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

<table>
<thead>
<tr>
<th>Motive Drive Subsystem</th>
<th>Power Control and Accessory Subsystem</th>
<th>Energy Storage Subsystem</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Cost-effective, high power density electric motors</td>
<td>• Flexible, models-based controls</td>
<td>• Low cost, high energy batteries</td>
</tr>
<tr>
<td>• Automated manual transmission</td>
<td>• Onboard inverter-charger units</td>
<td>• Robust, modular pack design</td>
</tr>
<tr>
<td></td>
<td>• Efficient electric accessories</td>
<td>• Advanced battery management</td>
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</table>
Adaptable to Many Applications

Class 8 On-Road Trucks

Yard Tractors

School Buses

Cargo Handling Equipment
## U.S. Market Potential – Electric Drive Systems

<table>
<thead>
<tr>
<th></th>
<th>U.S. Addressable Market (Annual)</th>
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<tbody>
<tr>
<td></td>
<td>Units</td>
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<tr>
<td>Port Drayage Trucks</td>
<td>4,000</td>
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<tr>
<td>Refuse Trucks</td>
<td>10,000</td>
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<tr>
<td>Local Delivery Trucks</td>
<td>20,000</td>
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<tr>
<td>Yard Tractors/Cargo Equipment</td>
<td>2,500</td>
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<tr>
<td>School Buses</td>
<td>10,000</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td>46,500</td>
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</table>
**Business Case for E-Trucks: Energy Savings**

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

Source: UC Riverside/CE-CERT Dynamometer Lab.

$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
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
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
• 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
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
Task 1, Administration

Task 2, Auxiliary Power Unit Design
2.1 System Requirements Analysis
2.2 Conceptual Design
2.3 Verification

Task 3, Controls Development
3.1 Controls Architecture Formulation
3.2 Simulation of Control
3.3 Hybrid Controls Development
3.4 Documentation

Task 4, Natural Gas Hybrid System Design
4.1 Space Claim
4.2 Detail Design
4.3 Documentation

Task 5, APU Integration and Checkout
5.1 System Integration
5.2 Controls Calibration
5.3 System Commissioning
### 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

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*TransPower*
• 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
• 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
• 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
Siemen’s catenary truck application of our test bed engine

3200 RPM max for the stationary powerplant
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
- 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

<table>
<thead>
<tr>
<th>Cycle/Condition</th>
<th>Avg. Speed (MPH)</th>
<th>Trip Range (miles)</th>
<th>Operating Economy (kWh/mi)</th>
<th>Time to goal (hrs)</th>
<th>APU output (kW)</th>
<th>DC energy req'd (kWh)</th>
<th>Battery Capacity (kWh)</th>
<th>APU energy req'd (kWh)</th>
<th>CNG req'd (DGE)</th>
<th>Min Tank req'd (GGE)</th>
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<td>313</td>
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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
3.7L Engine
EPC Inverter
150kW IPM Motor
Cooling System
• Task 2. Supply chain finally 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
Questions?