Zero Emission Cargo Transport ZECT 1 San Pedro Bay Ports

Vehicle Technologies Office Annual Merit Review

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South Coast Air Quality Management District

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[Project ID # ELT 115]

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ZECT I Overview

Timeline

- Project Award: 8/12
- Contractor Kickoff: 11/12
- Project Completion: 3/31/20

Contractors & Projects

- TransPower – Battery Electric and Series Hybrid Drayage Trucks
- US Hybrid – Battery Electric and Parallel Hybrid Drayage Trucks
- NREL – Data Acquisition and Analysis

Barriers & Challenges

- Evaluate Performance and Reliability
- Promote Market Acceptance
- Data Collection and Analysis

Budget

DOE:	$4,169,000
Cost Share:	$5,205,641
Total Cost:	$9,374,641
DOE Expended:	$3,945,212*

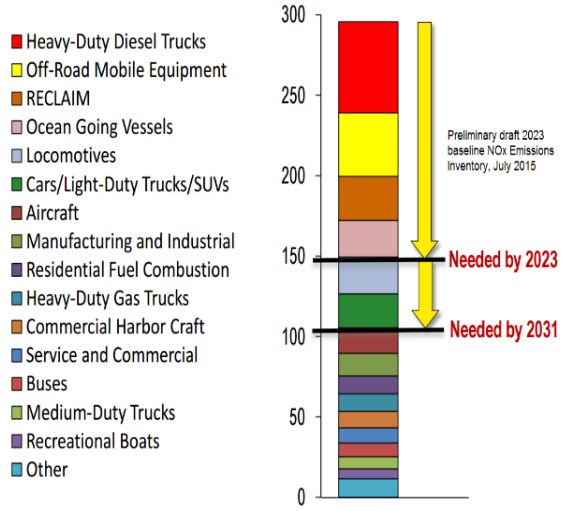
*All funds to be expended

Acknowledgements

- UC Riverside
- Fleet Operators: TTSI, Cal Cartage, Three Rivers Trucking, NRS, SA Recycling, Knight Transportation Services, Pasha Stevedoring and Terminals, BAE Systems, and Terminalift

Relevance: Goals & Objectives

- **Project Objectives:**
  - Develop and Demonstrate four Zero-Emission (ZE) capable Class 8 drayage trucks
  - Two BET and Two PHET platforms with all-electric-range (AER)
  - Complete demonstration with Fleet Operators
  - Complete data collection and analysis
- **Results:**
  - All four vehicle platforms completed
  - All four platforms demonstrated AER capability
  - Data collection and Final reports and analyses completed for all projects
- **Impact:**
  - Technology advancement and demonstration, and accelerated deployment of zero-emission transportation in drayage operations in California
  - Increased interest by consumers to choose ZE transportation for goods movement



Source: South Coast Air Quality Management District, "Goods Movement", 2016 AQMP White Paper, October 2015.

Technical Objectives

	BET		PHET	
Developer	TransPower	US Hybrid	TransPower	US Hybrid
No. of Trucks	4	2	2 - Series Hybrid	3 - Parallel Hybrid
Chassis	International Prostar	International Prostar	International Prostar	Peterbilt 384
Traction	Dual IPM Motors	Induction Motor	Dual IPM Motors	IPM Motor
Motor	300 kW	320 kW	300 kW	222 kW (402 kW total)
Transmission	Automated Manual	Direct Drive	Automated Manual	Automatic
APU Displ./Fuel	N/A	N/A	3.7L / CNG	8.9L / LNG
APU Power	N/A	N/A	65-110 kW	180 kW
Battery/Fuel Storage Capacity	215 – 315 kWh	180 - 240 kWh	138 kWh	80 kWh
			60 DGE	72 DGE
Charger On-Board	70 kW	60 kW	70 kW	20 kW
Recharge/Refuel Time	2.5-4 hrs	3-4 hrs	2 hrs	3-4 hrs
			10-15 min	10-15 min
Drayage Range (miles)	75-100 (@215 kWh)	70-100	250+	250+
	110-150 (@ 315 kWh)		35-50 AER	30 AER

Technical Progress: TransPower BETs

Accomplishments

- 4 EDD trucks built; two year demonstration completed by Q3 2017
- 3 additional EDDs added under separate funding during ZECT 1 project
- Two years of demonstration with multiple fleets
- Testing with UCR for performance and emissions

Performance Metrics

- Matched performance of baseline diesel power, torque, loads
- Energy Efficiency: 2.1 kWh/mi (avg.) ~ 18 mpDGE*
- Range: 60-65 miles fully loaded / 215 kWh storage
- 1.5 kWh/mi unloaded
- 37,000/43,000 amassed miles 4/7 trucks, respectively

Main Challenges

- Battery quality - three different suppliers; systems troubleshooting
- Reduced payload capacity for some drayage operators
- Driver availability, incentives, security to operate trucks

