the Energy to Lead

Natural Gas Hybridization

NGVTF
Gas Technology Institute
Ted Barnes

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GTI Company Overview

gti 75 YEARS ENERGY EXCELLENCE

> Independent, not-for-profit, established in 1941
> Over 300 employees (~100 in CA)
> 350 active projects
> 1,200 patents; 500 products

RESEARCH & DEVELOPMENT | PROGRAM MANAGEMENT | TECHNICAL / ANALYTICAL | CONSULTING | TRAINING

2

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Reasons for Heavy Duty Hybrids

- Heavy Duty Truck Hybridization – Why?
  - Critical environmentally sensitive areas looking for "zero emission" options; natural gas hybrids allow for near-term, at scale, real-world applications
    - Increased range, smaller battery pack, ability to keep same duty cycle as diesel
  - Fuel economy and low-end torque improvements can be substantial
  - Allows for zero tailpipe emissions in critical areas for limited range or through overhead (or rail) power transfer
  - NOx emissions already "near-zero" for natural gas but GHG needs constant improvement (diesel-hybrid and biodiesel have significant NOx issues)

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Current GTI Hybrids Projects

- Energy Commission – Hybrid Trucks
  - US Hybrid and UC Riverside major technology partners
  - Two projects with natural gas Class 8 trucks
- US DOE – SCAQMD – ZECT Program
  - BAE and Kenworth major technology partners
  - Drayage truck with natural gas "genset", BAE Hybrid Drive propulsion, Plug-in, Pantograph for zero-emission operation

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Abas Goodarzi, Ph.D., P.E. & Farzad Ahmadkhanlou, Ph.D., P.E. NGVT Forum 2016

Integrated Electric, Fuel Cell and Hybrid Powertrain Components Powering Clean Mobility

US Hybrid

US Hybrid Group

www.ushybrid.com		www.usfuelcell.com		www.magmotor.com	
US Hybrid **HQ: Torrance, CA**		**US FuelCell** **South Windsor, CT**		**Magmotor Corporation** **Worcester, MA**	
Year Established	1999	Year Established	2013	Year Established	1876 (Acquired by US Hybrid in 2008)
Core Competency	Electric Powertrain for Electric, Hybrid and Fuel Cell Heavy Duty Vehicles	Core Competency	Fuel Cell Power Plant	Core Competency	Servo Motors and Drives Automation, Robotic and Semiconductor Mfg.

US Hybrid

Business Focus is Commercial Vehicles

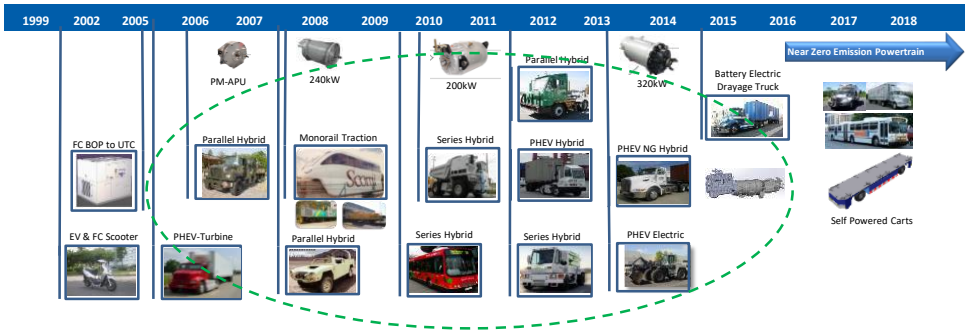
Business Focus is Heavy Duty Commercial Vehicles

Class	6	7	8
Category	Medium	Heavy	Heavy
Weight Range (GVWR)	19,501-26,000	26,001-33,000	>33,000
Examples	Shuttle Bus, Bucket, Municipality, Monorail Sao Palo Brazil, KL Malaysia, Mumbai, India	Delivery, Constructions, Agriculture, Mining	Transit Bus, Drayage, Refuse

