HEV ARCHITECTURES AND VEHICLE EFFICIENCY

PRESENTER: **MIKE DUOBA**

High Efficiency Hybrid Vehicles ARPA-E Workshop
Southfield, MI, October 12-13, 2017

ARGONNE VEHICLE SYSTEMS ANALYSIS PROGRAM

Testing PHEV / HEV / BEV since 1993

Technology Assessment

Assess state-of-the-art transportation technology for the Department of Energy and Argonne research interests

Advanced Testing Procedure Development

Adoption not possible unless test method provides fair and accurate results

Research Oriented Test Facilities

<u>4WD chassis dynamometer</u>

- Thermal Chamber: 0F to 95F
- Solar emulation

opened 2002, upgraded 2011

<u>2WD chassis dynamometer</u>

- Up to medium duty

opened 2009

Vehicle Technology Assessment

<u>Vehicle level</u>

- Energy consumption (fuel + electricity)
- Emissions
- Performance
- Vehicle operation and strategy

<u>'In-situ' component & system testing</u>

- Component performance, efficiency, and operation over drive cycles
- Component mapping

Downloadable Dynamometer Database <u>www.anl.gov/d3</u>

- Test summary results
- 10Hz data of major signals
- Analysis Presentations

HEV CONFIGURATIONS

HEV DISCUSSION IN 1995, 2001

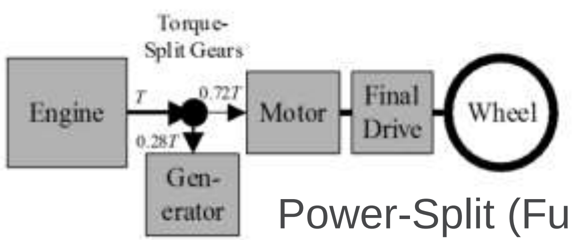
- Introduction to all the various configurations of HEVs
  - Parallel vs Series
  - Mild vs Full
  - Limitations and Strengths
  - (tested university-built prototypes)


960741

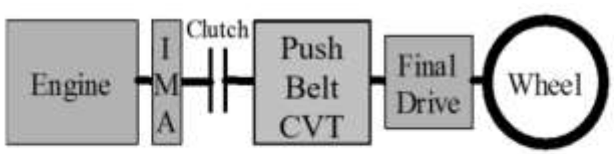
The 1995 HEV Challenge:
Results and Technology Summary

- Data Analysis from Insight and Prius (2001)
  - Hybrid functions mild vs full
  - Tested Prius and Insight on ANL Dyno

Method	Prius	Insight
Engine Start/Stop	Yes Normal operation	Yes Only in Neutral
Best Line in Map	Yes Power-split	No Manual trans
Engine Downsizing	Yes Eng 43kW, Elec 21kW	Yes Eng 49kW, Elec 10kW
Low-Load Electric Driving	Yes EOS ~ 15MPH	No Config not allow
Regenerative Braking	Yes Max ~ 15kW	Yes Max ~ 4.2kW
Transient Smoothing	Yes Drive by wire	No Connected throttle



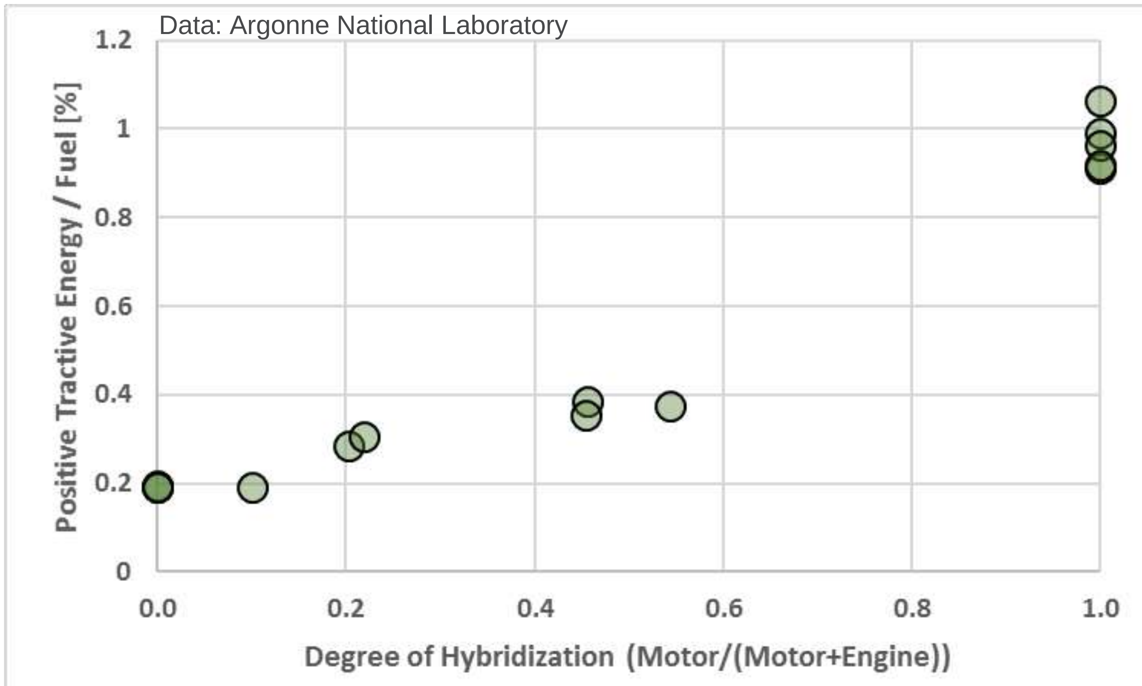
Power-Split (Full)

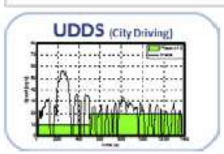


Parallel (Mild)

POSITIVE TRACTIVE ENERGY / FUEL

≅ **40%** (REGEN IS “FREE”)





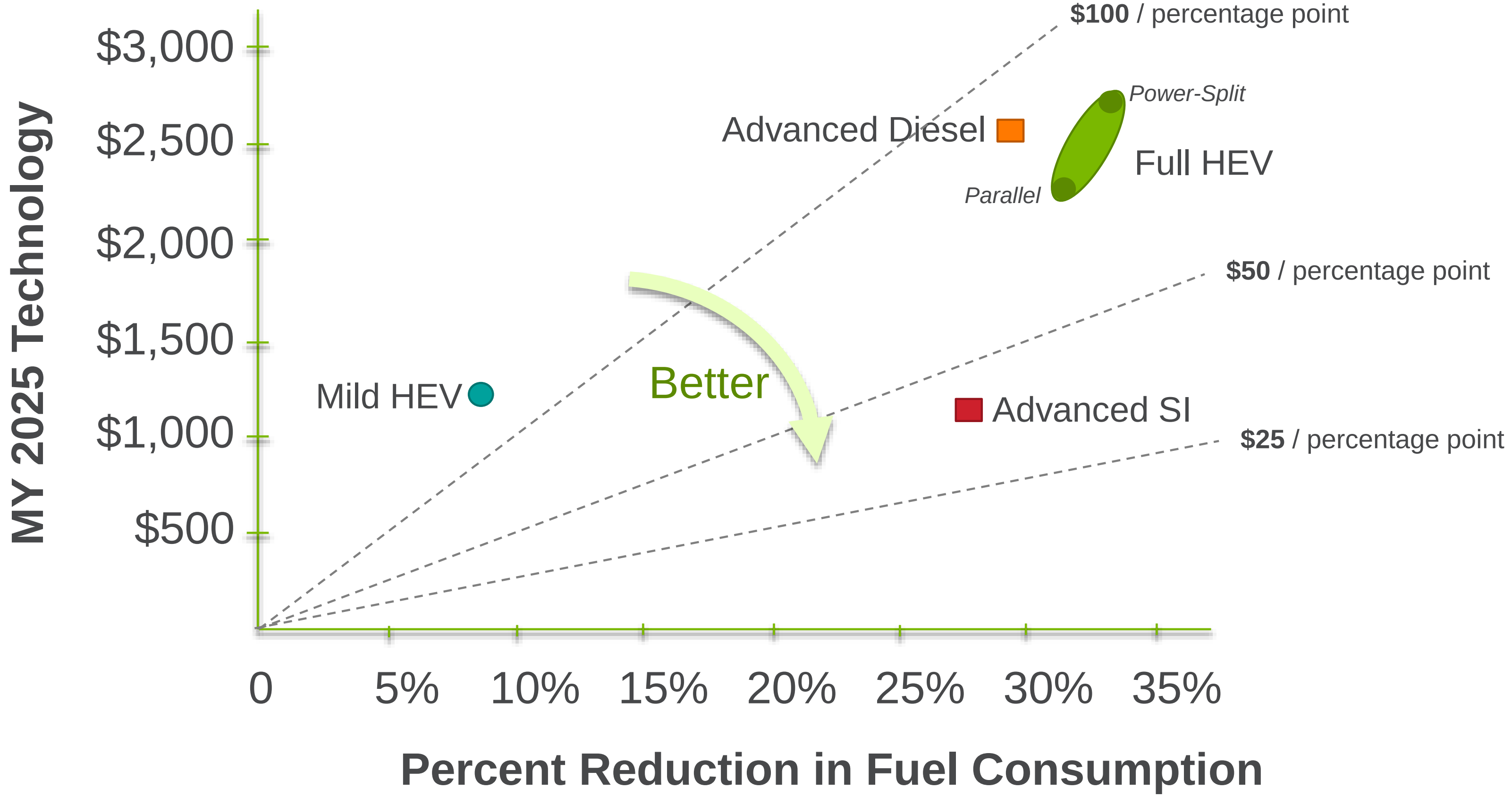
Data note:
UDDS hot start

Observations:

- Increased electrification provides efficiency increase in city type driving to a certain limit
- Pure electric Vehicles are not bound by ICE efficiency

Conventional	2012 Ford Focus
	2013 Jetta TDI
	2013 Chevy Cruze Diesel
Hybrid Electric	2013 Chevy Malibu Eco
	2013 VW Jetta HEV
	2013 Honda Civic HEV
	2010 Prius
	2013 Ford Cmax HEV
	2014 Honda Accord HEV
Battery Electric	2012 Nissan Leaf
	2013 Nissan Leaf BEV
	2015 BMW i3 BEV
	2015 Chevy Spark BEV
	2013 Ford Focus BEV

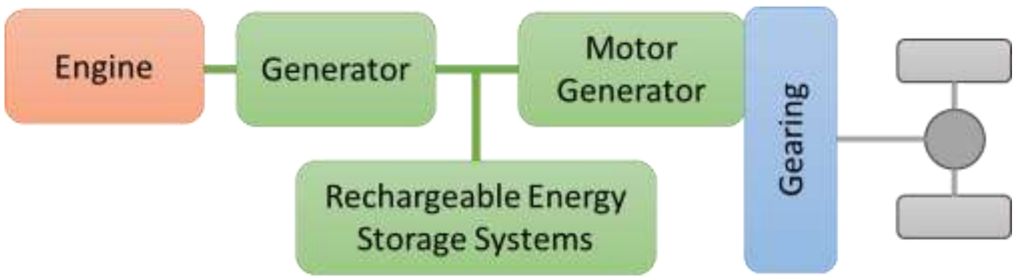
CURRENT HEV TECHNOLOGY: $ / MPG, "FULL" THE BEST HYBRID CHOICE



From: National Research Council. **2015**. *Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*. Washington, DC: The National Academies Press. https://doi.org/10.17226/21744.

WHAT ABOUT CONFIGURATION?

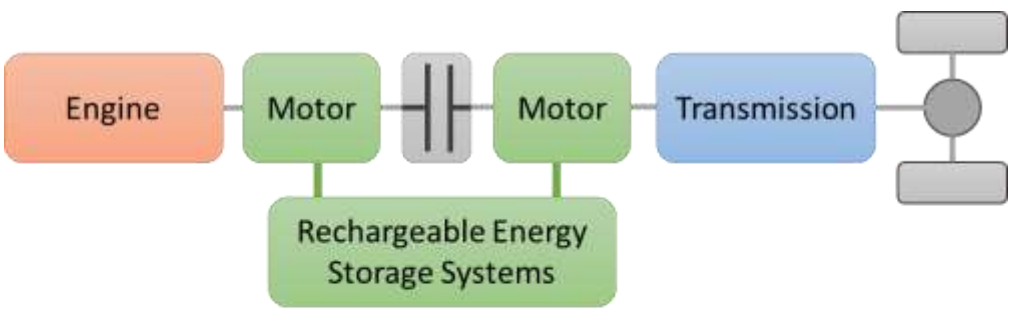
Series



PRO: Engine Operation Fully Decoupled *(good in city driving)*

CON: More Losses through motor & generator *(hurts steady driving)*

Parallel

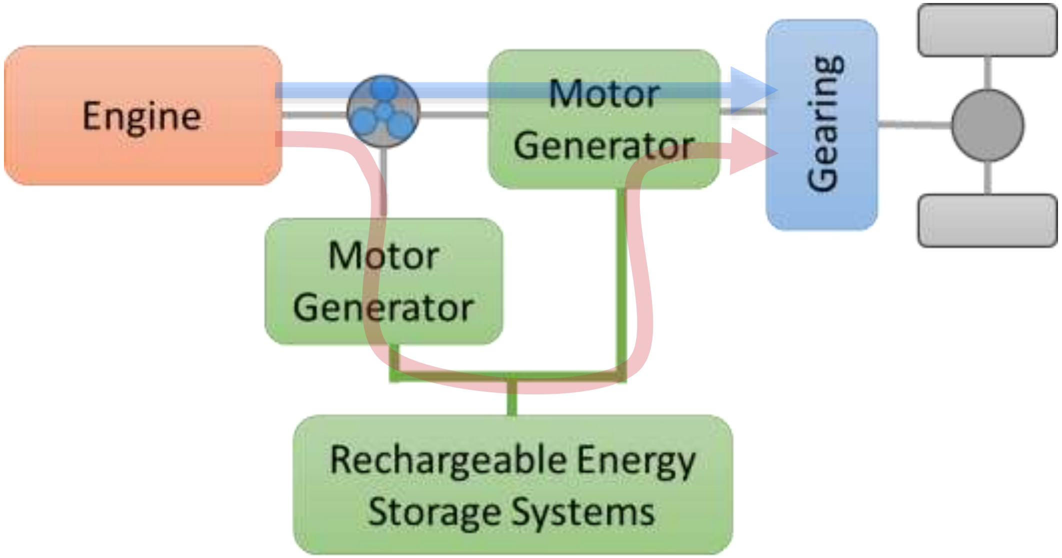


PRO: Low losses on highway, smaller motor kW (lower cost)

CON: Engine operation not as optimized. Drivability can suffer

WHAT ABOUT CONFIGURATION?

Power-Split – power flows through ***parallel*** *and* ***series*** *paths*



PRO: Engine Operation Fully Decoupled, Less losses than series HEV *(good in city driving)*

CON: "Recirculating Losses" at high speed *(more series path)*

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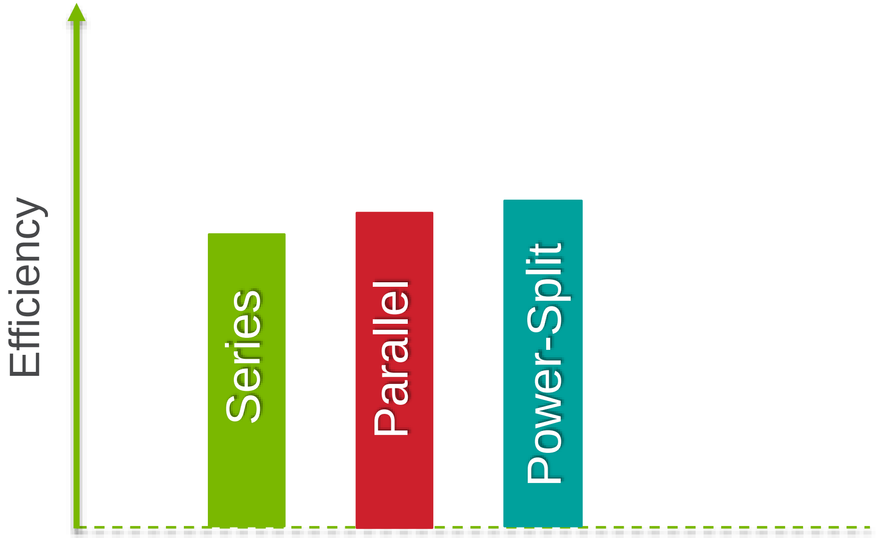
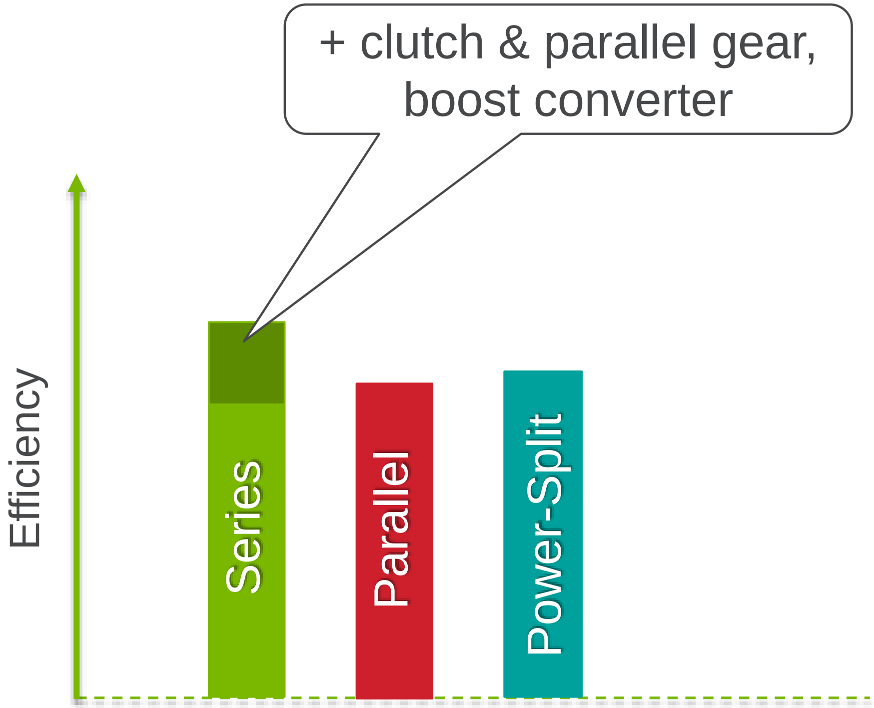
BASIC CONFIGURATIONS



