Heavy-Duty Electric Vehicle Solutions

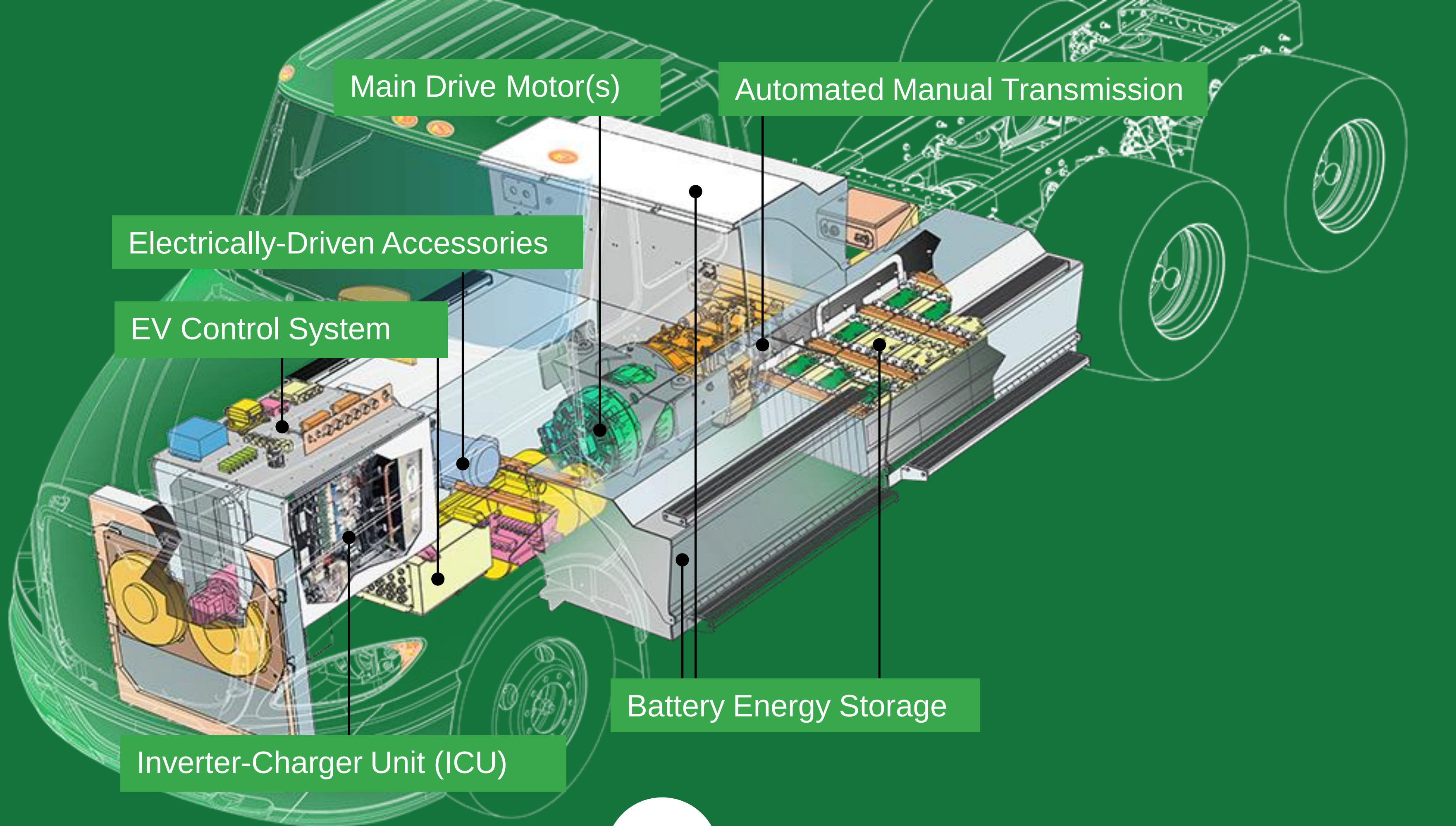
TransPower®

October 20-21, 2015

Heavy-Duty Vehicle Electrification Challenges

- High performance requirements
- Long-term reliability under harsh operating conditions
- Affordability for fleet operators

Challenges we must meet to achieve global emissions reductions



TransPower's advanced "ElecTruck™" solution

Game-Changing, Proprietary Technologies

Motive Drive Subsystem

- Cost-effective, high power density electric motors
- Automated manual transmission

Power Control and Accessory Subsystem

- Flexible, models-based controls
- Onboard inverter-charger units
- Efficient electric accessories

Energy Storage Subsystem

- Low cost, high energy batteries
- Robust, modular pack design
- Advanced battery management

