Natural Gas Plug-In Hybrid Class 8 Truck Development

NGVTF

James S. Burns, Ph.D.

2/22/2018

TransPower

Development Funding Path

- CEC PIR-13-012 Ended Q3 2017
  - Demonstration of Natural Gas Plug-in Hybrid Class 8 Trucks (NGPH-8)
- SCAQMD Contract No. 16046 Ends Q2 2018
  - Develop & Demonstrate Two Class 8 CNG Plug-In Hybrid Electric Drayage Trucks (ZECT)
- CEC proposed awardee under GFO-17-503
  - Demonstration of a CNG Hybrid-Electric Super-Truck (CHEST)

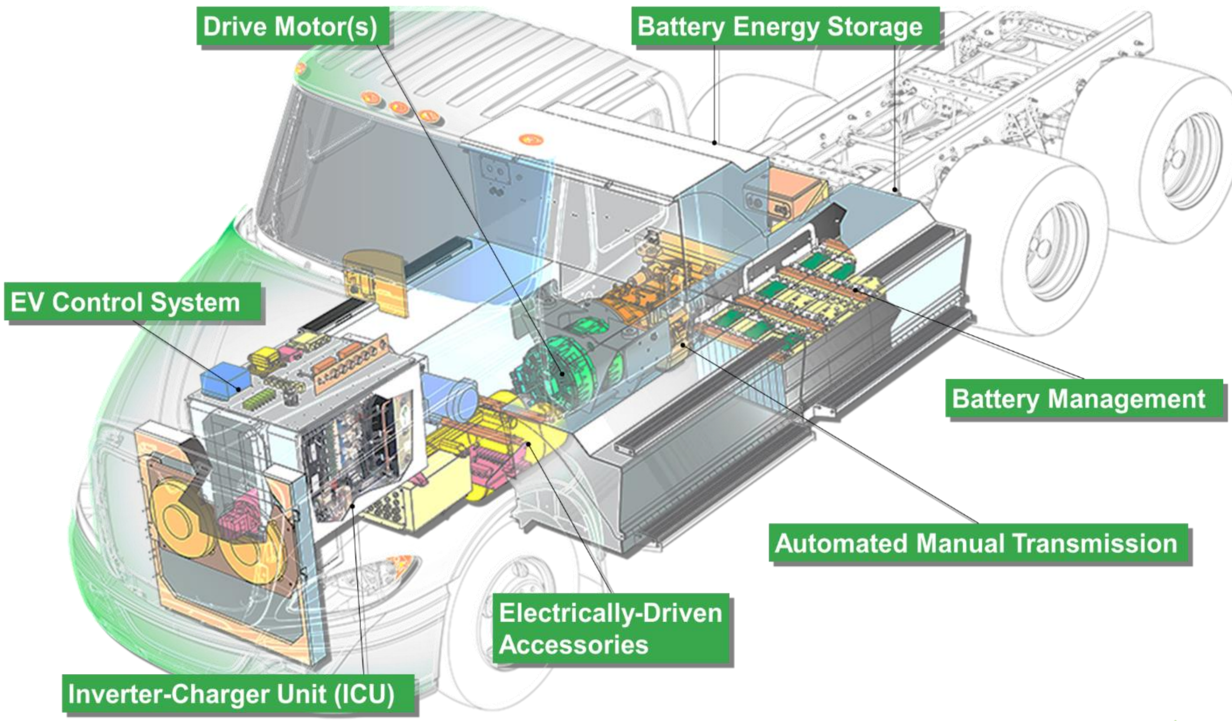
TransPower

Technical Advisory Committee (TAC) Members

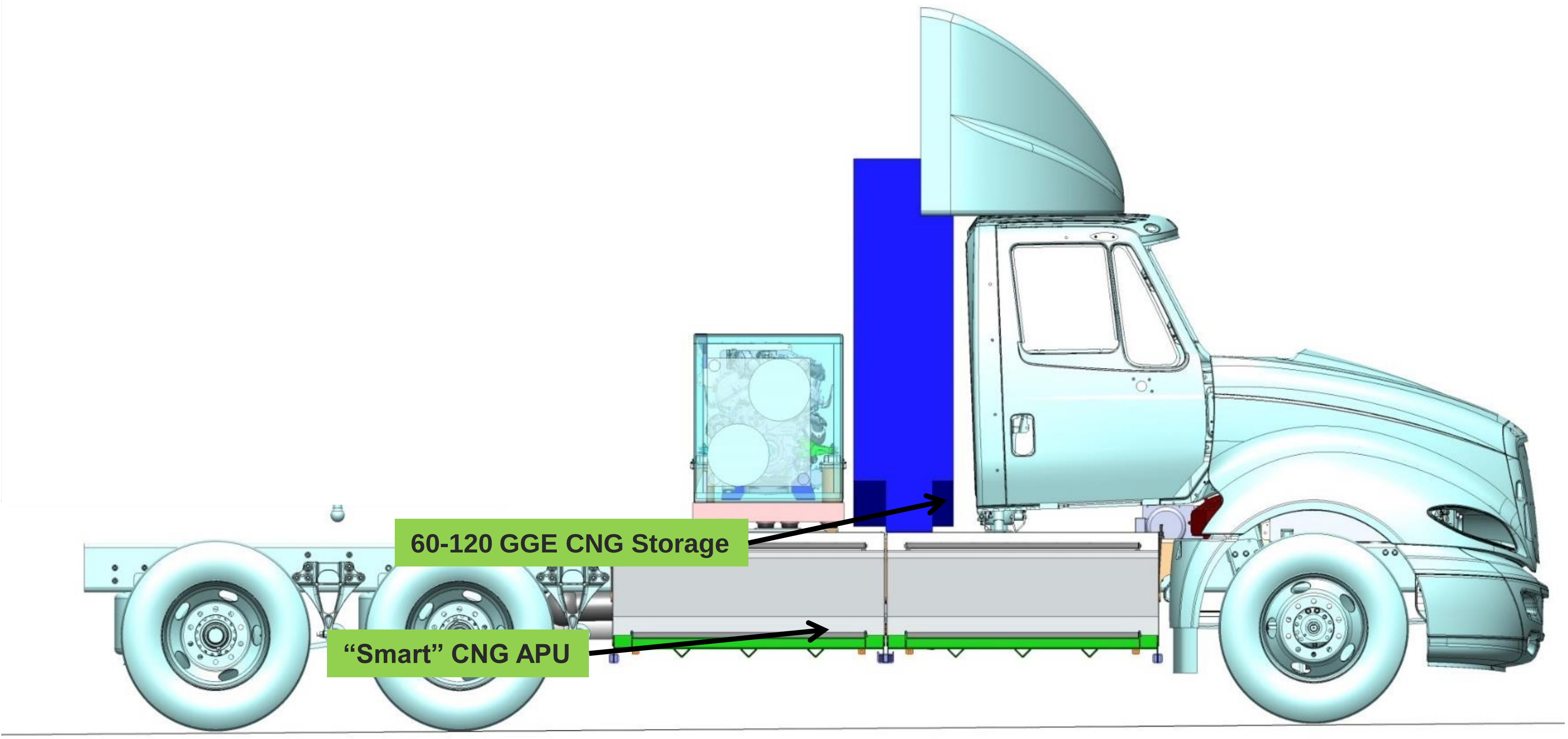
- Roger Galloway – Westport
- Michael Lee – Southern California Gas
- Kent Johnson – UC Riverside
- Vic La Rosa – Total Transportation Solutions
- Jon Coleman – Ford Motor Company

Plugin Range-extended CNG Hybrid Basics

- Serial hybrid combines TransPower's proven electric powertrain with a "smart" generator APU
- This APU incorporates a 3.7L Ford SI NG engine and JJE/EPC electric power systems



Electruck ™ with APU Range-extender



TransPower

Objectives for these designs

- Effective range extension
  - 135-250 mile range > Bakersfield to Long Beach
  - Vehicle weight “neutral” design
  - Significant fuel cost savings
- Program goals
  - Fuel economy in g/bhp-hr at those conditions equal or better than that of larger CNG truck prime mover engines
  - Heavy Duty FTP cycle compliant emissions at those conditions
  - Longevity sufficient for demonstration period
- Energy and power requirements for APU
  - 50-70 engine shaft hp average over 8 hours
  - 100-200 shaft hp peak for 5 minute bursts

TransPower

Challenge: Engine Choice and Availability

- All 3.7L NG-ready Ford engines are built with the same variable valve, and port-injected fuel system.
- <u>Automotive-Trim (AT):</u> Original Ford effort to supply 3.7L from dual-fuel F-150 production – these had a hard-to-procure controller with closed software – no help forthcoming
- <u>Stationary-Trim (ST):</u> has an added manifold injector and unwired VVT system – limited to 2900 RPM – available and stand alone w/controller