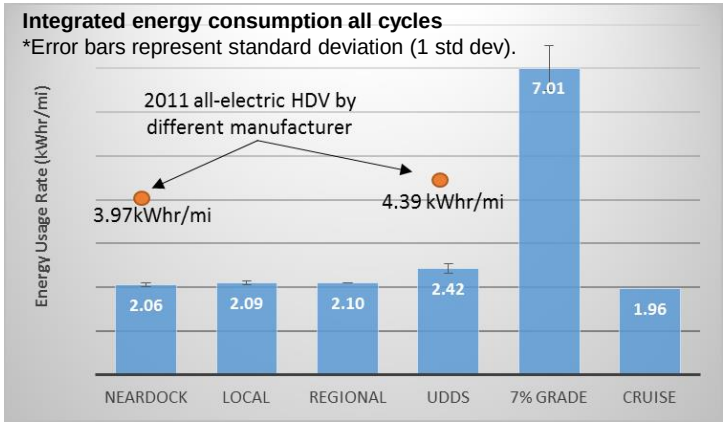
*** Conversion Factor - kWh/mi / mpg (DGE) 37.656**

EDD-2 undergoing testing on UC Riverside chassis dynamometer.

Test result summary of transient and steady state tests, UCR 2015

Drive Cycle	Avg. Speed	Duration	Distance	Avg. Power	Net Energy	Total Energy Used	SOC usage
	Mph	Sec	mi/cycle	kW	kWh	kWh/mi	%
Near-Dock	6.61	3051	5.6	12.7	13.85	2.06	5.23
Local	9.53	3367	8.9	21.8	23.85	2.09	9.19
Regional	23.39	4231	28.1	45.8	65	2.1	27.52
UDDS	19.13	1061	5.6	53.8	17.35	2.42	6.28
7% Grade	34.39	507	4.9	200.5	32.91	7.01	16.55
Cruise	50.17	1461	20.4	102.8	41	1.96	23.34

tests performed with an equivalent gross vehicle weight of 72,000-lb, or average fully loaded weight of drayage truck at San Pedro Bay Ports



Technical Progress: TransPower BETs

TransPower

Lessons Learned

- TransPower: “trucks need to have absolute minimum of 100 miles of operating range to gain even niche market acceptance, and 150-200 miles of range to gain broader acceptance.”
- Battery Supplier’s support and stability are critical

Next Steps

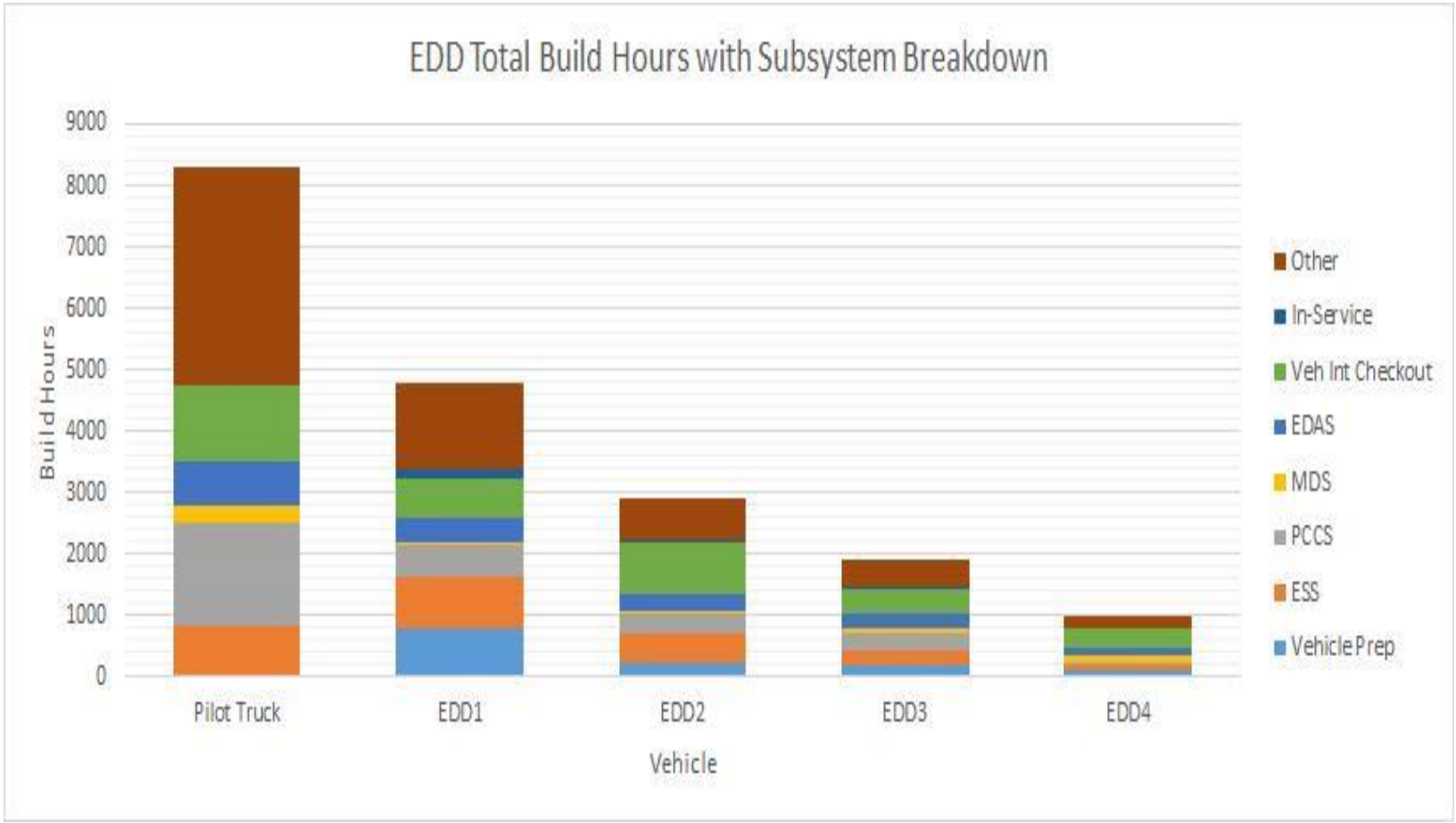
- TransPower improved electric drive system, added Nissan NMC battery modules on Peterbilt Class 8 tractor
- 308 kWh battery storage achieved 131 miles fully loaded @60mph at PACCAR test track
- EDD 1, 3, and 4 upgraded with fuel cell range extenders and NMC batteries under a separate project; in service at TTSI