Adaptable to Many Applications

Class 8 On-Road Trucks

Yard Tractors

School Buses

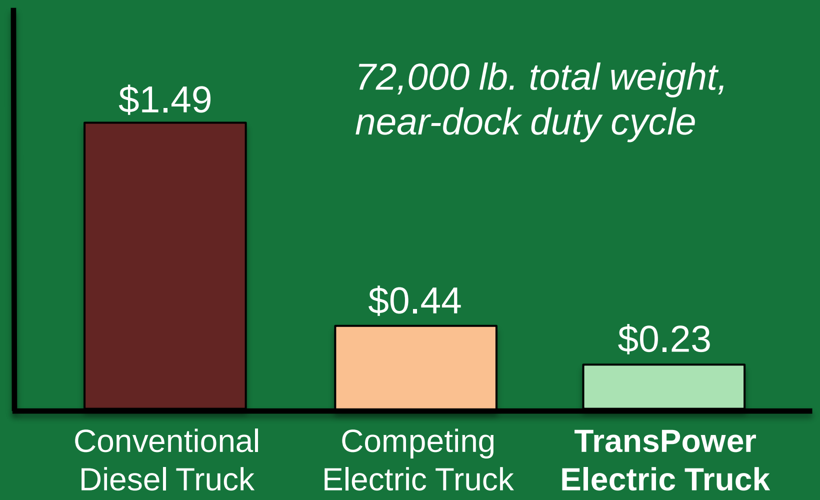
Cargo Handling Equipment

U.S. Market Potential – Electric Drive Systems

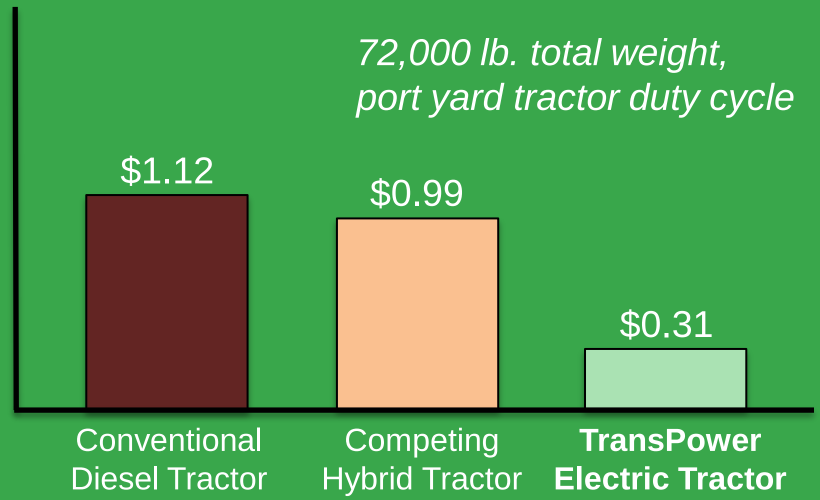
	U.S. Addressable Market (Annual)	
	Units	**Revenue**
Port Drayage Trucks	4,000	$1,000M
Refuse Trucks	10,000	$2,500M
Local Delivery Trucks	20,000	$5,000M
Yard Tractors/Cargo Equipment	2,500	$500M
School Buses	10,000	$2,000M
TOTAL	**46,500**	**$11,000M**

Business Case for E-Trucks: Energy Savings

Energy Cost Per Mile – Class 8 On-Road Truck



Energy Cost Per Mile – Class 8 Off-Road Yard Tractor



Source: UC Riverside/CE-CERT Dynamometer Lab.

$378,000 in energy savings over 300,000 miles

$121,500 in energy savings over 150,000 miles

Progression of TransPower EV Business

2011-2013

Product Development & Proof-of-Concept

2014-2016

Product Testing & Refinement

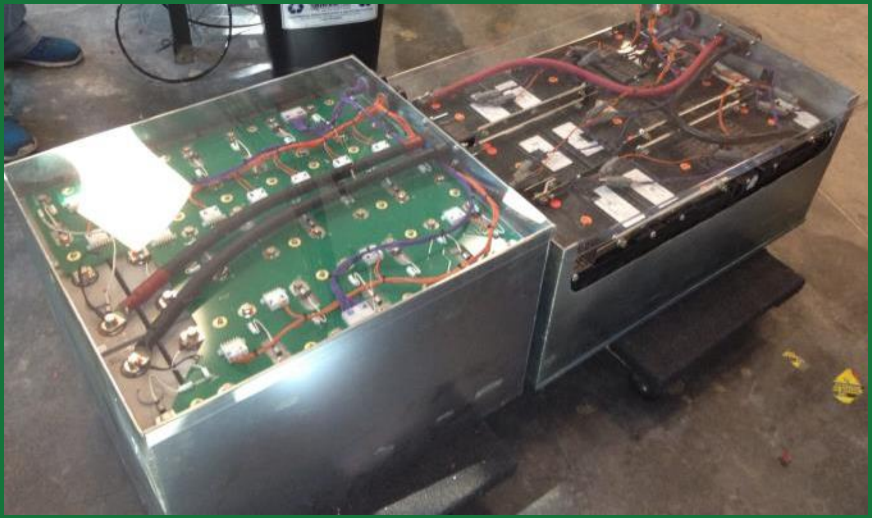
2017-

Commercial-Scale Manufacturing

Stationary Energy Storage

Adapting our vehicle technologies…

- Battery integration
- DC to AC conversion
- Energy management controls



To new stationary applications

- Renewable energy integration
- Disaster preparedness
- Wayside energy storage for trains

$35M in Investments Committed to Date

California Energy Commission: $19 million

U.S. Federal Government: $6 million

- **U.S. Department of Energy**
- **U.S. Environmental Protection Agency**
- **U.S. Department of Transportation**

California Air Resources Board, Air Quality Districts, and Ports: $6 million

Other public and private sources: $4 million

Development of Natural Gas Plug-In Hybrid Class 8 Trucks (NGPH-8)
PIR-13-012, CPR 1

James S. Burns, Ph.D.

10/18/2015

33 slides

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Electric Drayage Truck with CNG Range Extension

- Our current EV drayage truck and its use
  - 80,000lb GCVW based on Navistar Prostar
  - 300kW peak motor power
  - 172 kWh usable battery energy (80%DOD)
  - 2.6kWh/mile demonstrated drive cycle demand
  - 7% bridge grades on standard route
  - EV range of 80-100 miles
- Proposed truck with range-extending APU
  - Drop energy storage to 115kWh (80%DOD)
  - Add APU using a 3.7L Ford CNG engine
  - Increase range target to 135-200 miles

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- Electric drayage truck range is currently limited by affordable ESS capacity to 80-100 miles
- A serial hybrid APU can displace weight, volume and cost of ESS sufficient to buy its way onto our truck AND provide meaningful added range
- Meaningful total range in this application would be on the order of 135 miles plus reserve – the distance from Bakersfield to Long Beach

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Objectives for the APU

- Energy and power requirements for APU
  - 50-70 engine shaft hp average over 8 hours
  - 100-200 shaft hp peak for 5 minute bursts
- CEC program goals
  - Fuel economy in g/hp-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