TransPower

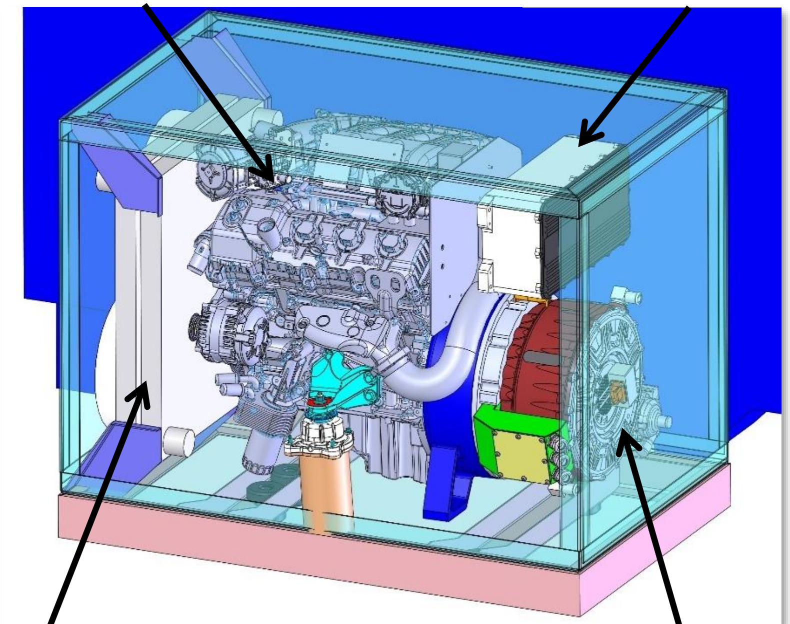
Engine Strategy

- Acquire ST engines from Powertech, run one as-is in the CCAT test truck to establish a baseline
- Develop a CNG test capability –a complete dynamometer facility – to author new engine controls for the AT (Seq. multi-port, VVT) engine.
- Procure additional ST engines and build APUs for the SCAQMD trucks, then upgrade the ST engines to operate as AT to reach the higher peak power goals and reduce fuel consumption and emissions

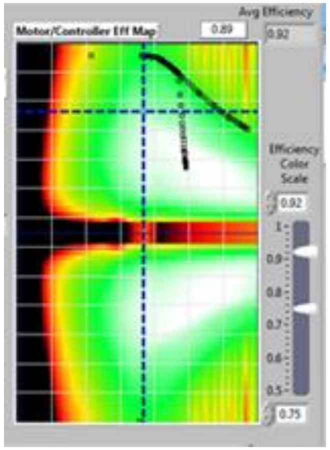
TransPower

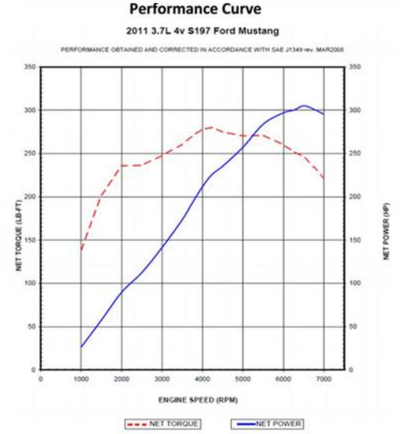
APU design details

3.7L Engine **EPC Inverter**



Cooling System **150kW IPM Motor**

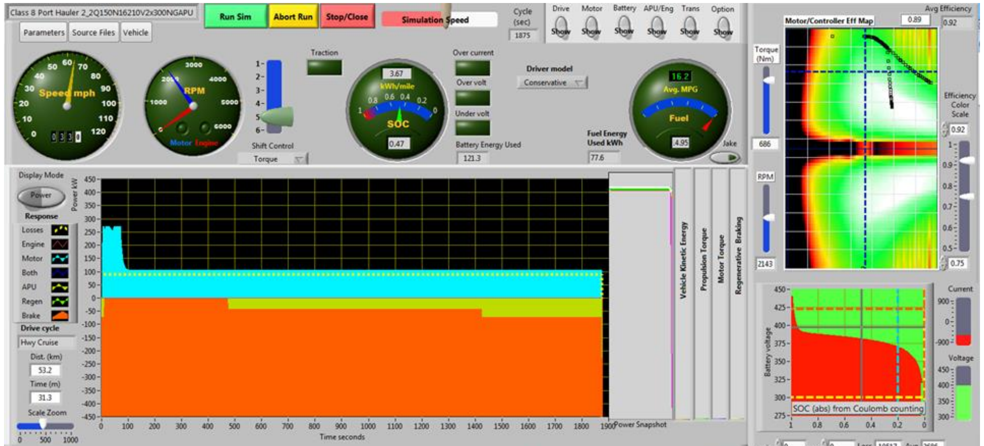




APU dry weight: ~1400 lbs
CNG storage system dry weight: ~450 lbs
Battery weight reduction: ~2300 lbs