US Hybrid

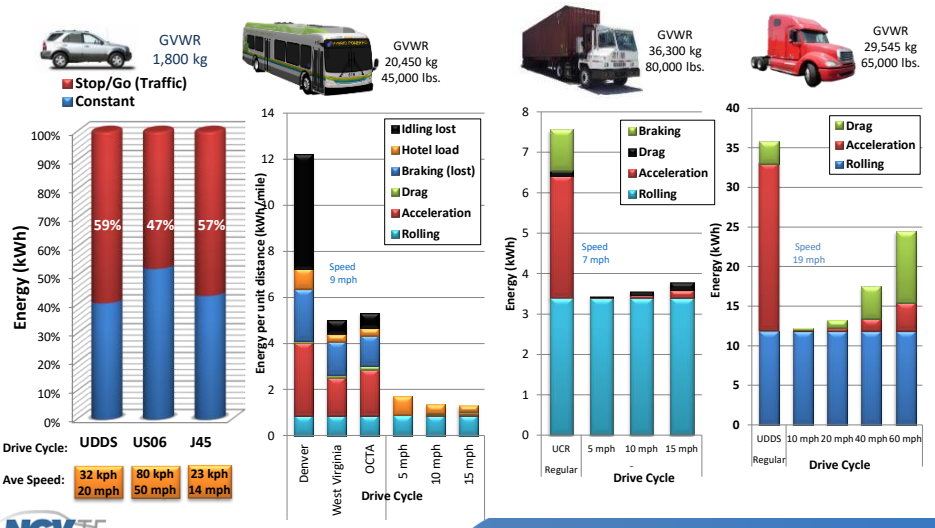
US Hybrid Time Line

We have been making and operating Hybrid Heavy Duty Commercial Vehicles for decades



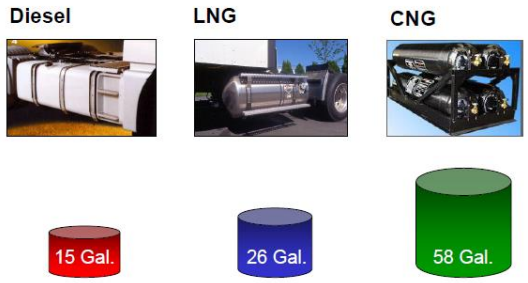
Transportation Engineering; Decoupling Traffic

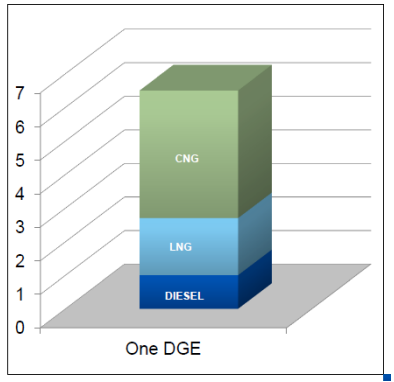
More than 50% of energy is wasted due to traffic



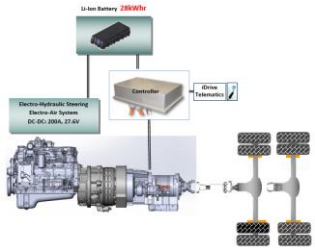
LNG or CNG?

Volumetric Ratio:
LNG=1.7 DGE
CNG=3.8 DGE

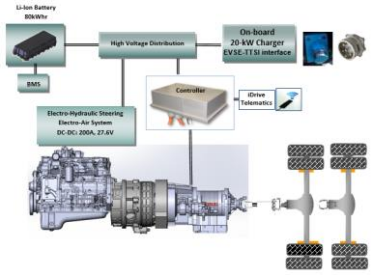




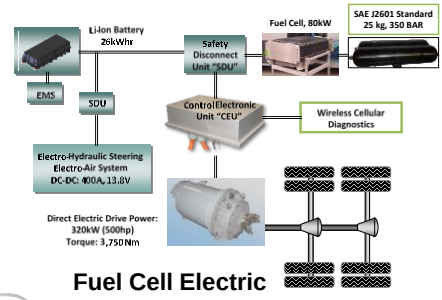
Class-8 Truck Powertrain System Configuration



LNG/CNG Hybrid Electric



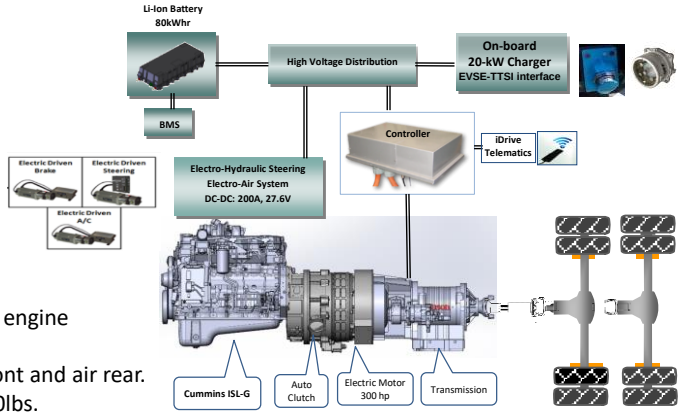
LNG/CNG Plug-in Hybrid Electric



Fuel Cell Electric

LNG/CNG Plug-in Hybrid Electric Powertrain

Enabling Near Zero Goods Movement
Double Power, Torque and Fuel Economy, 80% less NOx