EDD 2 with loaded trailer

EDD 3

EDD 4 with loaded trailer

TransPower BET (EDD) Build

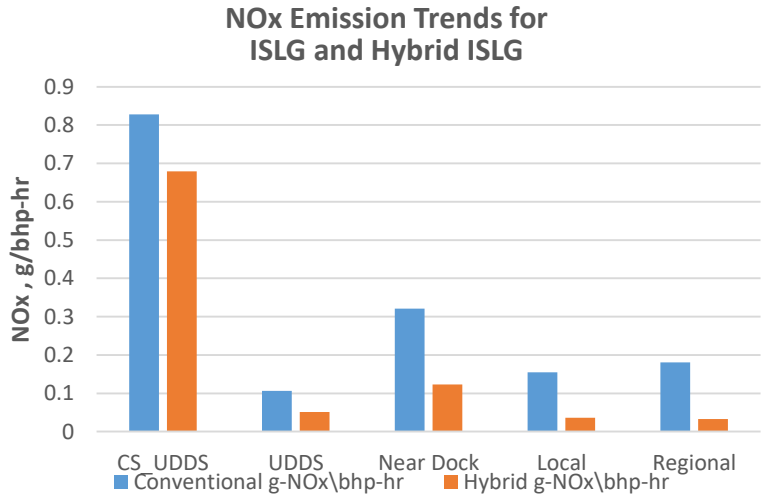


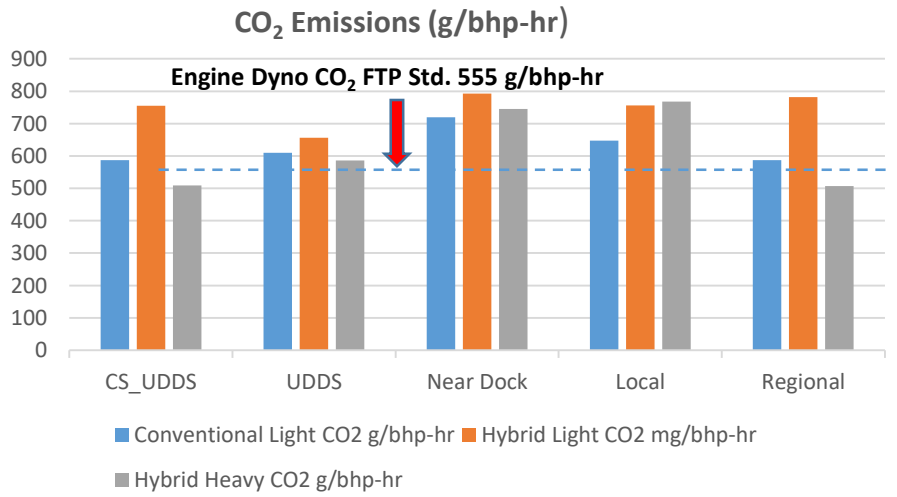
Technical Progress: US Hybrid – Parallel PHETs