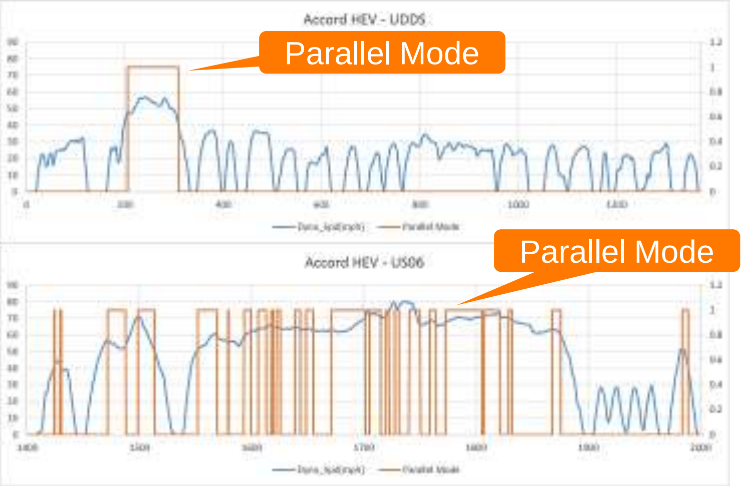
CONFIGURATION EVOLUTION

Series Config



Accord Series (+fixed gear)

Accord Parallel Operation



Data: Argonne National Laboratory

CONFIGURATION EVOLUTION

Parallel Config

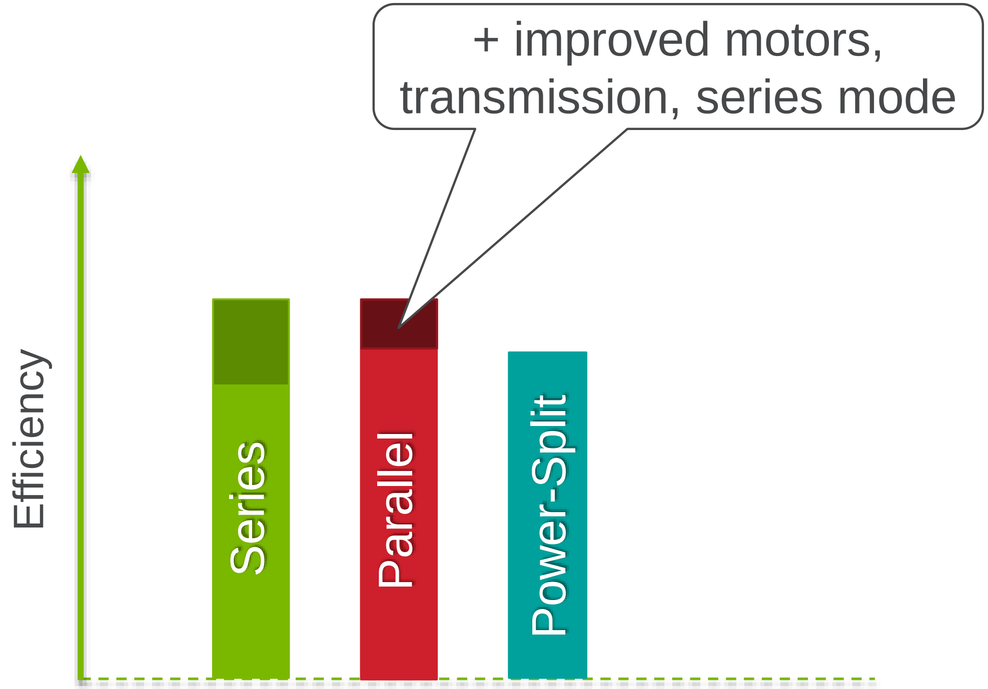


Photo: Argonne National Laboratory

Sonata Parallel P1,P2

Photo: Mariordo (Mario Roberto Durán Ortiz) Wikipedia

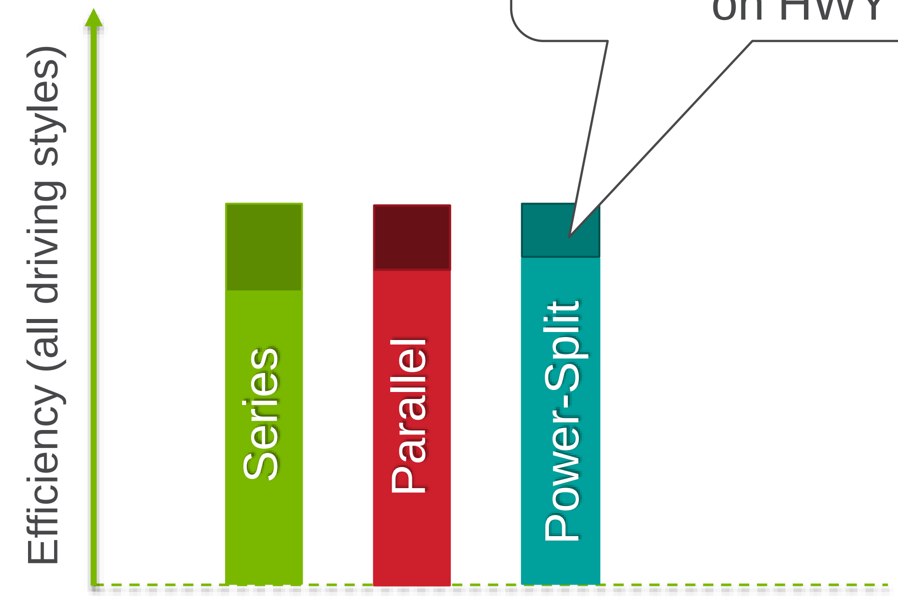
2018 Ioniq

CONFIGURATION EVOLUTION

Photo: Argonne National Laboratory

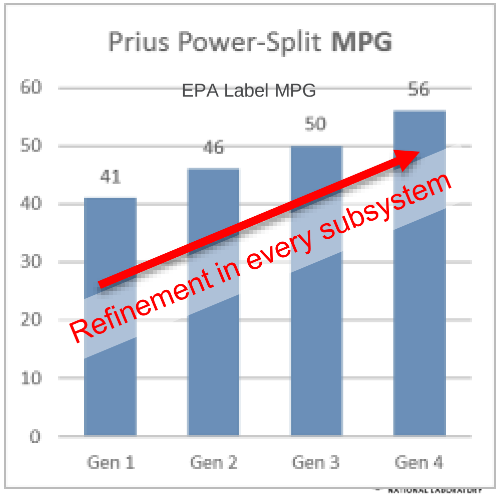
Prius Power-Split

Power-Split Config



Fuel Economy Contribution Rate
HV Control 26%
PCU 13%
Motor 16%
Battery 4%
Transaxle 13%
Engine 28%

*



***** Fushiki, S., "*The New Generation Front Wheel Drive Hybrid S*ystem," SAE Int. J. Alt. Power. 5(1):109-114, 2016, https://doi.org/10.4271/2016-01-1167