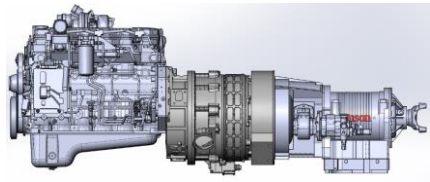


Peterbuilt LNG Truck

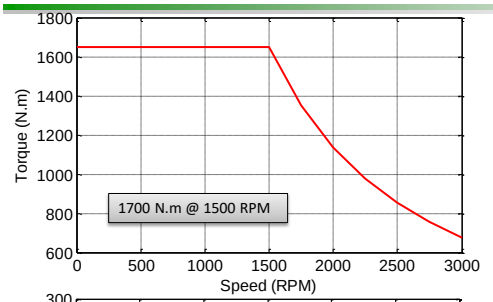
- Model 384 with ISL-G engine
- Wheelbase was 189”
- Suspension, spring front and air rear.
- Stock weight is 13,360lbs.

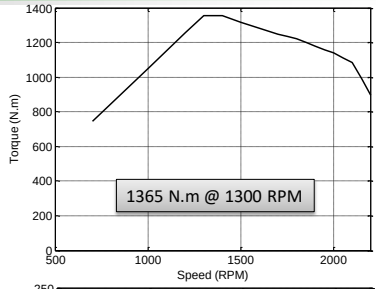
LNG/CNG Hybrid Electric Powertrains

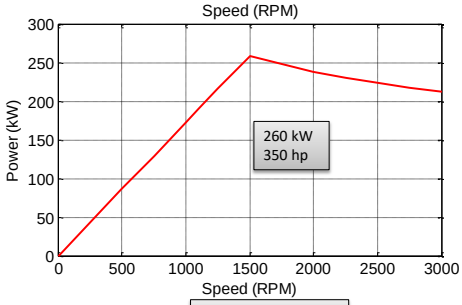
- ✓ Electric Regen Braking
- ✓ Electric only operation during que and traffic
- ✓ Idle control (Engine off operation)
- ✓ Manages low duty engine operation