- Accomplishments
  - Developed and demonstrated integration of ICE and Electric motor
  - Powertrain comparable to larger ICE power and torque
  - 80 kWh battery allows 30 miles all Electric
  - Seamless transition from all Electric to Hybrid
  - Favorable reviews from drivers
  - UCR testing completed
- Performance Metrics
  - Power / Torque : 580 h.p. / 1250 lb.-ft.
  - Energy Efficiency : 3.82 kWh/mi ~ *9.8 mpDGE (NREL)
  - Fuel Economy: CO_2 compared to ISLG (UCR)
  - NOx emissions 64% lower (UCR)
  - AER: 30 mile (80 kWh to 10%SOC)

Both US Hybrid PHETs at TTSI

* Conversion Factor - kWh/mi / mpg (DGE) 37.656

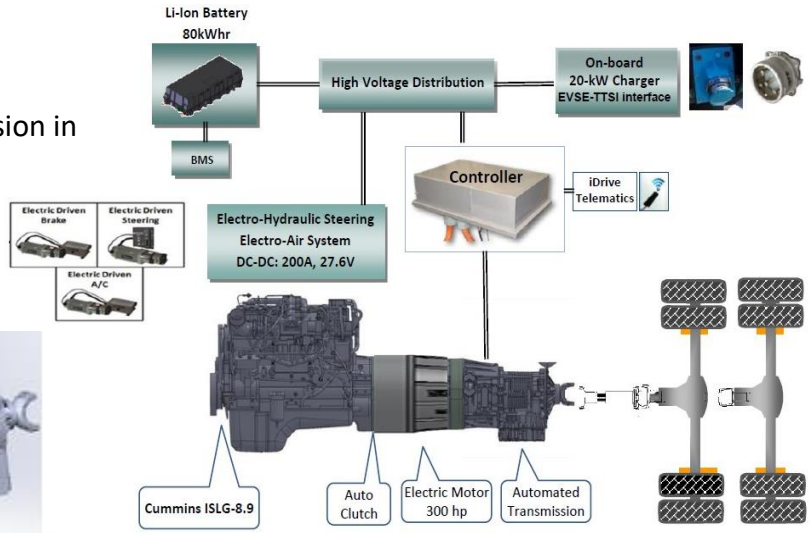




Technical Progress: US Hybrid – Parallel PHETs

- Main Challenges
  - Full AER potential not demonstrated in drayage use
  - Limited EVSE infrastructure and EVSE demand >> supply
  - Energy systems designed to maintain 50% SOC; drivers not required to plug-in
- Lessons Learned
  - Increased confidence in working with controller hardware for engine and hybrid systems
  - Feasibility of upfitting existing ICE trucks with hybrid system
- Next Steps
  - USH developing three Parallel Hybrid vehicles under DOE grant
  - NZE CNG engine and geo-fencing features to operate zero-emission in sensitive areas
  - PHETs (ZECT 1) to continue use at TTSI