TransPower

Truck System Simulation Results



Cycle/ Condition	Avg. Speed (MPH)	Trip Range (miles)	Operating Economy (kWh/mi)	Time to goal (hrs)	APU power (kW)	Trip energy (kWh)	APU energy (kWh)	CNG req'd (GGE)
Drayage	10	75	2.7	7.50	15	203	111	13.2
Drayage 2 shifts	10	150	2.7	15.00	21	405	313	37.5
Freeway	55	135	2.8	2.45	117	378	286	34.2
Interstate	65	135	3.3	2.08	170	446	354	42.3

- Simulated system efficiency to verify vehicle range using the stacked HD FTP drive cycle
- Used baseline control rules to explore operational impacts of ESS and SOC limits on second by second performance

- Sized system fuel requirements, estimated ESS performance impacts of this design, and explored limited load following rules

TransPower

Controls Development

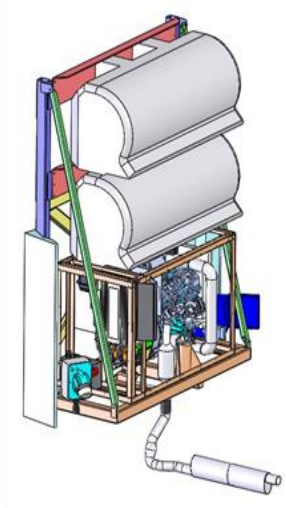
- Constant speed, always-on mode – developed.
  - Majority of testing to date has been in this mode.
- Voltage support during bridge pulls
  - Peak power set to increase with auto-trim engine and TransPower controls.
- Low-speed "off" mode - presently it's low idle mode
  - Geo-fencing add-on device has been developed.
- Ford ECM unavailable in dyno-calibrated version
  - Significant investment in dynamometer testing has met continuous power goals and can proceeded to vehicle test.

Range-extended Drayage Energy and Power Req'ments

- Baseline drayage – load leveling
  - 2.6kWh/mi for 8 hr drayage shift
  - Goal of 100 mile range extension (~150 miles total) min 32.5kW over 8hrs or 62kW ~50% duty cycle
- Extended highway operation
  - 3.5kWh/mi – 40% more than typical drayage
  - This is roughly 0.7 hp/mile per 8 hour drayage shift
  - At 25% thermal efficiency, this is 2x23GGE tanks
- Bridge climb (<5min)
  - Smaller battery design requires 80-120kW from APU
  - ST Engine output is capped in firmware to 62kW. AT engine should reach the 110-120kW peak output

TransPower

CCAT catenary program test truck with APU



Lessons Learned

- Assembly/ Layout
- Noise Control
- Air flow and Cooling
- Control Methods
- Fuel consumption

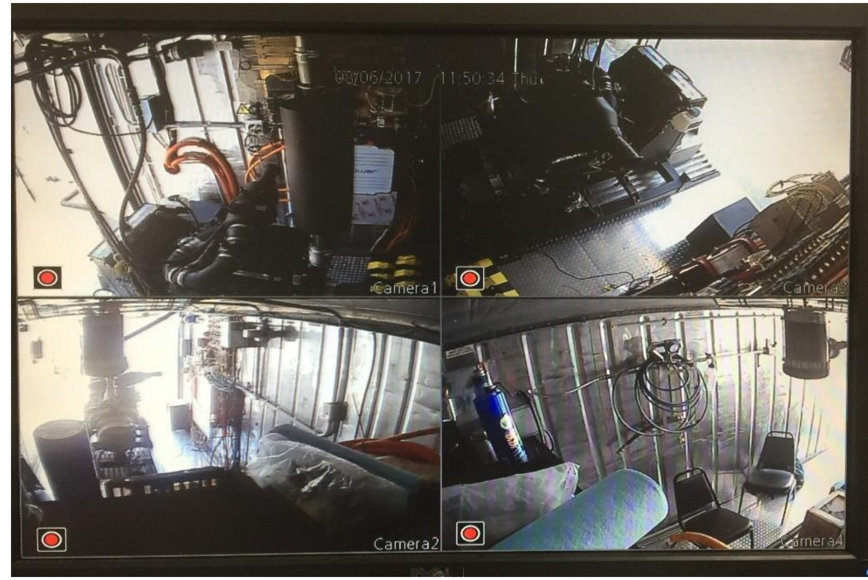
Operational and deployed at the E-Highway test site