CONFIGURATION EVOLUTION – MORE COMPLEXITY

Multi-Mode, Complex Power-Split…

- *More EV mode*
- *Higher towing*
- *Higher speed, accel*

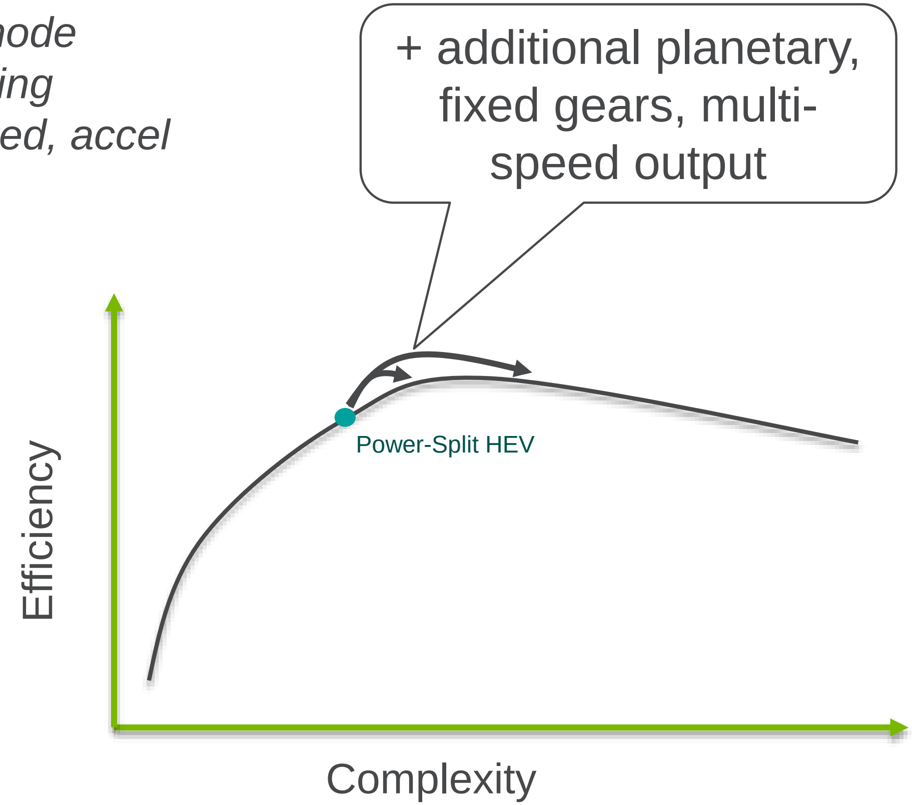


Photo: Argonne National Laboratory

Volt (Gen 2) Power-Split

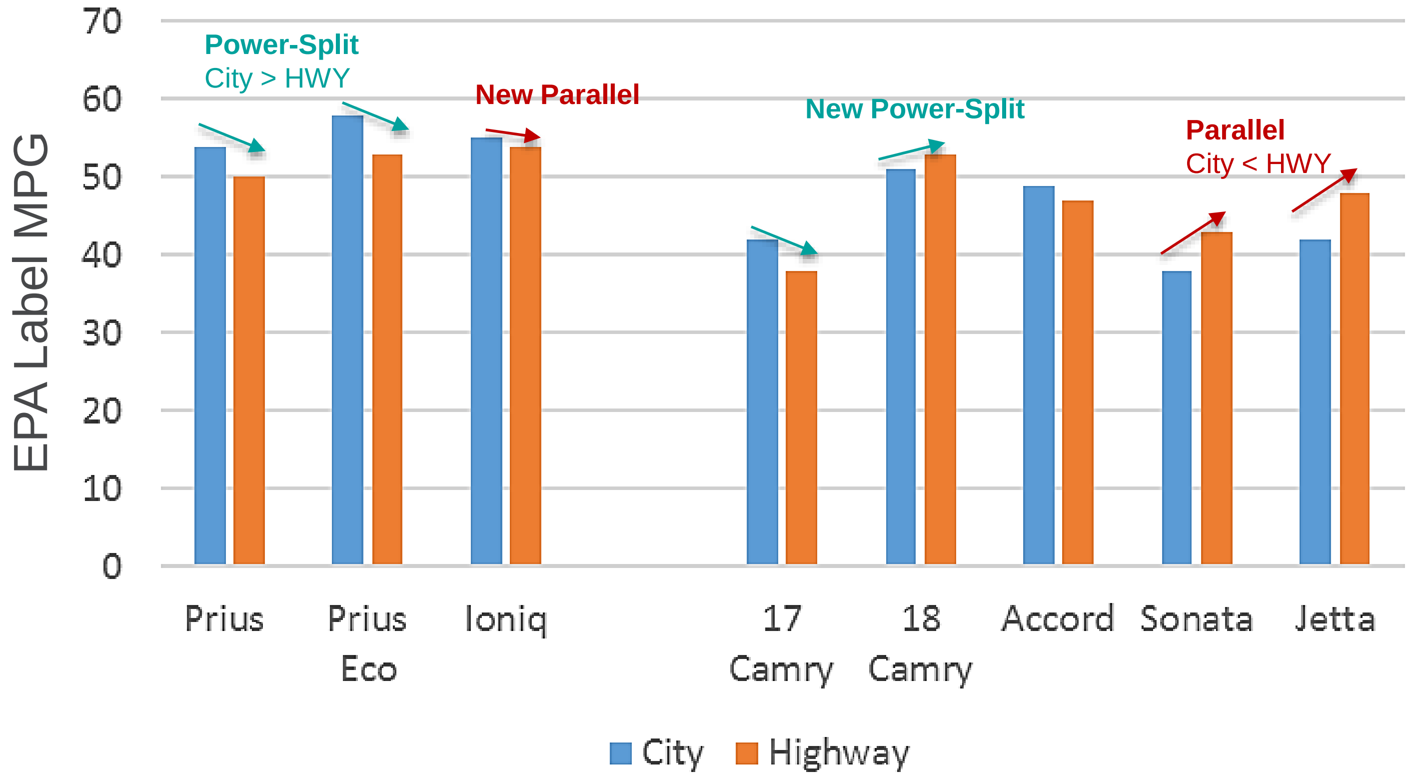
Photo: Argonne National Laboratory

Tahoe 2-Mode

Also: Lexus “Multi-Stage Hybrid”

TREND LINES IN HEV EFFICIENCY GETTING BLURRED

City vs Highway MPG was the calling card of configuration



→ Latest HEVs leave little left on the table - efficiency
Parallel ≅ Series/Parallel ≅ Power Split

CONFIGURATION CHOICE: MATTER OF OEM MANUFACTURING CHOICES

Europe

CV: Manual Transmissions
HEV: Parallel “P2”

Japan

CV: Automatic Transmissions
HEV: Power-Split (w/variations)

North America

CV: Automatic Transmissions
HEV: Power-Split (w/variations)

South Korea

CV: Automatic Transmissions
HEV: *Parallel (for cost)

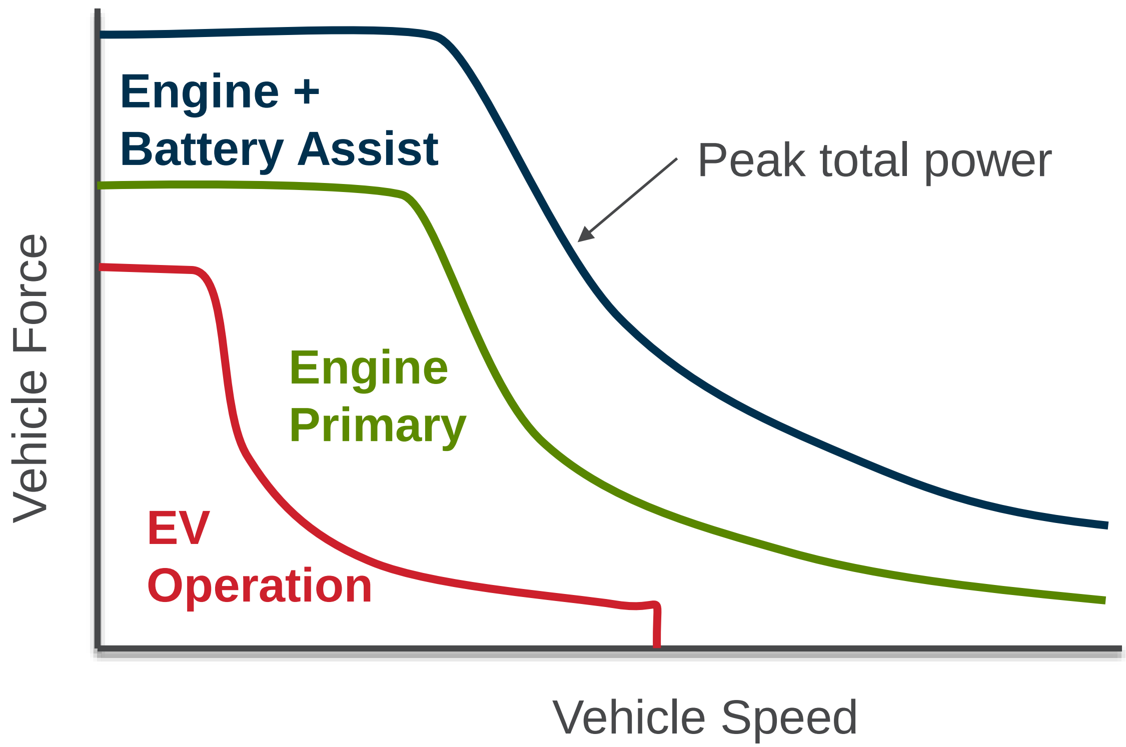
CV = Conventional Vehicle

HEV CONFIGURATIONS

HEV OPERATION & EFFICIENCY

FUNDAMENTAL HEV CONTROL CHOICE: ENGINE VS BATTERY

- EV operation envelope
  - Motor torque capability & Battery power for charge-balance *(important)*
- Engine Primary
  - **Load following** = all power by engine, no change in SOC
  - Decouple **Engine Load** from **Road Demand** for overall minimum losses