US Hybrid PHET with load

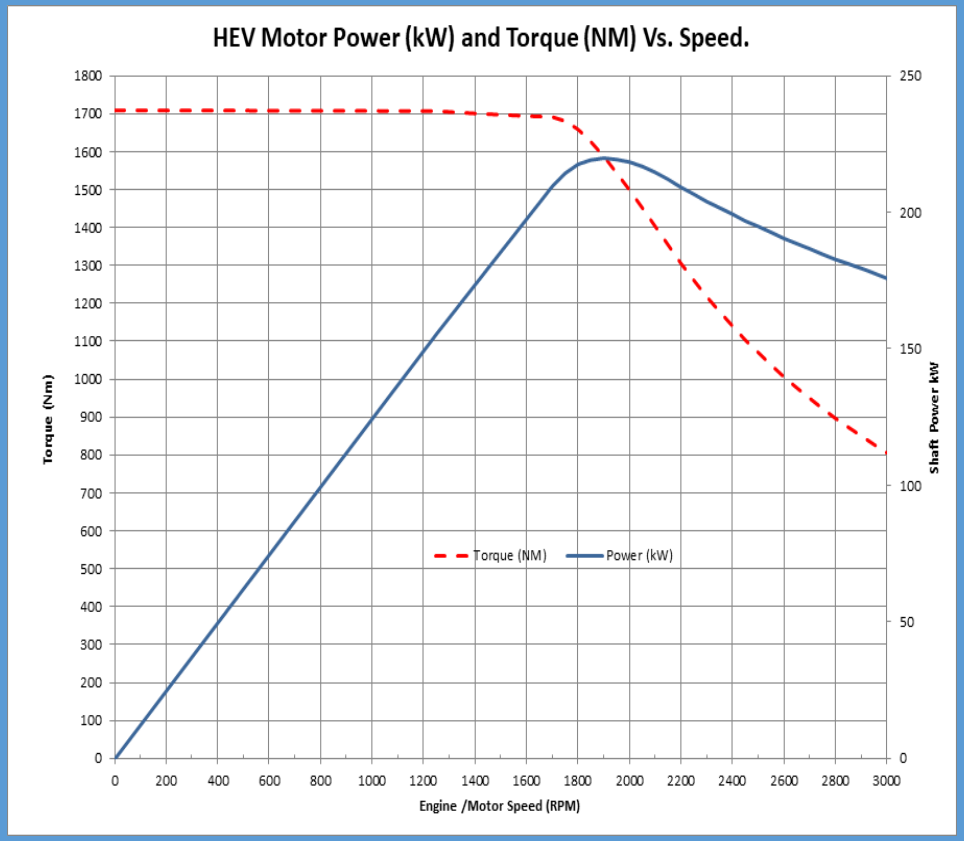


US Hybrid Plug-In Hybrid Powertrain

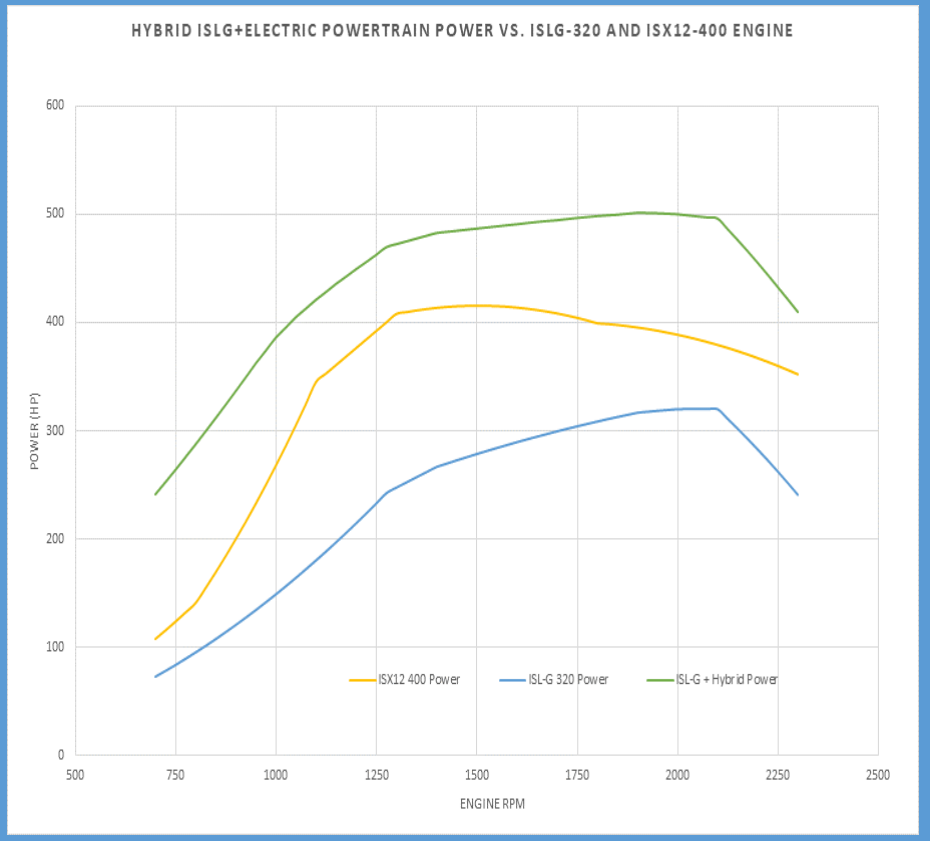
240 kW dual electric motors

ISLG - Auto Clutch – Motors - Transmission

US Hybrid PHET - Power/Torque



US Hybrid PHET Power and Torque electric motor



US Hybrid PHET Combined Power ISLG + Electric Motor

Technical Progress: US Hybrid - BETs

- Accomplishments
  - 2 BETs completed; demonstration continued through end of project
  - 2nd truck outperformed 1st truck: 180 kWh vs 280 kWh storage capacity
  - Met most objectives
- Performance Metrics
  - Sufficient Power and Torque
  - Energy Efficiency: 2.17 kWh/mi (NREL) ~ 17 mpDGE*; 2.5 kWh@65,000-lbs, 0% grade (USH)
  - Range: 100 miles @65,000-lbs GCWR
  - Maximum speed: 60 mph @65,000-lbs; 65 mph unloaded
  - Gradeability: 28 mph@6% grade @65,000-lbs; max 20%

		Local		Freeway	
Description	**Unit**	**with Trailer**	w/o Trailer	**with Trailer**	w/o Trailer
Average Power	**kW**	70	28	104	50
Energy Efficiency	**kWh/mi**	4.2	1.6	3	1.3