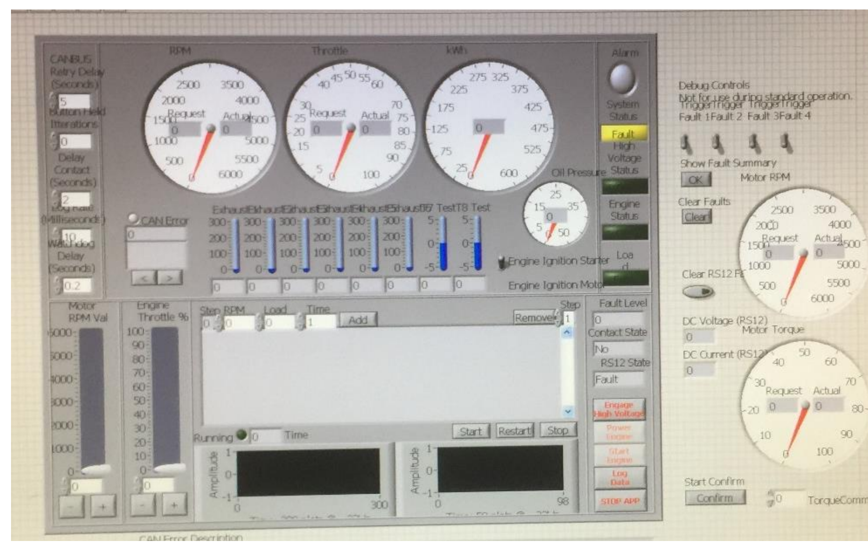
TransPower

Auto-trim Engine Dynamometer Test Cell

Instrumentation

- CNG flow meters
- O2 sensors
- Exhaust temps
- Std. engine sensors





Safety

- Remote SCADA
- Leak and fire detection
- AV900 ESS simulator
- External CNG storage

TransPower

SCAQMD-funded CNG hybrid range-extending trucks

View from the left rear

- Delayed deployment due in part to a battery cell failure and added diligence in testing and requalifying KAM cell products.
- These trucks will deploy with the ST engine and then be updates in the field to the AT operation with addition of TransPower ECU and harness, intake changes, and insertion of port injectors.

TransPower

APU and Vehicle Testing Results

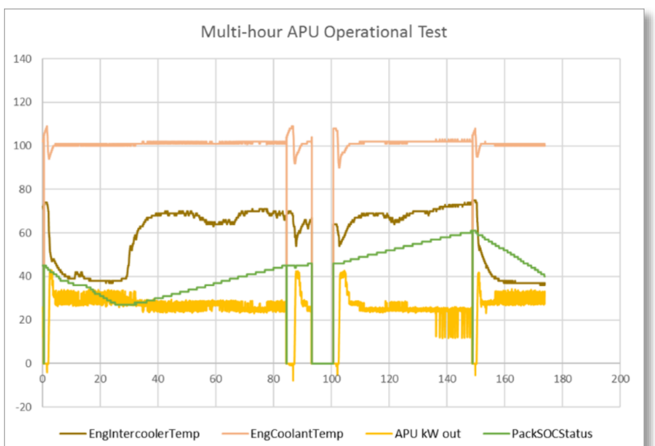
Stationary-trim APU Fuel consumption:

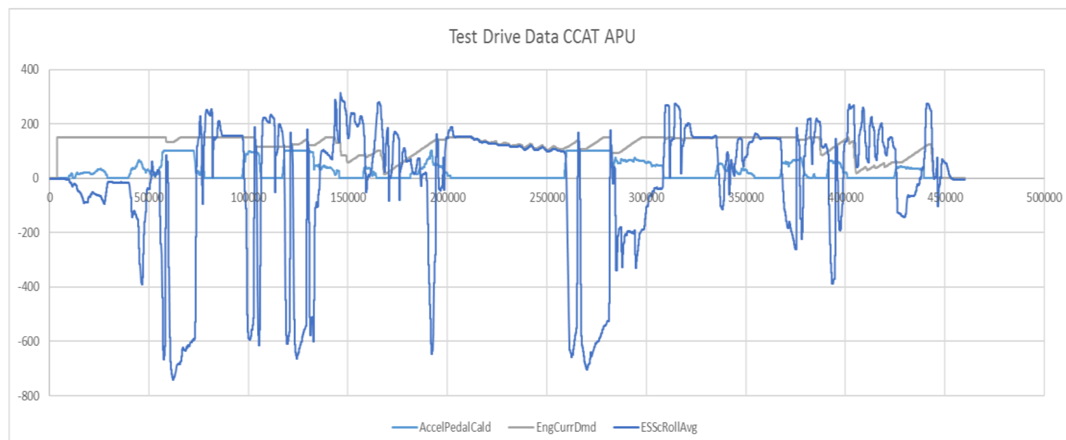
RPM	Load (%)	APU Output (kW)	Engine Temp. (.C)	Minutes	kWh/kg	Eff.
1000	0	0	16	14.13	0	0
1000	0	0	90	20.25	0	0
1400	75	22.4	89	2.48	1.85	0.14
1400	75	22.5	95	3.58	2.69	0.20
2850	90	59	98	1.68	3.31	0.25
2900	100	62	N/A	N/A	N/A	N/A

CNG diesel gallon equivalent (DGE). – 1 DGE = 6.384 pounds (2.896 kg) of CNG or
CNG diesel liter equivalent (DLE). – 1 DLE = 0.765 kilograms (1.687 pounds) of CNG.

Conversion factors	
2.90	kg/DGE
0.746	kwh/hp-h
0.875	DGE/kWh
0.653	DGE/hp-h
Superior (gross) calorific	
14.61	kWh/kg

Stationary-trim on-road testing traces (typical):





TransPower

Emissions Measurements

ST-based APU emissions measured w/ UCR portable equipment

	Test Condition			Emission Rates g/KWhr			
Test Index	rpm	%Torque	power kw	NOX		PM	
#		Nominal	Measured	AVE	STD	AVE	STD
3	1400	42%	12	4.93	0.6	0.000	0.000
4	1400	75%	24	13.9	1.6	0.001	0.000
5	2100	65%	25	12.8	0.5	0.002	0.001
6	2400	65%	31	10.6	0.3	0.001	0.000
8	2400	85%	41	0.2	0.2	0.005	0.003
16	2900	100%	62	8.4	3.6	0.004	0.002
17	2900	75%	52.7	2.9	0.6	0.000	0.000
18	2900	66%	42.7	0.9	0.7	0.004	0.006
19	2900	100%	62	12.4	3.4	0.003	0.002
20	2900	80%	54	6.9	0.4	0.001	0.000
21	2900	70%	45	5.1	1.7	0.001	0.000
22	2900	50%	32	0.2	0.2	0.001	0.000
23	1400	67%	20	12.4	1.1	0.000	0.000
24	1400	50%	15	9.3	1.0	0.000	0.000
26	2600	100%	55.7	3.9	2.1	0.009	0.003
27	2600	90%	51.5	3.8	1.3	0.001	0.001
28	2000	60%	25.6	10.8	4.3	0.000	0.000
29	2900	25%	15.7	4.0	1.0	0.002	0.001
30	2900	10%	4.4	2.9	1.4	0.002	0.001
31	2900	25%	15.7	4.1	1.2	0.002	0.001
32	2900	10%	4.4	2.0	0.7	0.001	0.000

Emission targets (HD FTP):

- 0.01 g/bhp-hr NOx
- 0.01 g/bhp-hr PM
- 0.14 g/bhp-hr HC
- 15.5 g/bhp-hr CO

Observations:

- NOx is high in the ST
- AT should improve
- PM is of course low
- Full weighted duty cycle not used in calculations
- UCR equipment did not measure HC and CO

Meritor / TransPower Partnership @ November 20th, 2017

Both parties bring valuable competencies to this relationship:

TransPower + MERITOR

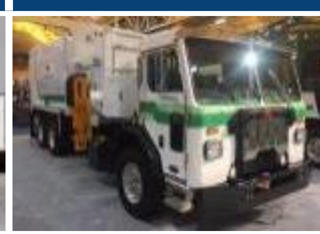
- Software / controls
- Battery integration & controls
- On road experience
- Research and development
- Commercial vehicle system integration

- 100+ year Brand
- Commercial relationships
- Production manufacturing
- Global infrastructure
- Sales, service, and aftermarket networks
- Capital and resources