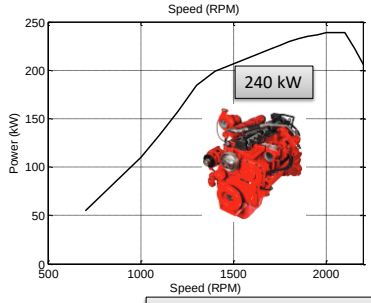


Specs of Electric Motor and Engine





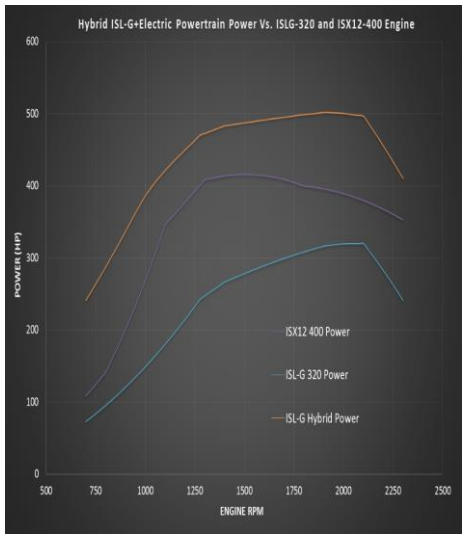


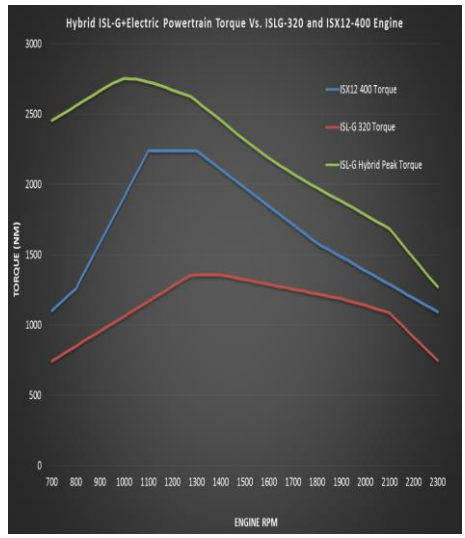


Electric motor

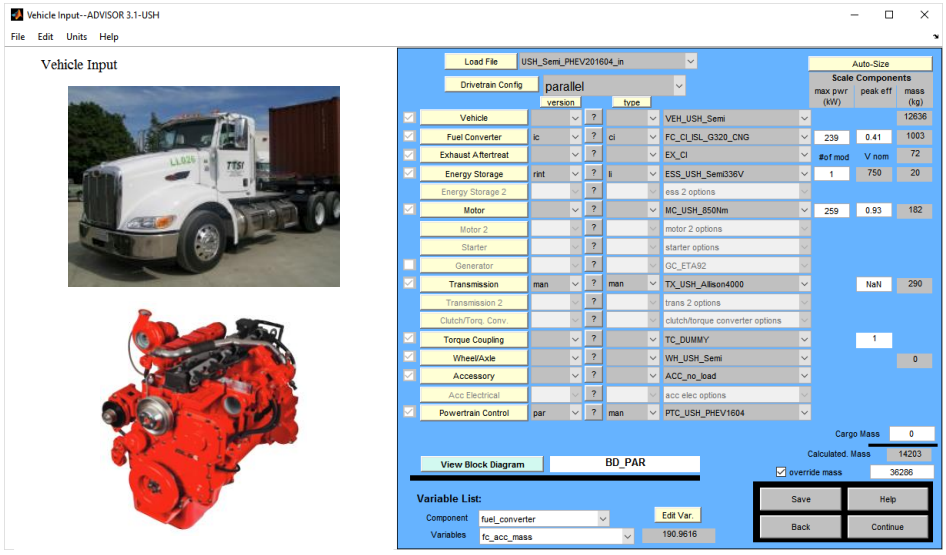
ISL-G 320 Engine (8.9 Liters)