BET Energy Efficiency Performance – US Hybrid Final Report

* Conversion Factor - kWh/mi / mpg (DGE) 37.656

US Hybrid eTruck™ #1 layout with EnerDel battery pack 180kWh (11 packs)

US Hybrid eTruck™ #2 layout with A123 battery pack 280kWh (6 Packs)

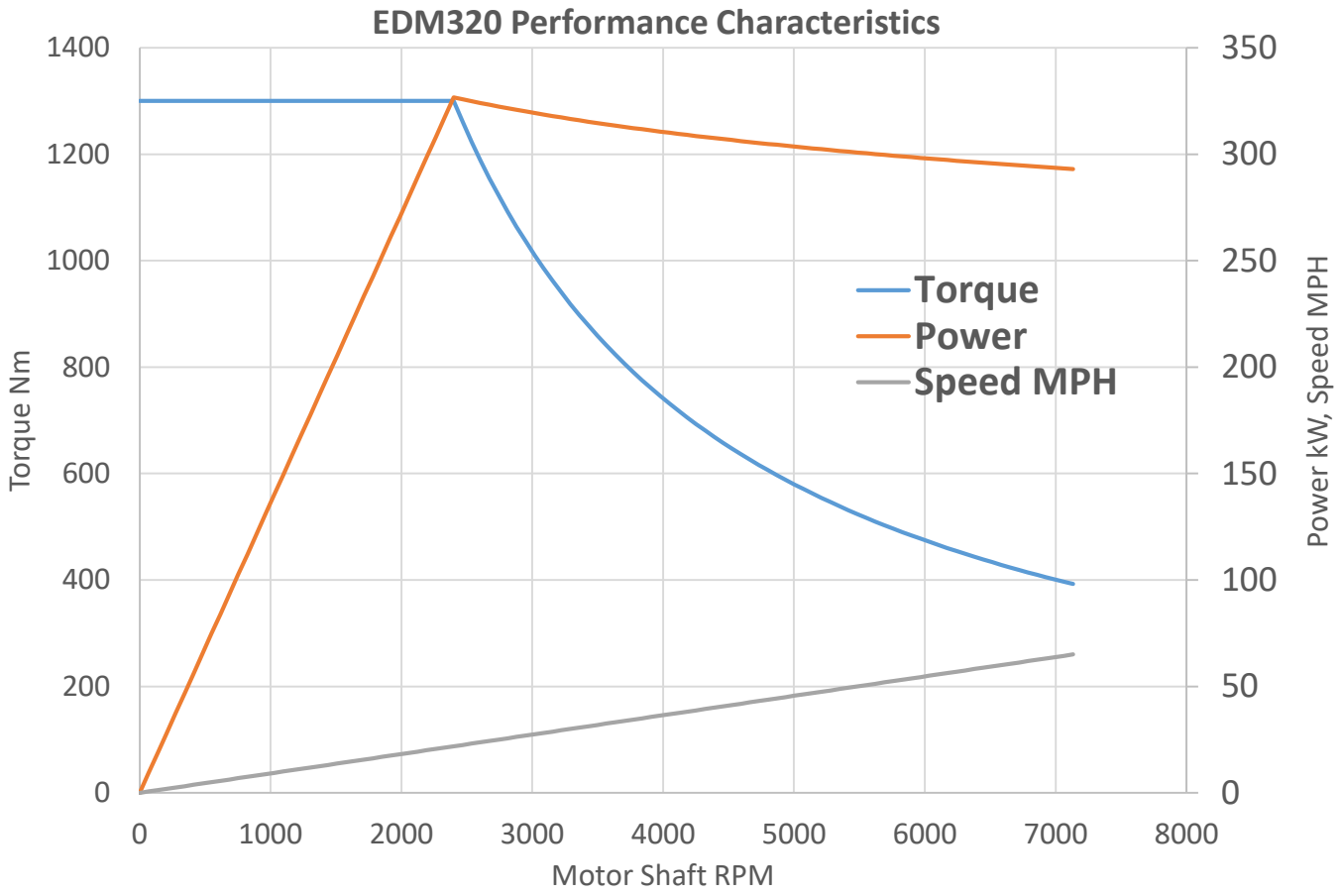
Technical Progress: US Hybrid - BETs

- Main Challenges
  - Energy storage: Initial Batteries lacked sufficient range, power, life
  - Battery suppliers: technical performance and charge profiling
  - Thermal management
  - Driver availability, incentive-to-operate trucks
- Lessons Learned
  - Higher energy density and battery quality
  - Increased confidence in working with controller hardware for engine and hybrid systems
  - Upgrade of traction drive to maintain power delivery at lower Voltage
  - Loss of payload due to added weight of batteries needed to increase range
- Next Steps
  - US Hybrid will pursue customers to continue use
  - Drayage customers looking towards zero-emission transport