- $900k over 33 months
- 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
- Our plan is to build and install two Smart Generator Modules (APUs) on two trucks – Siemens NG catenary and a truck TBB
- These are fully integrated truck system, with limited demonstration during drayage testing
- APU emissions/fuel economy will be verified

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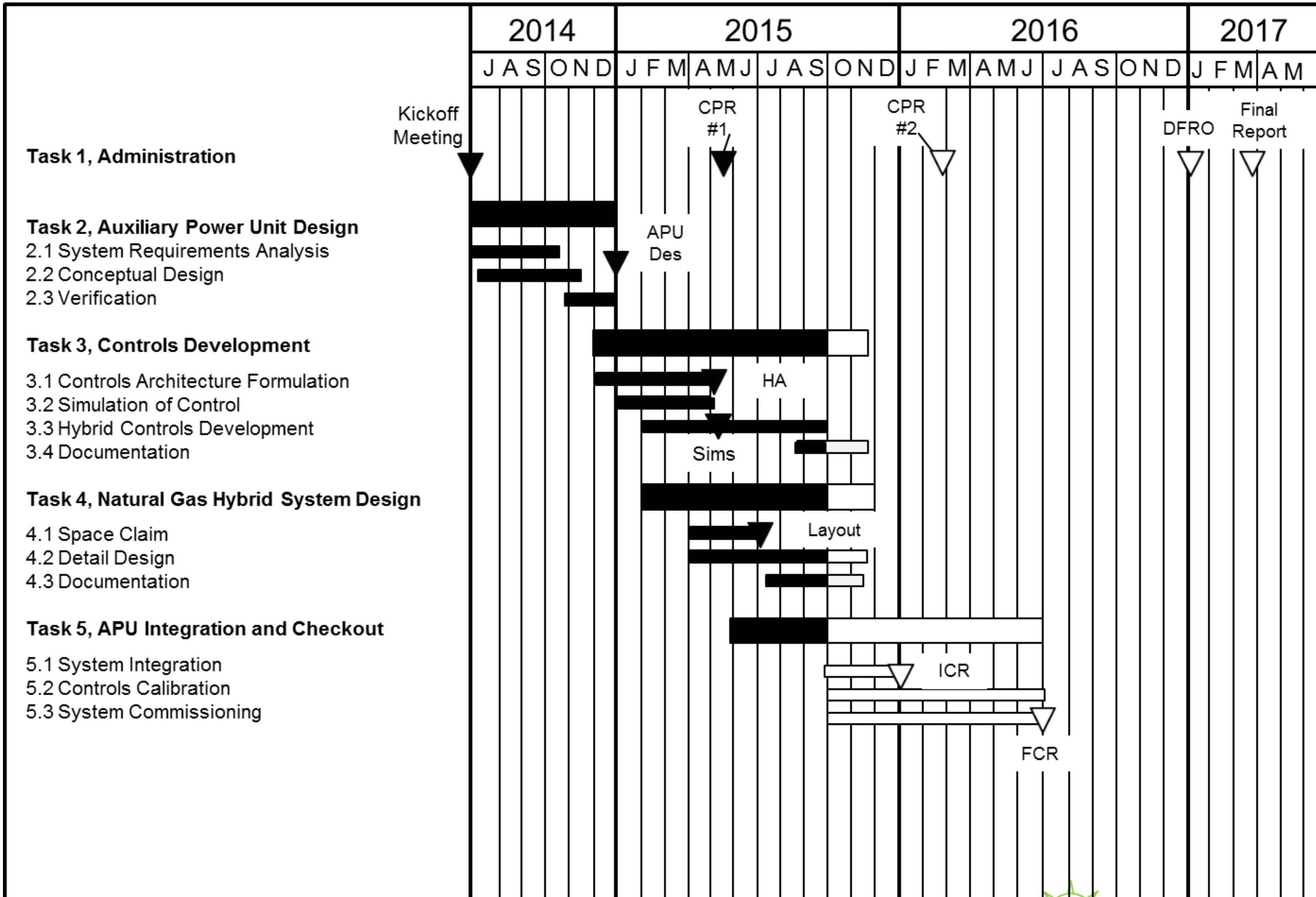
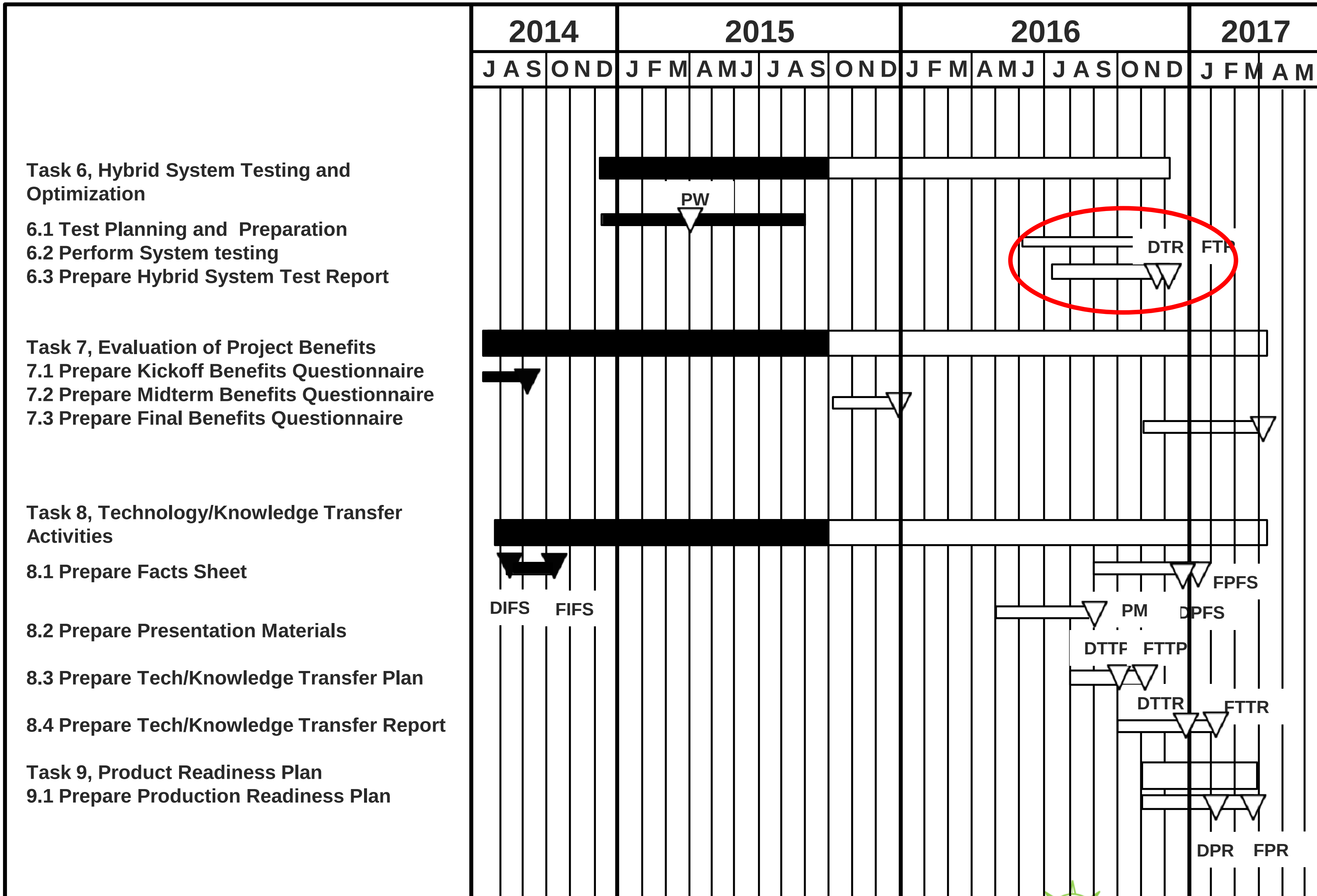