Class 8 Drayage

Terminal Tractor

Refuse



School Bus

Reach Stacker

TransPower

TransPower

Results Highlights

- Working ST system operating on CCAT truck now.
- ST efficiency predictions were verified.
- ST emissions measured as baseline
- First SCAQMD truck integrated- awaiting calib.
- AT engine software calibrated to 4000RPM
- AT engine meets average power requirement
- AT emissions tuning slated for April at UCR
- AT engine software will evolve during deployment
- Fuel cost-per-mile and emission reduction benefit spreadsheet tool developed for ST engine

Fuel Savings Benefit Predictions

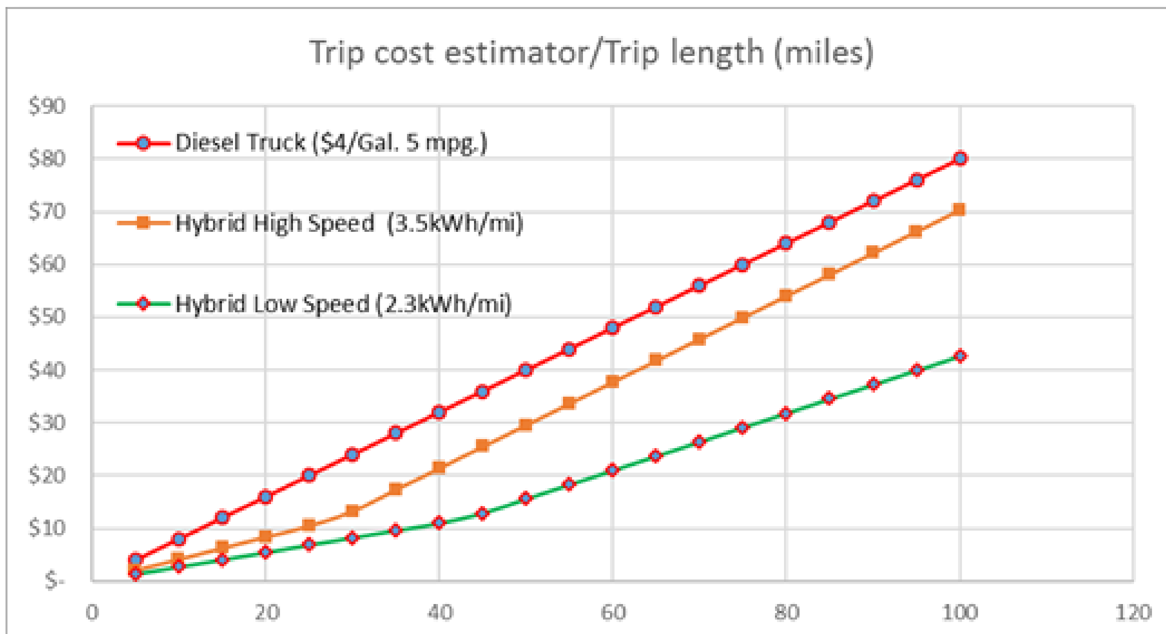
100	mile trip target		Condition		fraction	kWh/kg
2.3	kWh/mi	Low speed	1	idle	0.1	0
3.5	kWh/mi	High speed	2	22 kW	0.1	2.69
155	kWh ESS nomnal		3	60 kW	0.8	3.31
0.80	SOC avail. fraction				avg	2.92
53.9	mile range electric		Assumed			
1.00	starting SOC		Diesel MPG	5	kg CNG req	44.8
0.8	ESS DOD max.		Fuel/units	Cost/unit	scf/DGE	144
43.1	Electric miles driven		Diesel/Usgal	$ 4.00	scf/kg	49.4
56.9	CNG miles		CNG/DGE	$ 2.00	scf req	2215
131	kWh CNG required		Electricty/kWh	$ 0.12	DGE required	15.4

Operating modes

- Idle (not “off”)
- Low charge-sustaining
- High charge-sustaining
- Peak (hill climb)