US Hybrid eTruck No. 2 at South Coast AQMD January 10, 2020

US Hybrid eTruck with loaded trailer

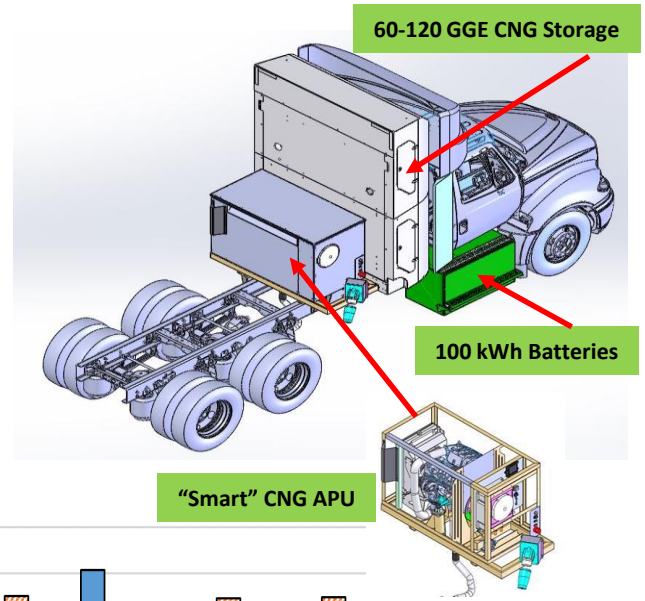
US Hybrid BET - Power/Torque

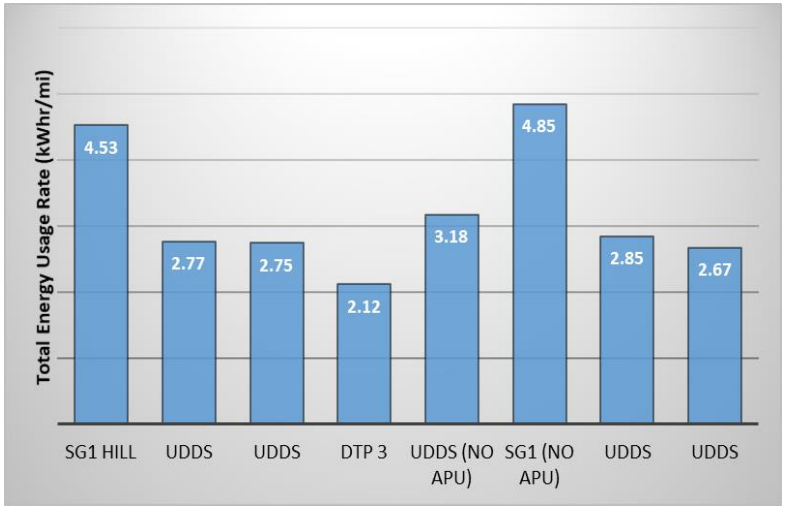


US Hybrid BET Power and Torque electric motor

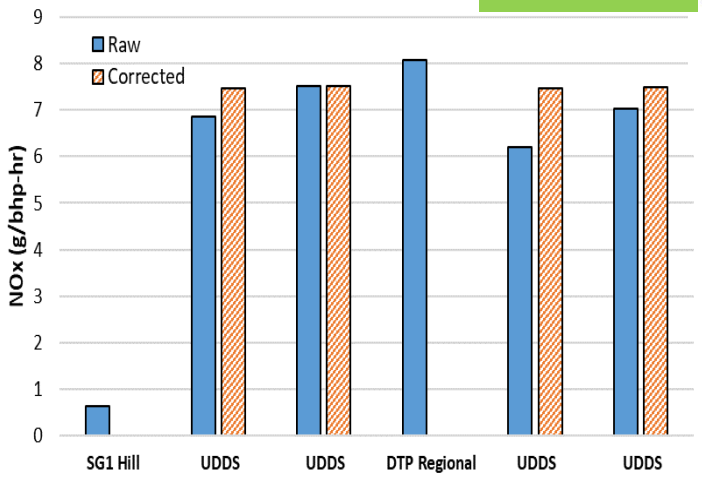
Technical Progress: TransPower – Series PHETs

- Accomplishments
  - 2 Series PHETs completed; demonstration continued through end of project
  - 2nd truck outperformed 1st truck
  - Near-dock operations demonstrated
- Performance Metrics
  - Energy Efficiency: 2.12 – 4.85 kWh/mile (UCR)
  - Genset significantly reduced battery use
  - High NOx and PM emissions
  - Miles accrued: limited by technical issues and usability





Integrated energy consumption all cycles @72,000-lbs GCVW (UCR)



NOx emissions on g/bhp-hr basis for each test run (UCR)

Technical Progress: TransPower – Series PHETs

- Main Challenges
  - APU: engine controller information was not available = limited power and high emissions
  - Thermal management of small, rear-mounted APU
- Lessons Learned
  - Series hybrid concept demonstrated technically
  - Small APU: technically feasible to significantly supply power, reduce and prolong batteries
  - Access to engine controller is critical and likely reduce emissions
  - Minimum APU power needed is 110 kW as originally proposed
  - Rear-mounted APU has airflow limitations that impact genset to cool and limits optimum performance
- Next Steps
  - This platform is not currently expected to continue usage with drayage fleet operators

TransPower PHET No. 2

TransPower PHET No. 2 w/ Trailer

TransPower PHET No. 2 rear view showing APU

TransPower PHET UCR Data

Integrated Power Results for all cycles.