2014
2015
2016
2017
J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M
Kickoff Meeting
CPR #1
CPR #2
DFRO
Final Report
Task 1, Administration
Task 2, Auxiliary Power Unit Design
2.1 System Requirements Analysis
2.2 Conceptual Design
2.3 Verification
APU Des
Task 3, Controls Development
3.1 Controls Architecture Formulation
3.2 Simulation of Control
3.3 Hybrid Controls Development
3.4 Documentation
HA
Sims
Task 4, Natural Gas Hybrid System Design
4.1 Space Claim
4.2 Detail Design
4.3 Documentation
Layout
Task 5, APU Integration and Checkout
5.1 System Integration
5.2 Controls Calibration
5.3 System Commissioning
ICR
FCR



2014
2015
2016
2017
J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M
Task 6, Hybrid System Testing and Optimization
6.1 Test Planning and Preparation
6.2 Perform System testing
6.3 Prepare Hybrid System Test Report
Task 7, Evaluation of Project Benefits
7.1 Prepare Kickoff Benefits Questionnaire
7.2 Prepare Midterm Benefits Questionnaire
7.3 Prepare Final Benefits Questionnaire
Task 8, Technology/Knowledge Transfer Activities
8.1 Prepare Facts Sheet
8.2 Prepare Presentation Materials
8.3 Prepare Tech/Knowledge Transfer Plan
8.4 Prepare Tech/Knowledge Transfer Report
Task 9, Product Readiness Plan
9.1 Prepare Production Readiness Plan
PW
DTR
FTR
DIFS
FIFS
FPFS
PM
DPFS
FTTP
DTTR
FTTR
DPR
FPR

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

TransPower Engineer's wish list

- Dyno data on 3.7L NG engine mechanical output, fuel consumption and criterion pollutant maps sufficient to verify:
  - Generator behavior matching assumptions
  - Satisfaction of program fuel efficiency goal and $/mile economics assumptions
  - Satisfaction of criterion pollutant goals @ generator-matched operating points for average power and peak power estimates for the use scenarios outlined
- Access to two engines and emissions mandated hardware and dyno cal ECMs for easy prototyping in our vehicle and test cell
- Technical advice and POC