Double Power and Torque

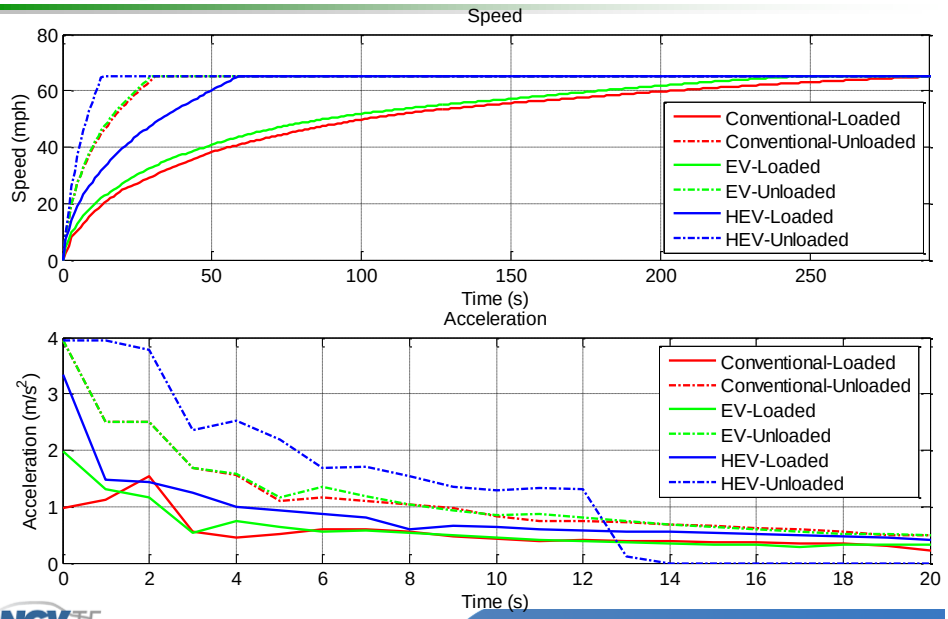




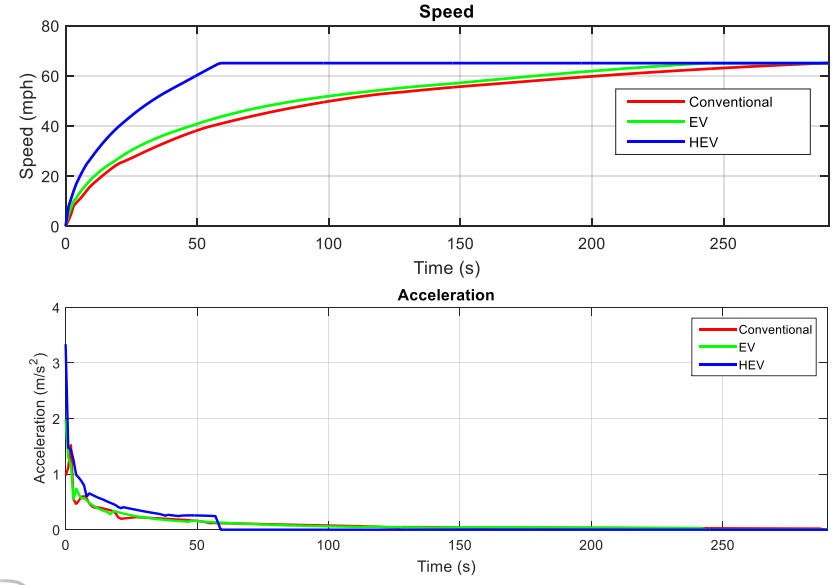
Modeling and Simulation



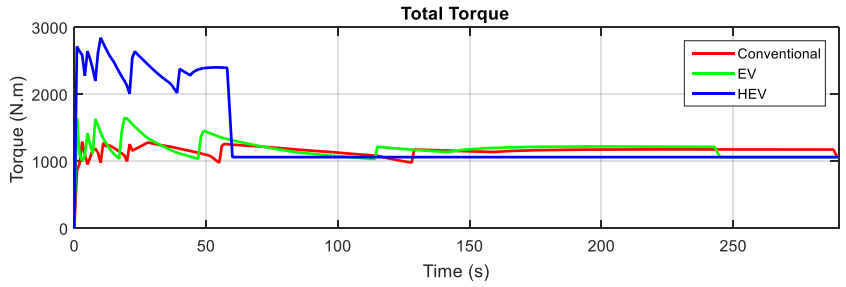
Conventional versus EV and HEV

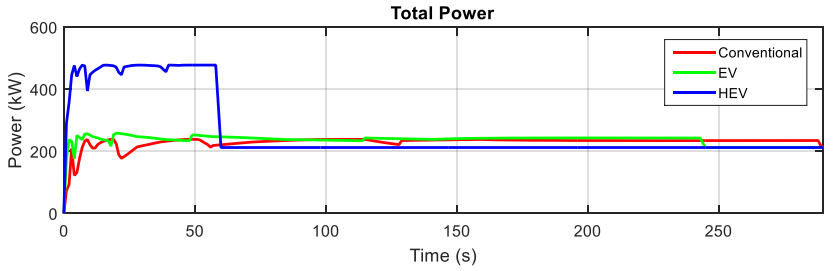


Speed and Acceleration

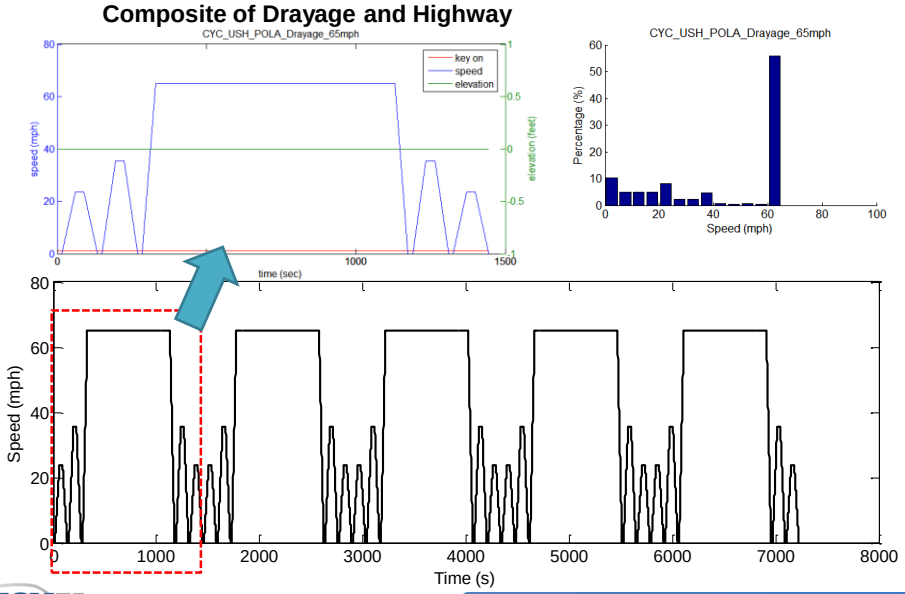


Torque and Power



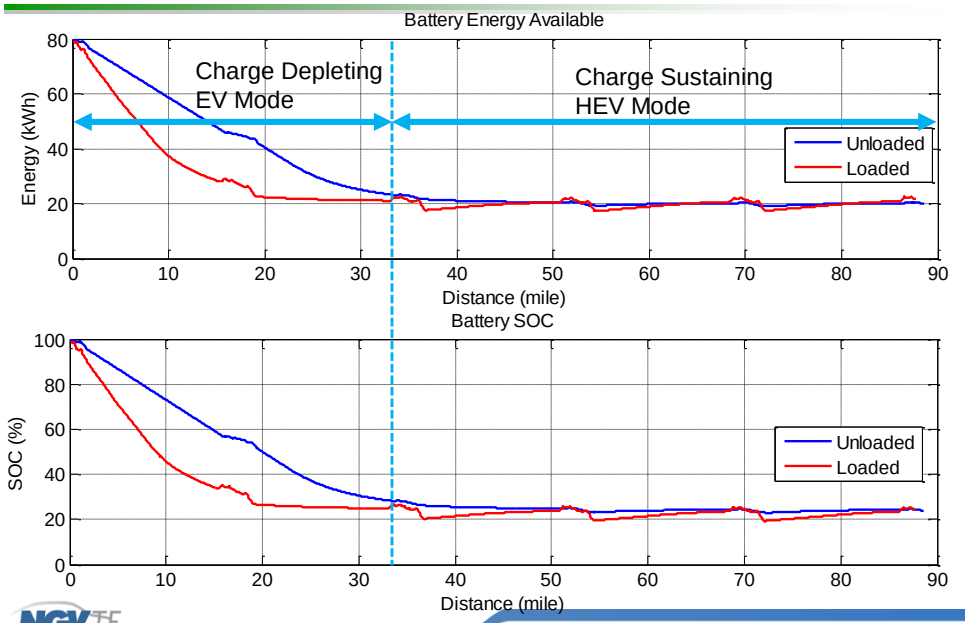


Drive Cycle 1: Port 710-110



US Hybrid