Cycle n/a	Ave Speed mi/hr	Duration sec	Distance mi/cycle	Average Total Power kW	Average Generator Power kW	Average Battery Power kW	SOC usage %
SG1 Hill	40.79	448	5.07	184.39	35.12	149.27	11
UDDS	18.39	1061	5.42	50.95	41.89	9.06	2
UDDS	18.48	1061	5.45	50.80	43.54	7.25	1
DTP 3	23.98	4229	26.65	48.11	42.74	5.38	5
UDDS (No APU)	18.31	1061	5.40	58.15	0.00	58.15	10
SG1 (No APU)	33.15	427	3.93	160.16	0.00	160.16	12
UDDS	18.46	1061	5.44	52.55	40.27	12.29	2
UDDS	18.59	1061	5.48	49.71	41.03	8.68	2

TransPower PHET No. 2 at UCR's heavy duty chassis AC transient dynamometer

Energy Results Summary for all cycles

Cycle n/a	Ave Speed mi/hr	Duration sec	Distance mi/cycle	Net Total Energy kWhr	Net Generator Energy kWhr	Net Battery Energy kWhr	Total Energy usage kWhr/mi	Generator energy usage kWhr/mi	Battery Energy usage kWhr/mi	SOC usage %
SG1 Hill	40.79	448	5.07	22.95	4.37	18.58	4.53	0.86	3.66	11
UDDS	18.39	1061	5.42	15.02	12.34	2.67	2.77	2.28	0.49	2
UDDS	18.48	1061	5.45	14.97	12.83	2.14	2.75	2.36	0.39	1
DTP 3	23.98	4229	26.65	56.52	50.20	6.32	2.12	1.88	0.24	5
UDDS (No APU)	18.31	1061	5.40	17.15	0.00	17.15	3.18	0.00	3.18	10
SG1 (No APU)	33.15	427	3.93	19.04	0.00	19.04	4.85	0.00	4.85	12
UDDS	18.46	1061	5.44	15.49	11.87	3.62	2.85	2.18	0.67	2
UDDS	18.59	1061	5.48	14.65	12.09	2.56	2.67	2.21	0.47	2

Remaining Challenges and Barriers

- **Performance and Reliability**
  - Range of Battery-Electric trucks
  - OEMs investing in R&D to develop commercially acceptable BETs
- **Market Acceptance**
  - BETs and PHETs still finding their place in fast changing technology and regulatory environment
  - Total Cost of Ownership: CapEx, OpEx, infrastructure(s)
- **Costs: batteries and drive systems and infrastructure**
  - Costs/kWh of batteries expected to continue to fall with expanding market and technology development
  - Improvements in drive systems and overall efficiencies/energy management
  - Real costs of EVSE Infrastructure coming more into view with OEM commercial vehicle roll-out projections

ZECT I Summary

Pros

- All four ZECT 1 platforms completed and demonstrated with drayage operators in the South Coast AQMD
- All platforms demonstrated sufficient power, torque, gradeability to transport most payloads
- “Hands-on” operation - drivers recognize differences and benefits of electric power: quiet, clean, power, torque
- ZECT 1 efforts increased knowledge of battery-electric technologies and management systems
- ZECT 1 efforts increased knowledge of plug-in hybrid systems from two different perspectives
- Both Hybrid platforms improved the concepts of series and parallel technologies for Class 8 trucks
  - Proof of concept for small APUs in series hybrid
  - Parallel hybrid performance comparable to larger displacement ICEs
- ZECT 1 concepts have established a new foundation for improved technologies:
  - TransPower BETs upfitted with fuel cell range extenders
  - US Hybrid developing a NZE CNG PHET with L9N and geofencing under DOE/SCAQMD grant
  - TransPower now with Meritor and Peterbilt developing Class 8 battery-electric platforms
  - Both integrators expanding into Fuel Cell heavy-duty platforms
- Drayage operators expecting customer demand for zero-emission transport

Cons

- BETs need to improve range, minimize weight and loss of payload capacity, address costs, and TCO
- Projects need a broader demonstration - increase infrastructure costs, but improve technology exposure and vehicle usage
- Range anxiety: drivers expecting > 100 mile range as standard
- Range anxiety contributed to limited demonstration
- Battery Supplier’s stability and support is significant