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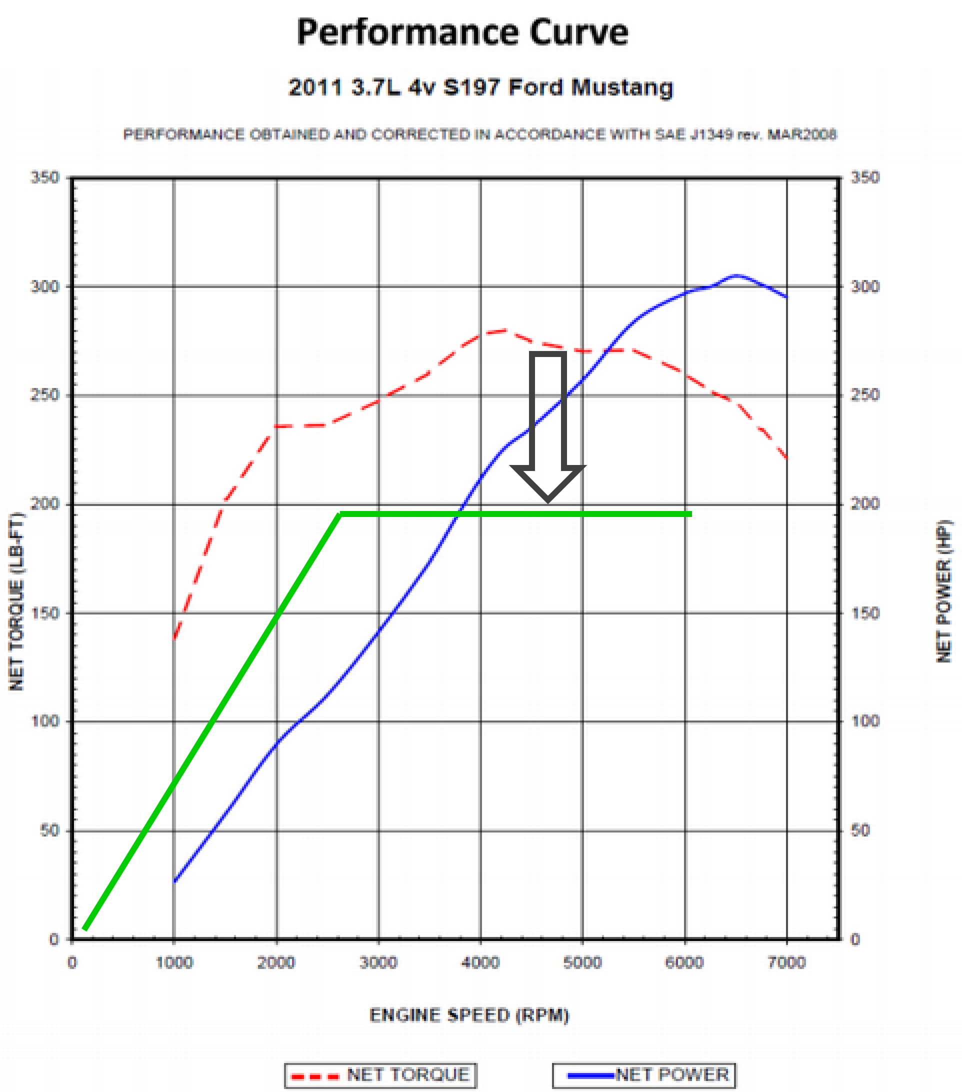
- Links of a non-existent supply chain
  - Ford Engine and related hardware
  - CNG conversion parts
  - ECU and control code
- Specialty, locked ECU programming chain
  - We elected to develop our own engine code
- No engine dyno data for NG operation
  - We elected to develop our own dyno data
- CNG make or buy
  - We elected to use COTS CNG storage

Related 3.7L Ford Engine Specs

- Subtract 10% for NG
- Peak torque at 4200rpm
- High torque out to 5500rpm
- Typical peak efficiency at ¾ redline=5000rpm
- Matches the JJE operating range
- Provides 240 ft lb (325 Nm) at 5000rpm
- 200hp net above 4000rpm



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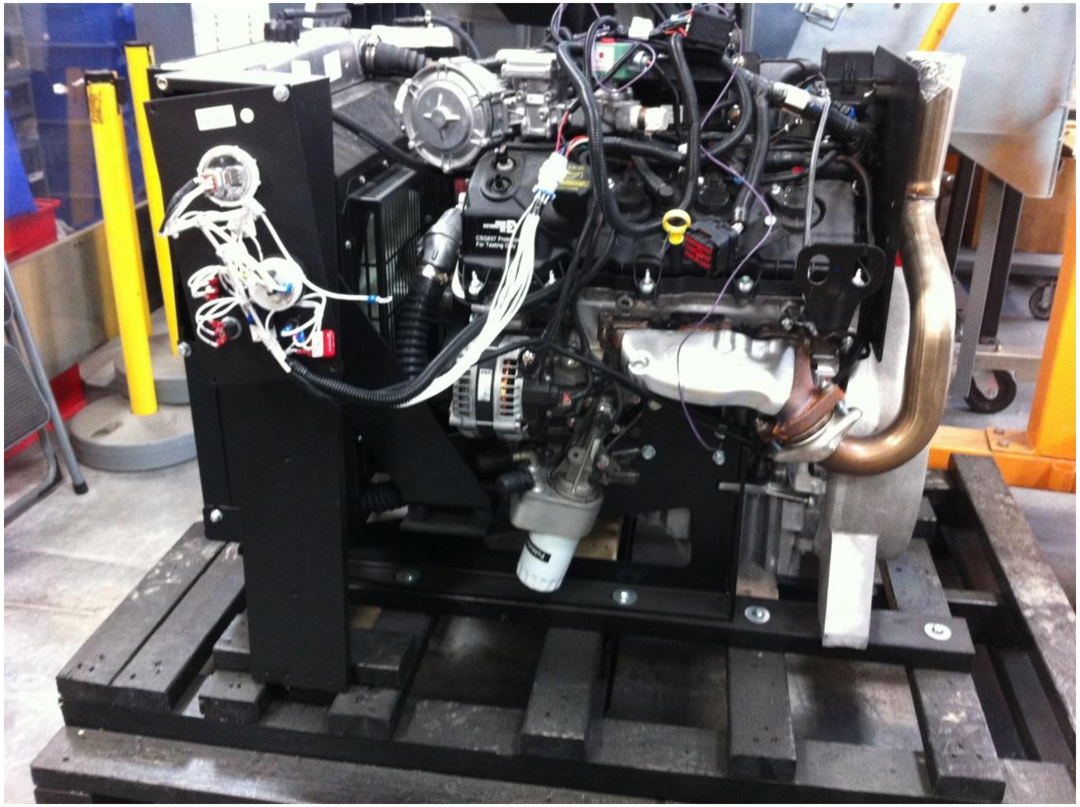
Siemen’s catenary truck application of our test bed engine