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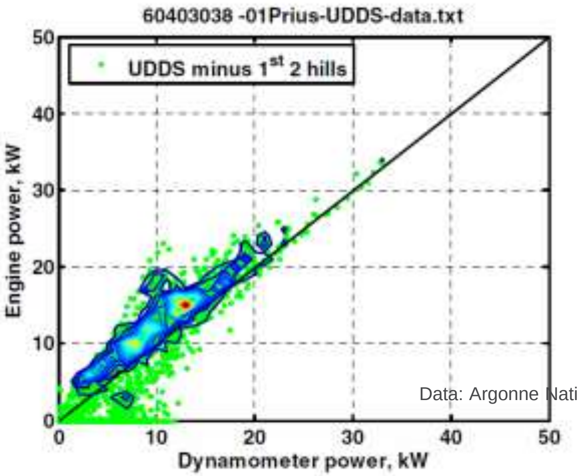
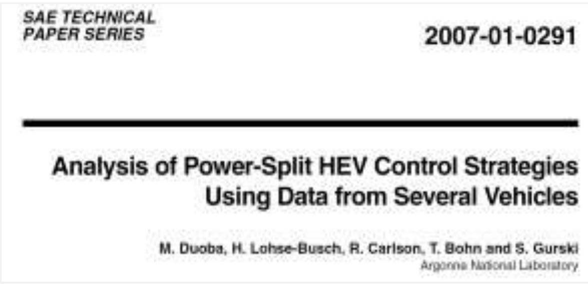
“LOAD FOLLOWING” VS “THERMOSTAT” (aka “Bang-Bang”)



Data: Argonne National Laboratory

From:

Argonne Paper (2007)


SAE TECHNICAL PAPER SERIES

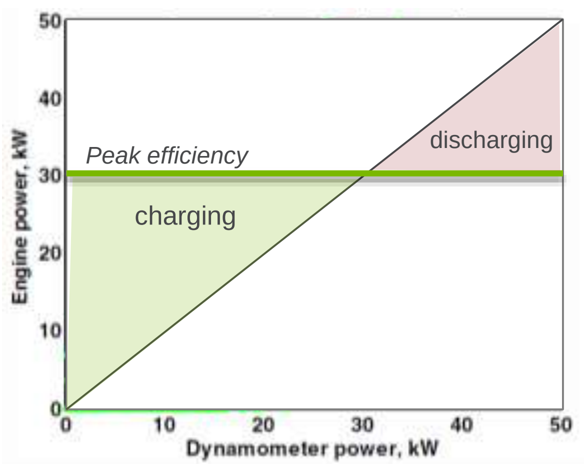
2007-01-0291

Analysis of Power-Split HEV Control Strategies Using Data from Several Vehicles

M. Duoba, H. Lohse-Busch, R. Carlson, T. Bohn and S. Gurski
Argonne National Laboratory

Gen 1 Prius – Load Following

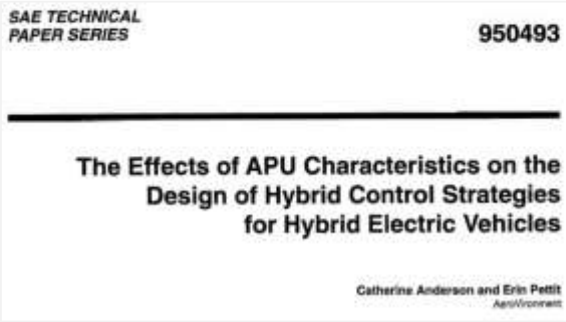
- Engine load “follows” required power



Thermostat

- Engine on or off
- Turn on/off = *f* (SOC)
- Engine at best efficiency

AeroVironment Paper (1995)


SAE TECHNICAL PAPER SERIES

950493

The Effects of APU Characteristics on the Design of Hybrid Control Strategies for Hybrid Electric Vehicles

Catherine Anderson and Erin Pettit
AeroVironment

Losses in/out battery too high
In/out damage battery life

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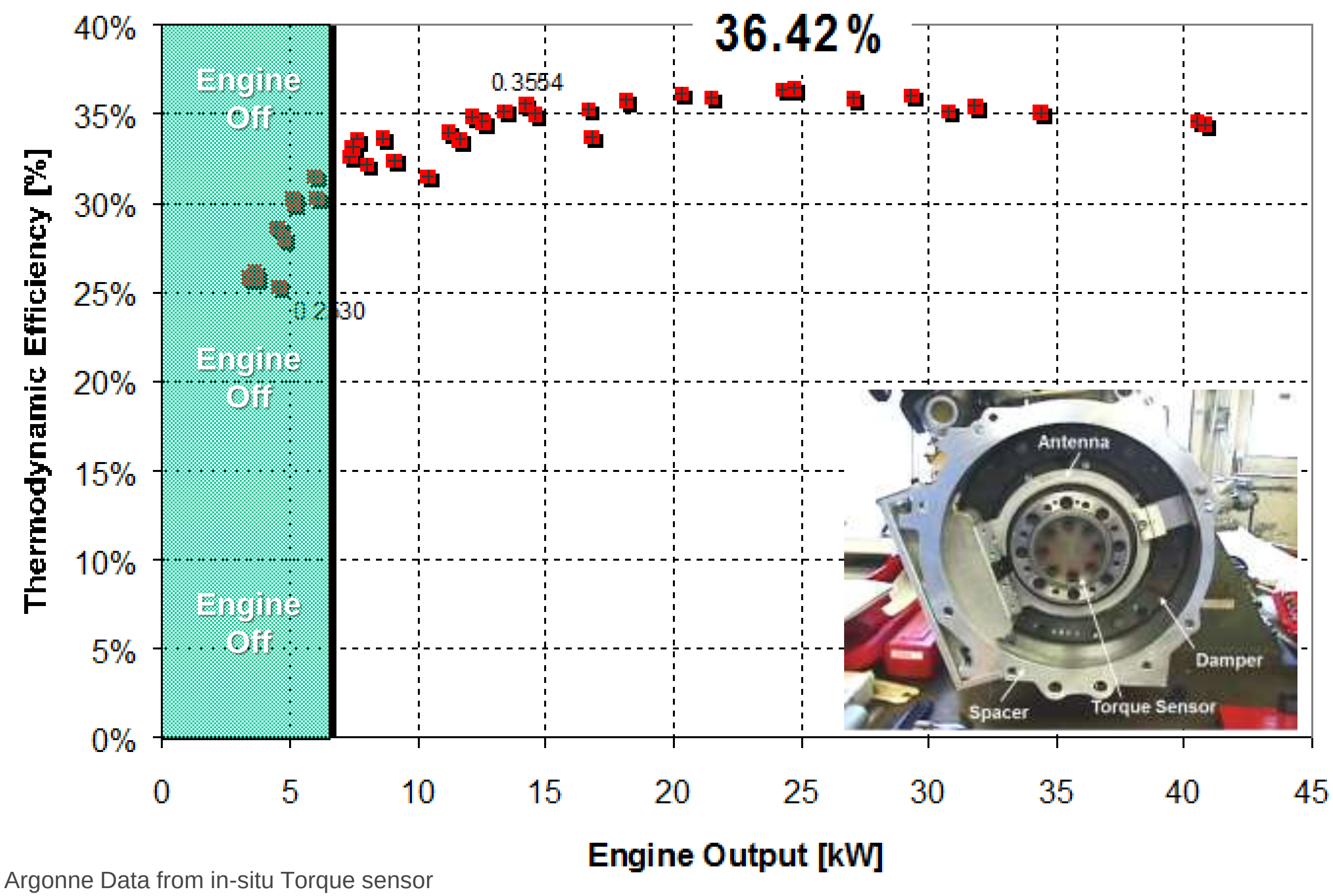
GEN 1 PRIUS ENGINE EFFICIENCY VS ENGINE-ON LOAD