Battery Energy and SOC



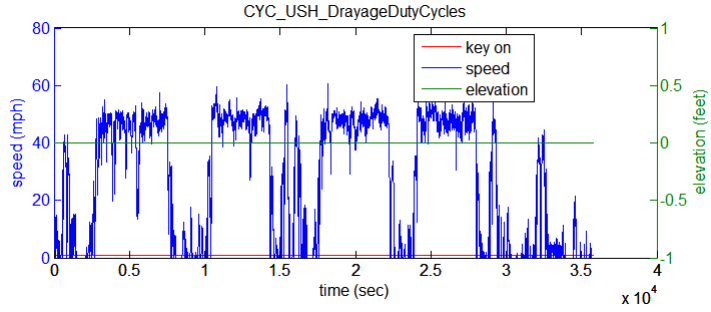
US Hybrid

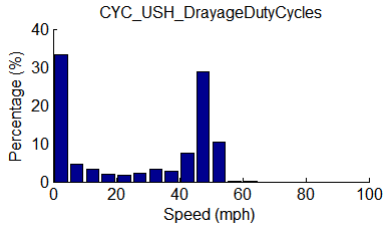
Simulation Results

Parameter	PHEV		Conventional	
	Loaded	Unloaded	Loaded	Unloaded
Torque T_{max} (N.m)	2856	1517	1354	1304
Power P_{max} (kW)	478	303	239	239
Power P_{ave} (kW)	140	79	144	96
EV Range (miles)	19.5	39.7	0	0
MPG (Diesel Equivalent)	5.0	9.2	4.1	6.8
Fuel Efficiency Increase	+22%	+35%	-	-