3200 RPM max for the stationary powerplant



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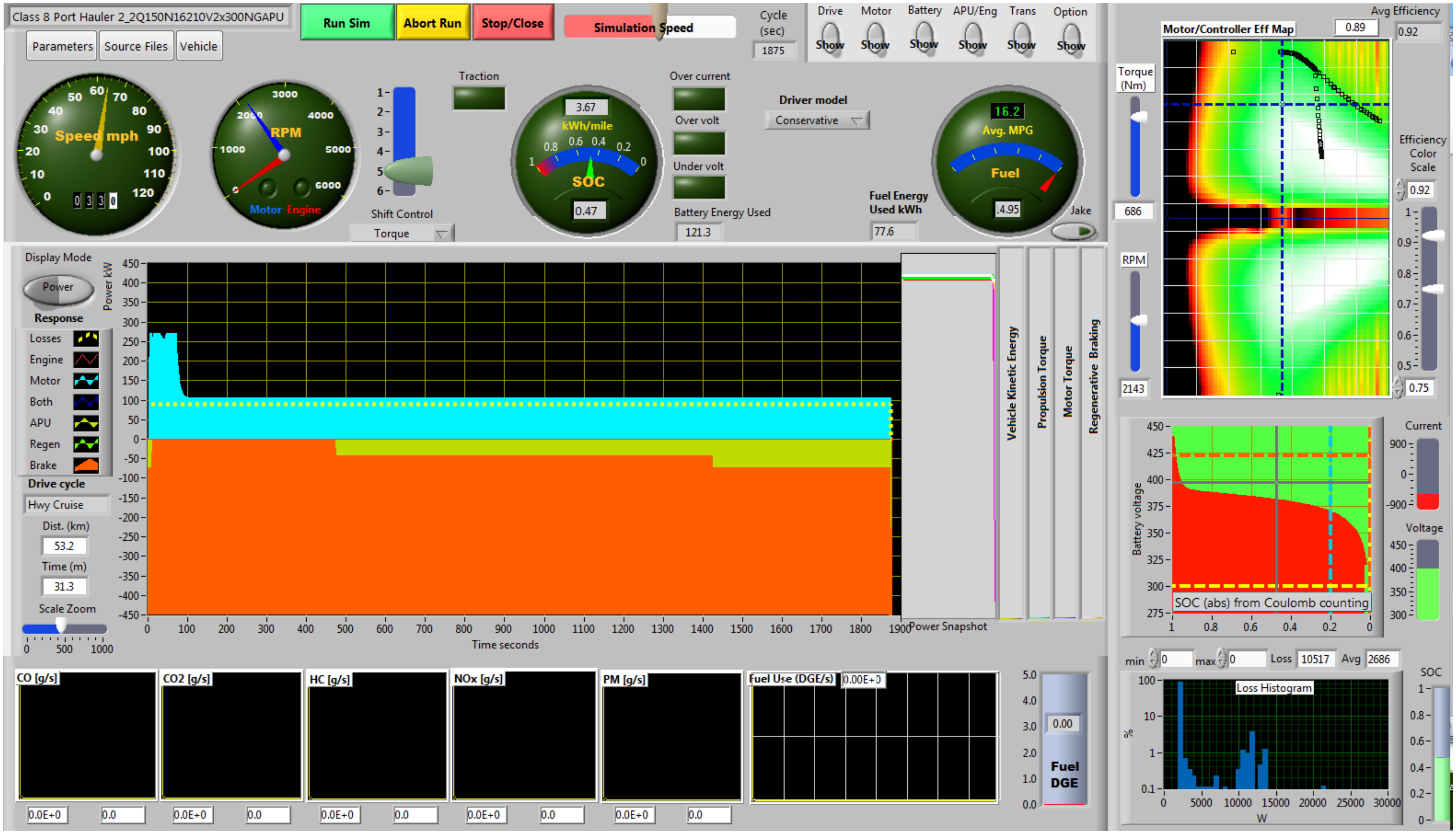
APU Voltage Support for the DC link

- Bridge climb requires 8-900A from DC link
- Target 1.5C Calb 400, or 2C Voltronix 300's
- This is 600A on the DC bus from the ESS and leaves 200-300A for the APU
- At 400V this requires an idealized 80-120kW, and realistically 100-150kW peak power to the DC bus from the gen set

- Validates System Go-No go decision
- HD FTP drive cycle used in stacked format
- Key outcomes sought:
  - Impact of ESS capacity choice
  - Charge depletion threshold (SOC min)
  - Impact of control on emissions


Class 8 Port Hauler 2_2Q150N16210V2x300NGAPU
Run Sim
Abort Run
Stop/Close
Simulation Speed
Cycle (sec)
1875
Drive
Motor
Battery
APU/Eng
Trans
Option
Show
Avg Efficiency
Parameters
Source Files
Vehicle
Speed mph
RPM
Motor Engine
Traction
Shift Control
Torque
kWh/mile
3.67
SOC
0.47
Over current
Over volt
Under volt
Battery Energy Used
121.3
Driver model
Conservative
Fuel Energy Used kWh
77.6
Avg. MPG
16.2
Fuel
4.95
Jake
Motor/Controller Eff Map
0.89
0.92
Torque (Nm)
686
RPM
2143
Efficiency Color Scale
0.92
0.75
Display Mode
Power
Response
Losses
Engine
Motor
Both
APU
Regen
Brake
Drive cycle
Hwy Cruise
Dist. (km)
53.2
Time (m)
31.3
Scale Zoom
Power kW
Time seconds
Power Snapshot
Vehicle Kinetic Energy
Propulsion Torque
Motor Torque
Regenerative Braking
Current
Voltage
Battery voltage
SOC (abs) from Coulomb counting
min
max
Loss
10517
Avg
2686
Loss Histogram
SOC
CO [g/s]
CO2 [g/s]
HC [g/s]
NOx [g/s]
PM [g/s]
Fuel Use (DGE/s)
Fuel DGE
0.00