Load Following charge-sustaining: Regen Energy = Electric Driving Energy

1998 Prius: Load-Following above 7 kW

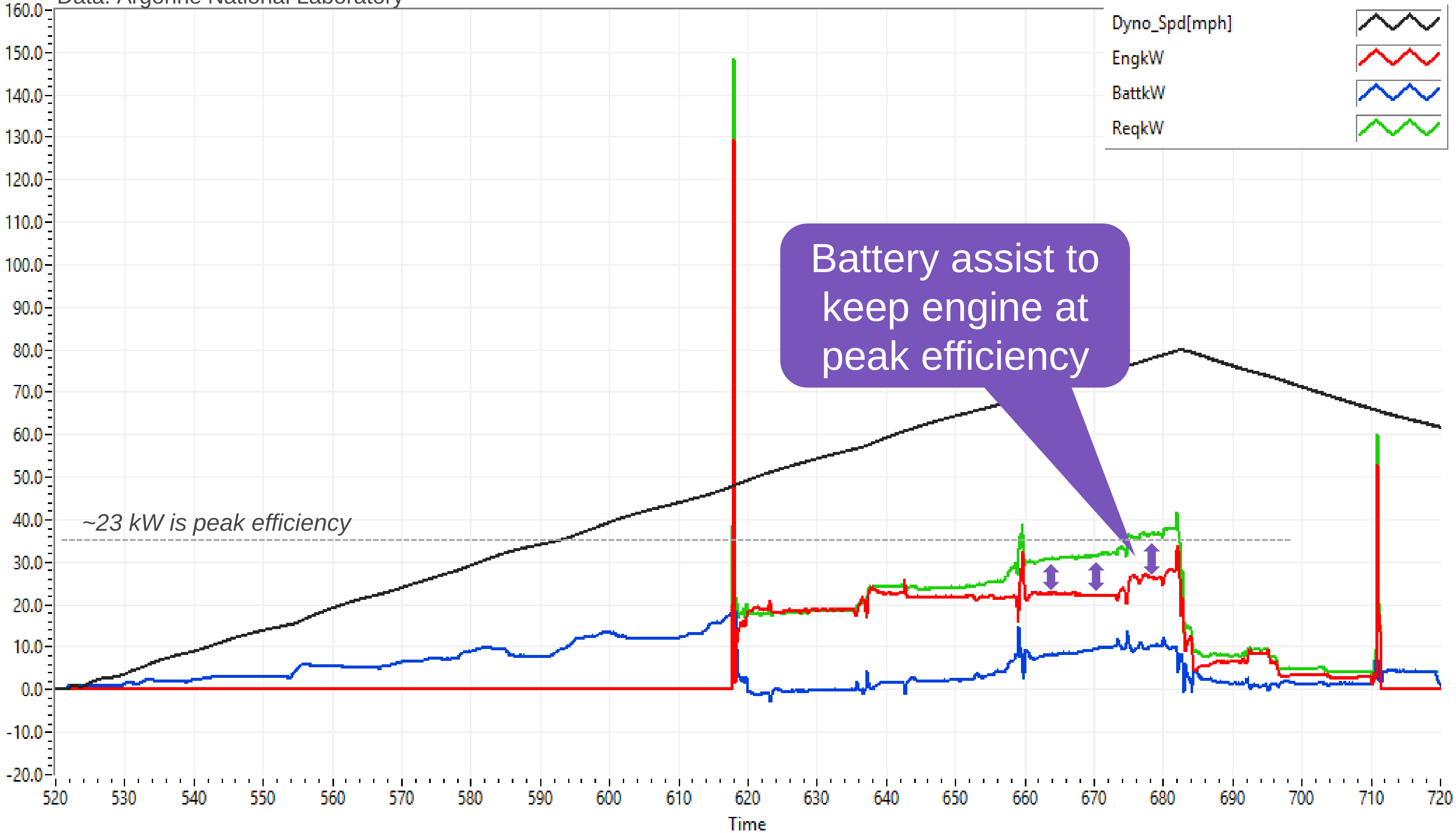


Argonne Data from in-situ Torque sensor

TREND: LESS LOAD FOLLOWING
MORE ELECTRIC ASSIST

Photo: Argonne National Laboratory

Data: Argonne National Laboratory



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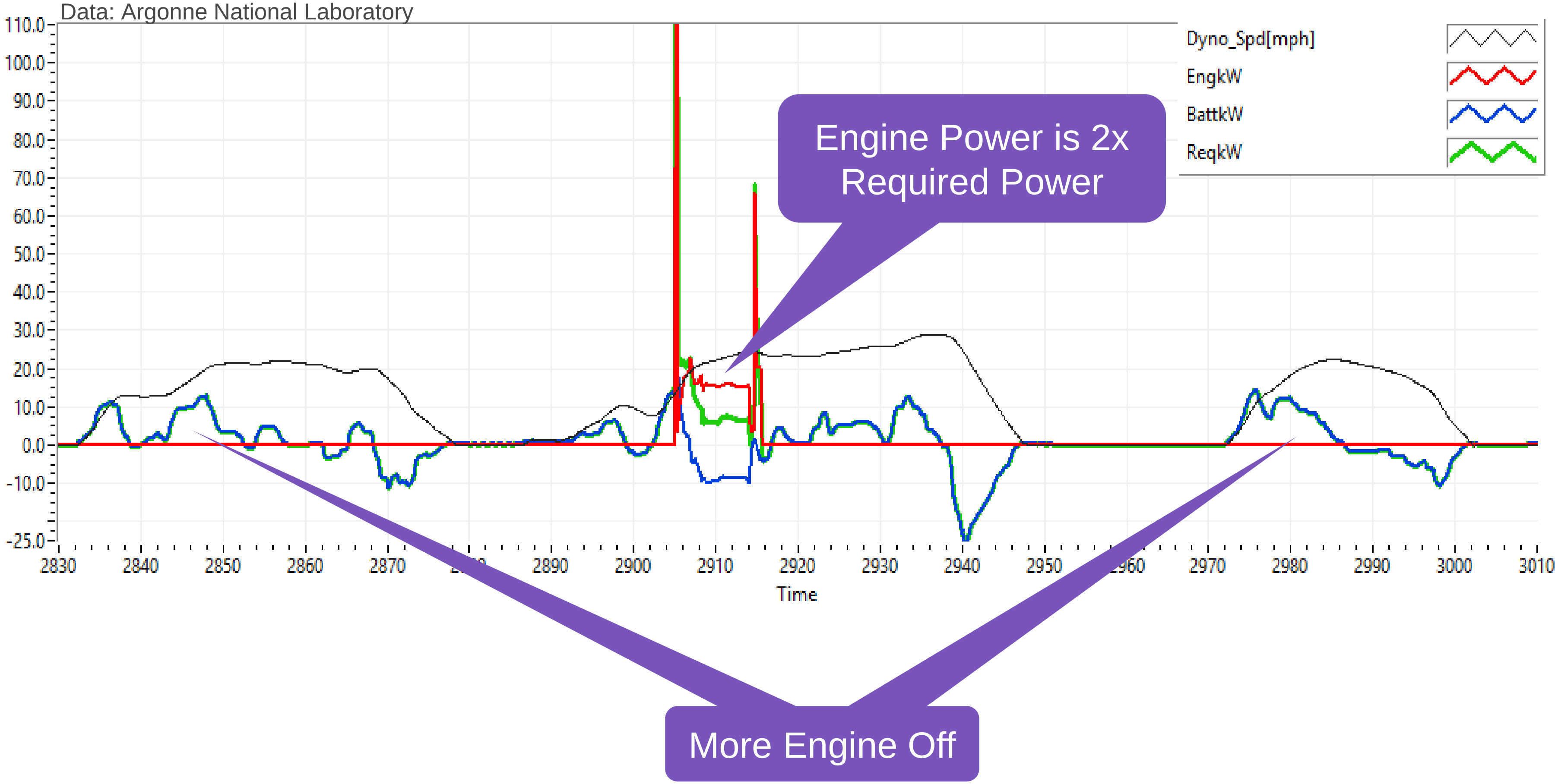
TREND: LESS LOAD FOLLOWING
ENGINE OFF + EXTRA CHARGING

