valley of death.

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