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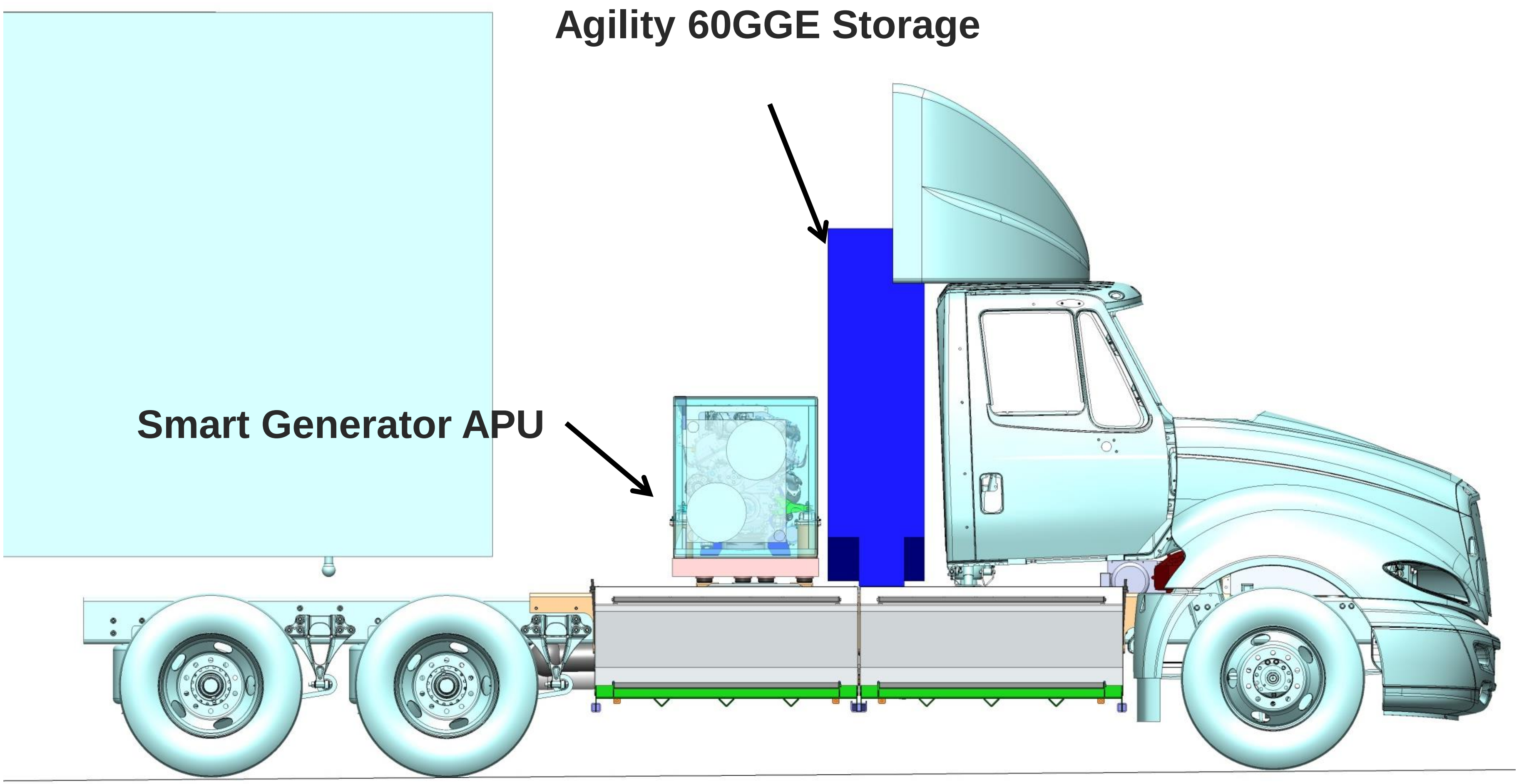
- **Simulated system efficiency to verify vehicle range using the stacked HD FTP drive cycle**
- **Used baseline control rules to explore operational impacts of ESS and SOC limits on second by second performance**
- **Sized system fuel requirements, estimated ESS performance impacts of this design, and explored limited load following rules**

Cycle/ Condition	Avg. Speed (MPH)	Trip Range (miles)	Operating Economy (kWh/mi)	Time to goal (hrs)	APU output (kW)	DC energy req'd (kWh)	Battery Capacity (kWh)	APU energy req'd (kWh)	CNG req'd (DGE)	Min Tank req'd (GGE)
eco cruise	55	135	2.8	2.45	117	378	92	286	30.1	34.2
truck cruise	60	135	3	2.25	139	405	92	313	33.0	37.5
hwy cruise	65	135	3.3	2.08	170	446	92	354	37.3	42.3
Drayage	10	75	2.7	7.50	15	203	92	111	11.6	13.2
Drayage 2 shifts	10	150	2.7	15.00	21	405	92	313	33.0	37.5

Controls Development Topics

- Constant speed-always-on is likely more efficient than on-off due to engine temp influence on efficiency
- Voltage droop during a bridge pull can likely be offset by APU throttle-up during climb – partial load-following
- Low-speed “off” mode may preserve EV perceptions of quiet operation and zero pollution
- Route learning and self-optimization are interesting new potentials if progress permits
- Wanted partner with engine ECM available in a dyno-calibrated version – it was not to be