Photo: Argonne National Laboratory

Data: Argonne National Laboratory



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LESS LOAD-FOLLOWING
NARROW ENGINE OPERATING RANGE

Photo: Argonne National Laboratory

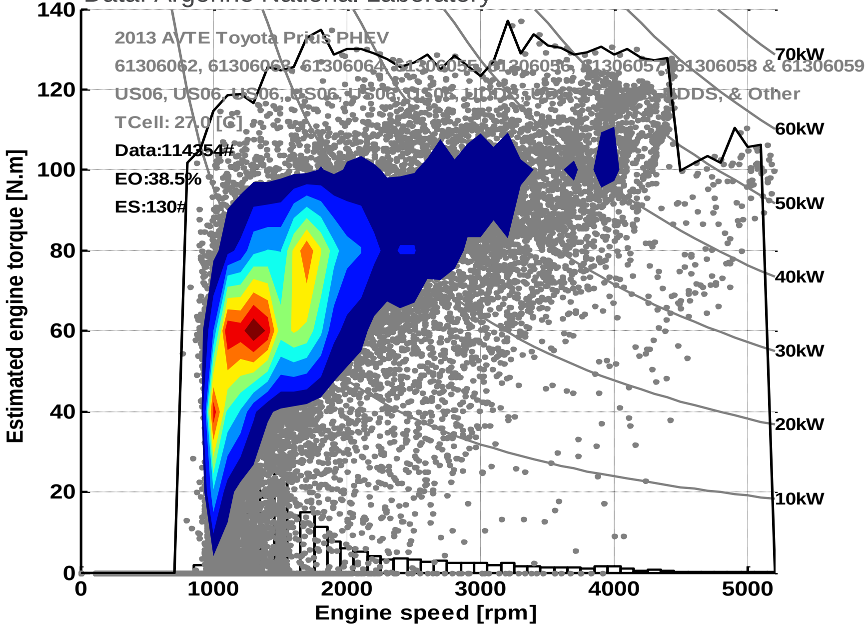
2013 Prius PHEV

Data from FCT UDDS + FCT Highway + FCT US06 @ 72F
Based on CAN torque message

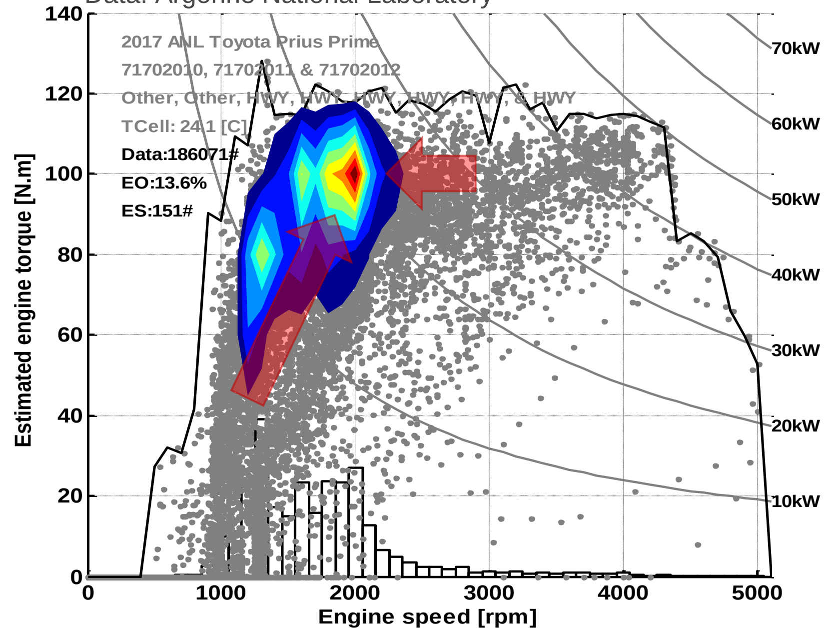
Photo: Argonne National Laboratory

2017 Prius Prime

Data: Argonne National Laboratory



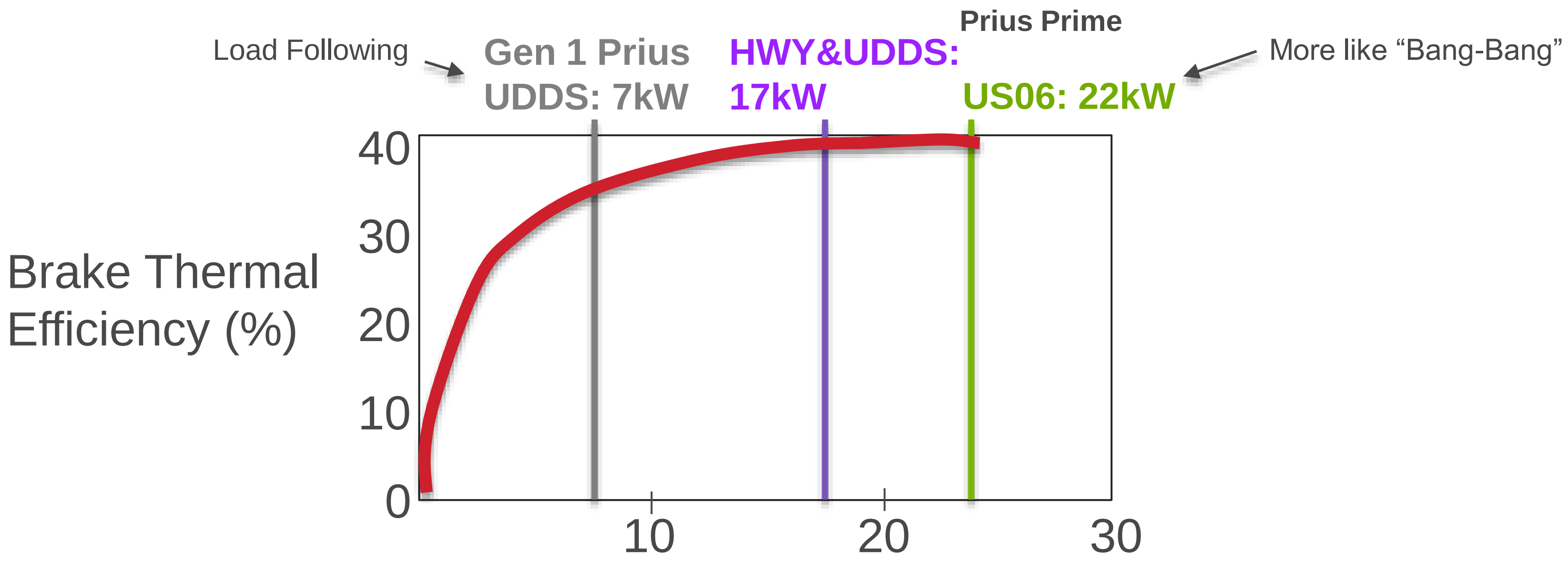
Data: Argonne National Laboratory



Very Thermostatic

ENGINE TURN-ON LOAD INCREASED

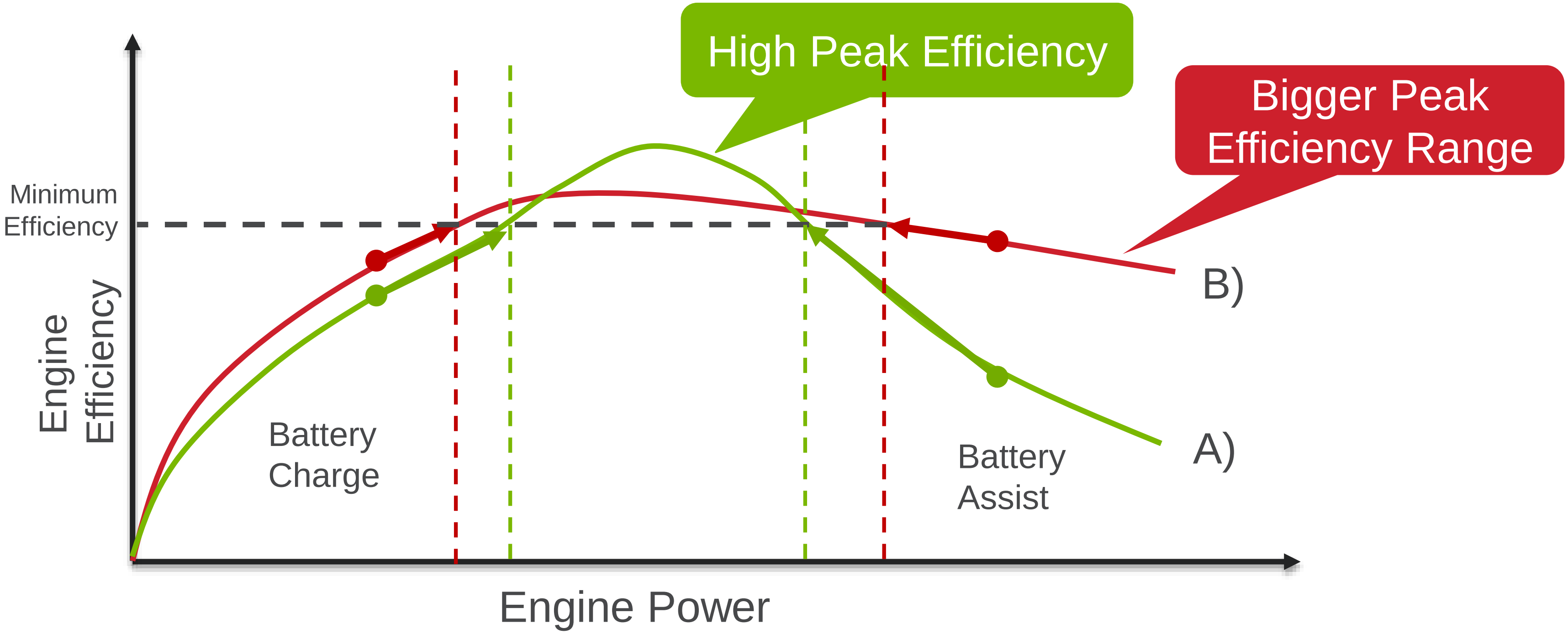
(CHARGE SUSTAINING REQUIRES MORE ENGINE CHARGING LATER)