Considering the idling time, the fuel economy is doubled

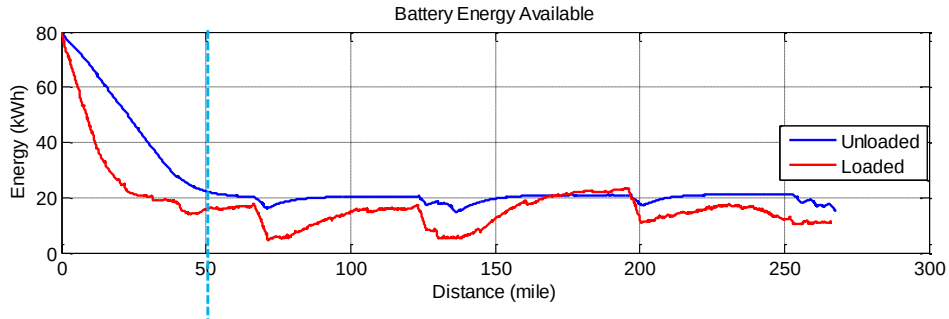
Drive Cycle 2: Drayage Port-Ware Houses





time:	35870 s
distance:	267.86 miles
max speed:	60.6 mph
avg speed:	26.88 mph
max accel:	19.07 ft/s^2
max decel:	-23.03 ft/s^2
avg accel:	0.86 ft/s^2
avg decel:	-0.88 ft/s^2
idle time:	9210 s
no. of stops:	259

Battery SOC



Charge Depleting
EV Mode

Charge Sustaining
HEV Mode

Simulation Results

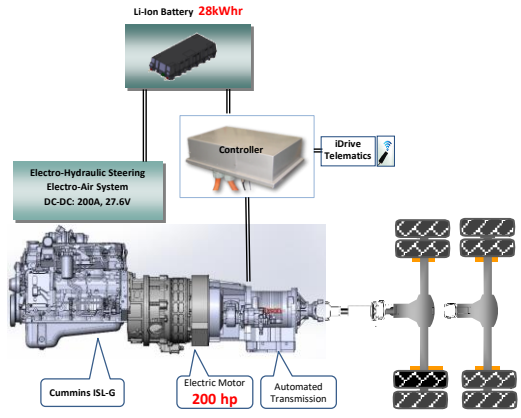
Parameter	PHEV		Conventional	
	Loaded	Unloaded	Loaded	Unloaded
Torque T_{max} (N.m)	3012	3003	1356	1356
Power P_{max} (kW)	478	474	239	238
Power P_{ave} (kW)	74	33	78	34
EV Range (miles)	22.7	58.6	0	0
MPG (Diesel Equivalent)	5.8	13.0	4.7	10.3
Fuel Efficiency Increase	+23%	+26%	-	-

Considering the idling time, the fuel economy is doubled

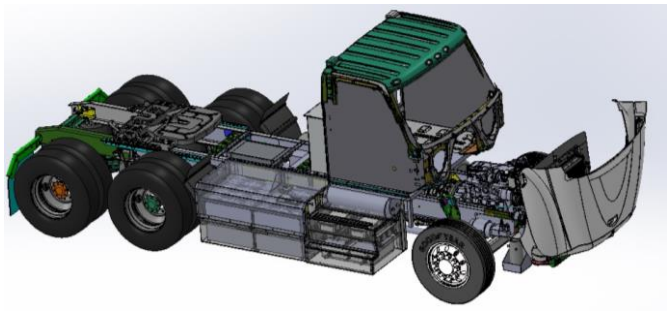
Hybrid Electric LNG/CNG Class 8 truck

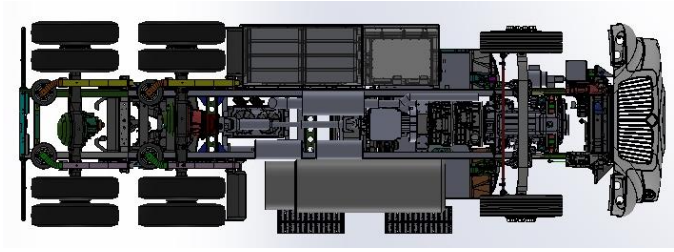
Commercially viable Near Zero Goods Movement
Hybrid Electric ISL-G at the same cost as ISX-15G
with double the range/fuel economy

Peterbuilt LNG Truck
- Model 384 with ISL-G engine
- Wheelbase was 189”
- Suspension, spring front and air rear.
- Stock weight is 12,000 lbs.