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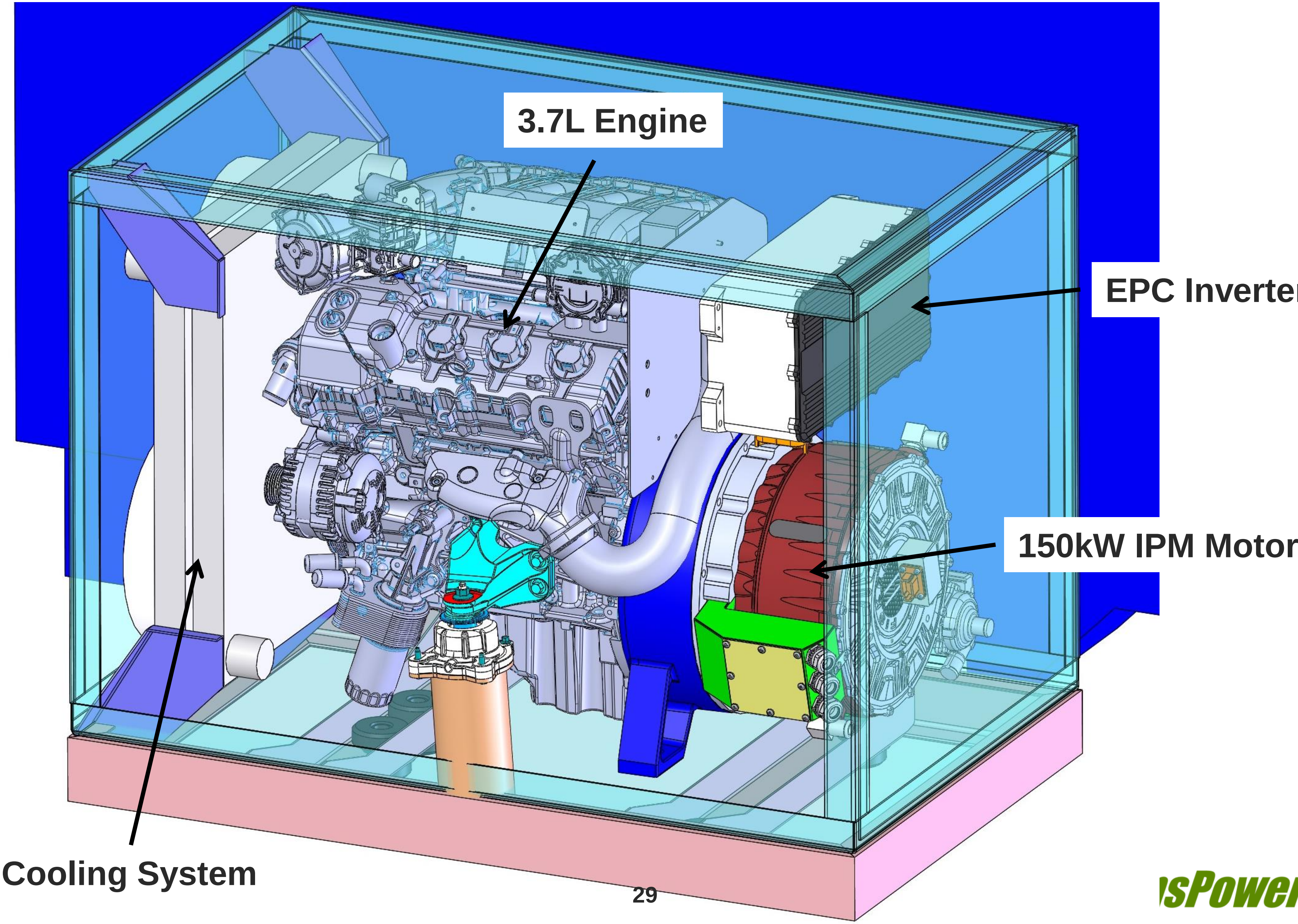
3.7L Engine
EPC Inverter
150kW IPM Motor
Cooling System

- Task 2. Supply chain <u>finally</u> complete and all parts in house, with testbed hardware in integration phase
- Task 3. Engine control code libraries procured, ECU, harnessing, and injector specs all selected, engine, APU code in development
- Task 4. Vehicle configuration decided: CNG storage chosen, ESS size chosen, performance verified in simulation, and truck code in development

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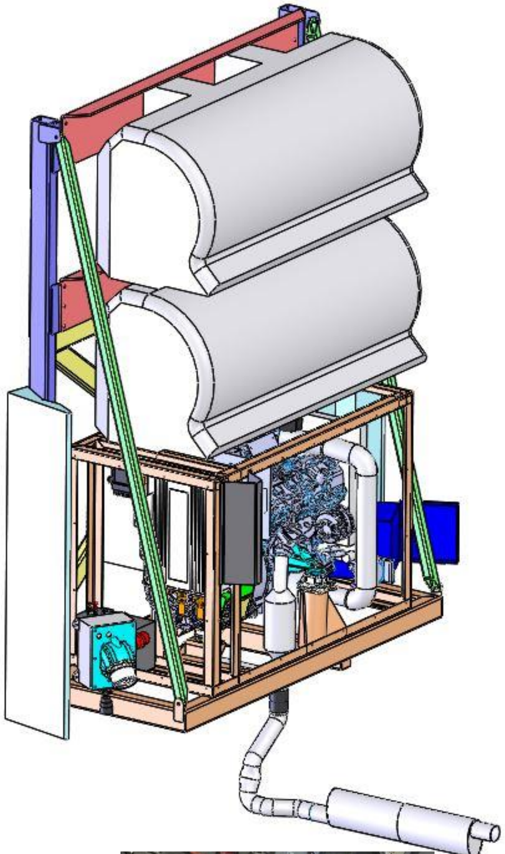
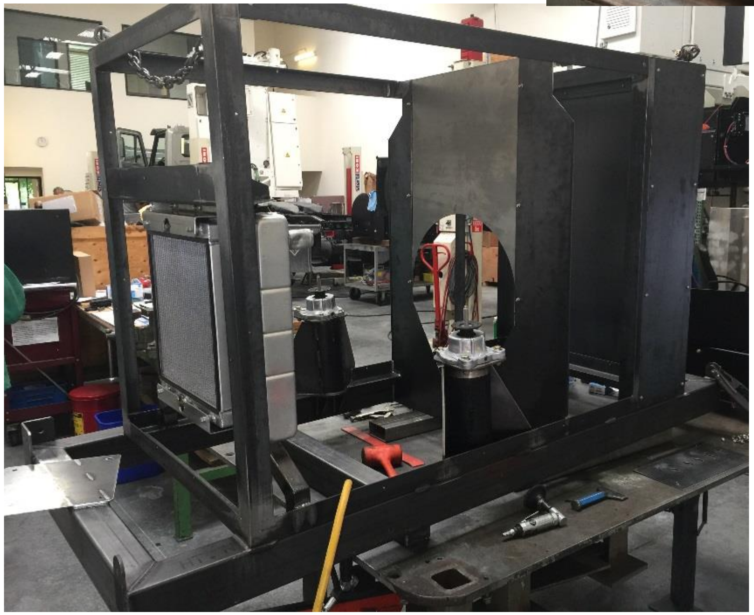



EMERGENCY SHUT OFF
VALVE INSIDE
CNG


WARNING



Questions?