Observations

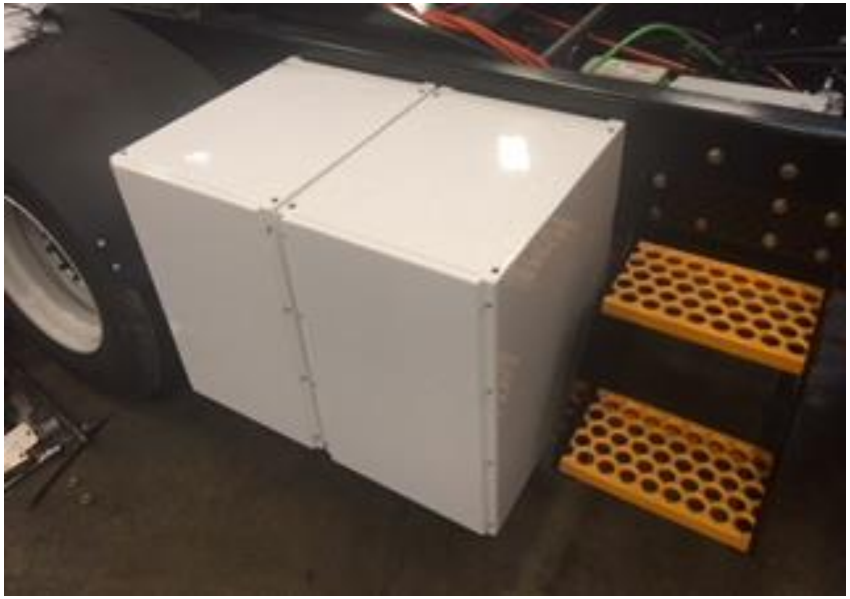
- Knee at AER limit
- Adjustable SOC limits
- Low-speed drayage significant savings



TransPower

Changing Landscape

- AESC batteries
  - Lower impedance
  - Lower cost
- Meritor partnership
  - E-axle
  - Investment
  - Midwifery
- New missions
  - Medium range
  - Long haul
- New competitors

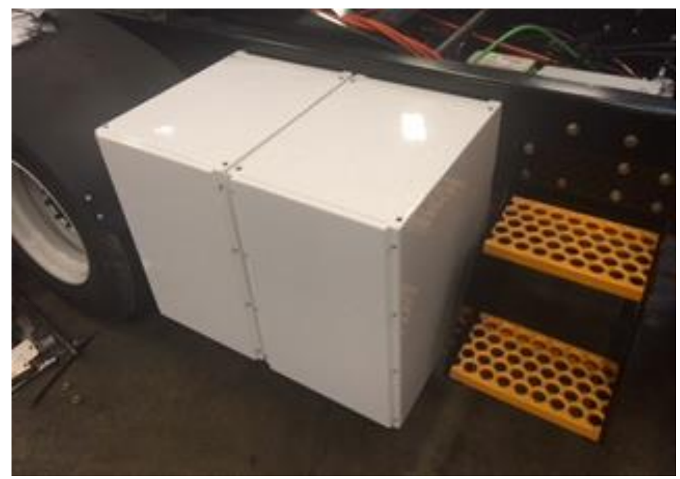


TransPower

Better Batteries

Cell chemistry and type	Li-NMC, prismatic pouch
Cooling type	Air. Opt. Water/Glycol and Refrig.
Pack dimension （D, W, H) mm	675 x 500 x 550 (Width along frame)
Pack mass kg	360
IP rating	IP 67
Vehicle mounting method	Frame side mounting w/ spreaders
Capacity nom./usable, kWh	Per pack - 44, 37
Nominal voltage VDC	400
SOC range %	10%-95%
Max contiin. discharge current	330 @45 ℃
Pulse discharge current A	550 @ 27 ℃
Max. charge current A	110 , 55 recommended
Min charge time Hour	1 hour, 2 recommended
Battery control	Volt/Temp with current derate
Operation/Store temp limits C	(-25 ～ 60 ℃)/(-40 ～70 ℃)

- Modular design for packs with 44kWh increments
- High energy density ~50% more than LFP system
- US sourced, high quality Li NMC pouch cell
- BMS with CANBUS and 200 mA of balancing
- Air cooled with optional water/glycol and refrigerant Battery heating and cooling options
- Each module has fusing and contactor control



TransPower

NACV show in October 2017

- ***Fully integrated electric motor*** **saves cost and weight and frees packaging space b/w frame rails**
- ***PM motor technology*** **tailored for CV duty cycles is extremely power dense and efficient**
- ***2-speed automated shifting*** **enables smaller, lighter motor and higher system efficiency**
- ***Fits existing MTOR axle hsgs*** **for easy vehicle integration**
- ***250 kW Peak power*** **(3 ratings 150 / 180 / 200 kW Cont.) in the same package for appl. Flexibility.**
- **Prototypes available in mid-2018**

TransPower

- Q and A Period