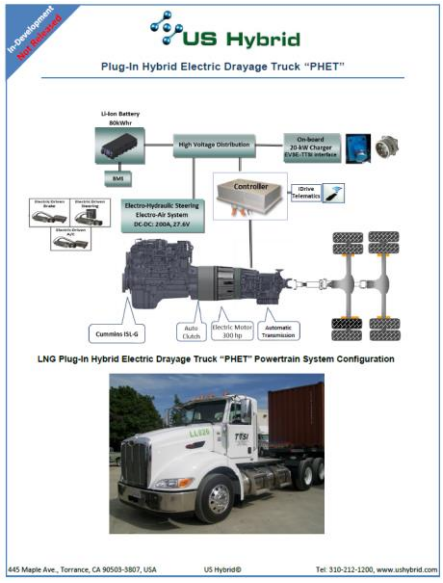
LNG/CNG Hybrid Electric Powertrains





LNG/CNG Hybrid Electric Vehicle

LNG/CNG Hybrid Electric Specification

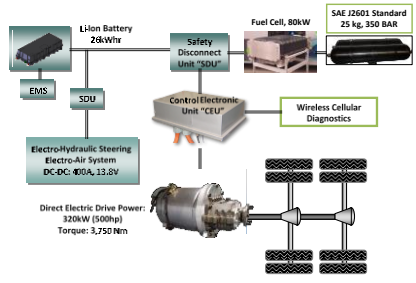


Drayage Class 8 Truck Specifications	
OEM Manufacturer and Model	**Peterbilt, Model 384 Day Cab**
G.C.W.	80,000lbs
Front Axle (Dana Spicer E1202I)Rating	12,000 lbs.
Rear Axle (Dana Spicer DSP40) Rating	38,000 lbs.
Rear Axle Ratio	6.17
Wheel Base	176"
Tire Size	295/75/R22.5 (FF:R280, RR: R250F)
Truck Performance	
Range LNG and Battery	250 miles
Range Battery Electric	30 miles
Top Speed	65 MPH
Acceleration 0-40 MPH	10 sec
Engine System Specifications	
Engine Supplier	Cummins Inc.
Model and Type	2009-ISL-G, 8.8 LNG engine
LNG Tank Storage System Specifications	
LNG Tank Supplier & Model	NexGen, Model HLNG150,
LNG Storage Capacity	Capacity: 147 G.Vol
Energy Storage Specifications	
Battery Type	Li-Ion
Battery Energy	80kWhr
Hybrid Electric Traction Drive System Specifications	
Motor Type	Internal Permanent Magnet
Traction Drive Power	**222kW/ 300HP**
Motor with Integrated Gear Unit Weight	1496lbs
Integrated Traction Inverter Power	240kW
Integrated Traction Inverter Weight	127lbs
Charger-On-board	**20kW**
Control, Communication and Diagnostics	**SAE J1772, and EVSE TTSI Interface**
Auxiliary Systems Specifications	
DC/DC Converter	27.8, 300A
Air Conditioning	Electric
Power Steering	Electro-hydraulic
Air Compressor	Integrated Electric, Oil-less

Fuel Cell Electric Heavy duty Powertrain

Zero & Near Zero Emission Road map

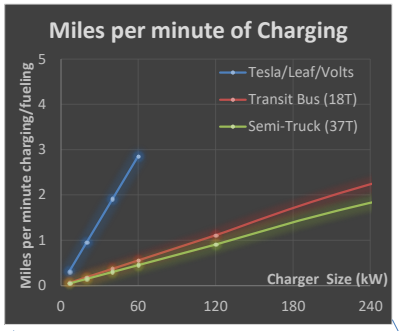
- Plug-in Hybrid
- Battery Electric
- Hybrid Electric
- Fuel Cell Electric

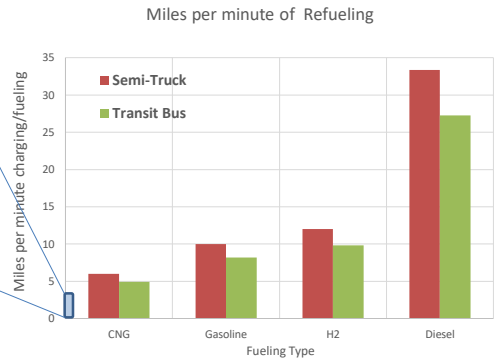


Fuel Cell Electric Class-8 Truck Powertrain System Configuration

Charge Fueling Time and Convenience

Limitation of Battery Electric MD/HD Trucks





Conclusions

- Plug-in Hybrid Electric with 30 miles Battery range (dual battery)
- Hybrid Electric with 5 miles, 30 minutes Port queuing battery operation (single battery)

Hybrid NG Electric, Commercially feasible, Commercial Delivery: Q2-2017, taking orders now

CNG

- Take up more space
- Refueling takes considerably longer

+ Safety advantage in the case of a leak

+ Lower cost to produce and store

+ Double the range (miles) with Hybrid

+ No need to fuel twice a day → saves time

Thank you!

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