From: Takahashi, D., Nakata, K., Yoshihara, Y., Ohta, Y. et al., "Combustion Development to Achieve Engine Thermal Efficiency of 40% for Hybrid Vehicles," SAE Technical Paper 2015-01-1254, 2015, doi:10.4271/2015-01-1254

ENGINE EFFICIENCY:
A) HIGH PEAK VS B) LARGE PEAK

Optimum Engine Operation in a Hybrid



New Technology → Less In/Out electric energy losses
→ More use of engine loads at peak efficiency

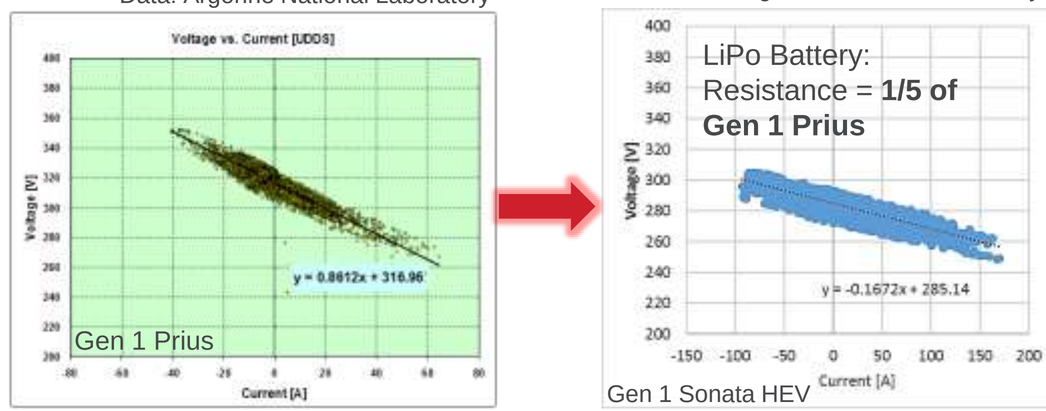
ELECTRIC POWER TECHNOLOGY → LESS IN/OUT ELECTRIC ENERGY LOSSES

For series path & for in-out battery

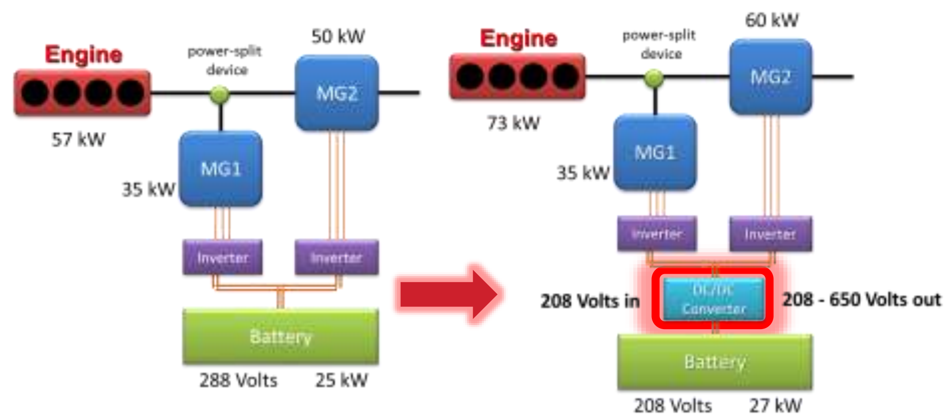
- Low Battery Resistance
  - LiPo, Li-ion
  - Future batteries (must be low R?)
- Batteries More Robust
  - More in-out possible

Data: Argonne National Laboratory

Data: Argonne National Laboratory



- Optimized Motors / Electronics
  - Boost converter (higher voltage)
  - Rotor topology
  - Future: Low-loss wide bandgap inverters

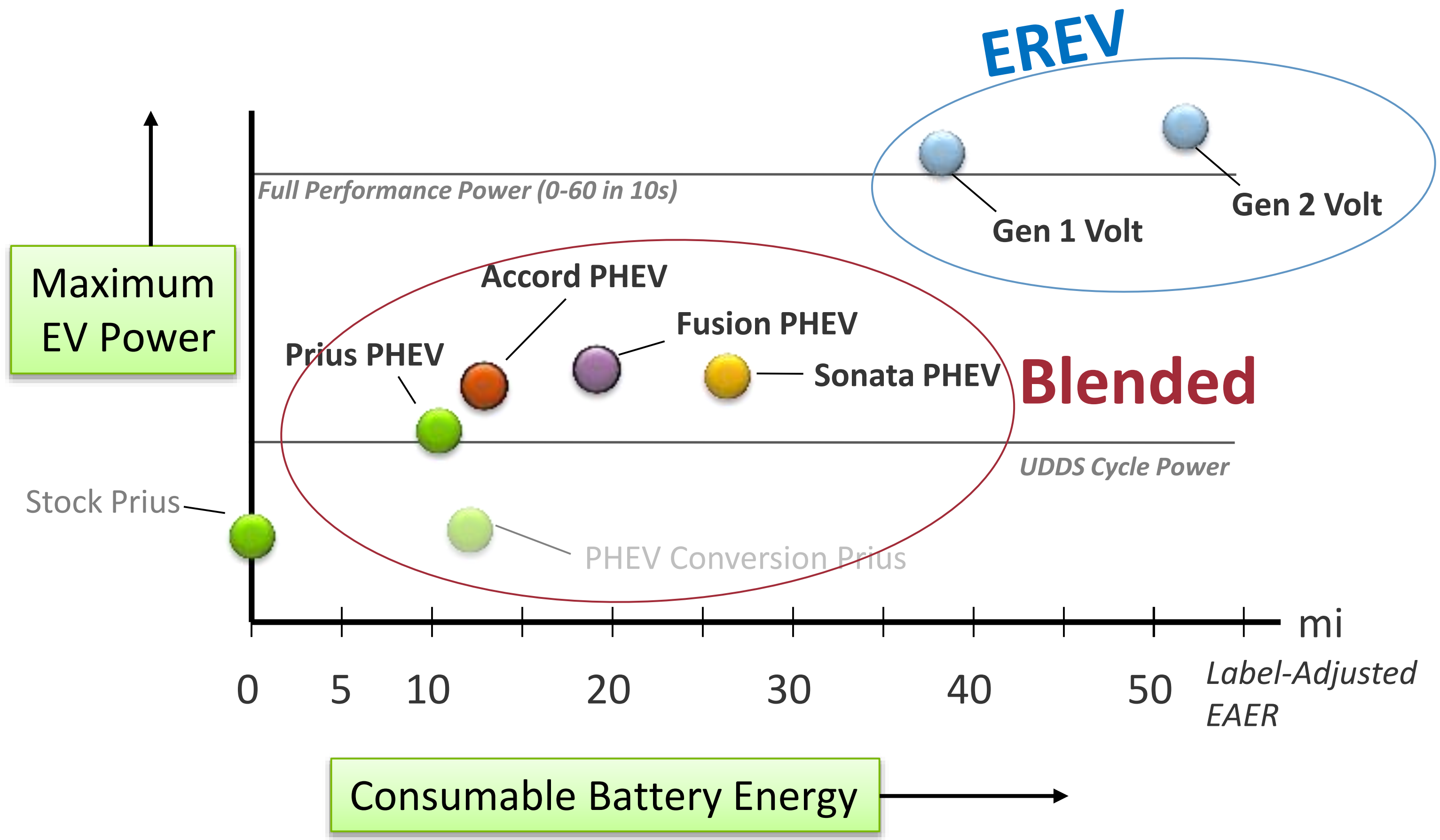


HEV CONFIGURATIONS

HEV OPERATION & EFFICIENCY

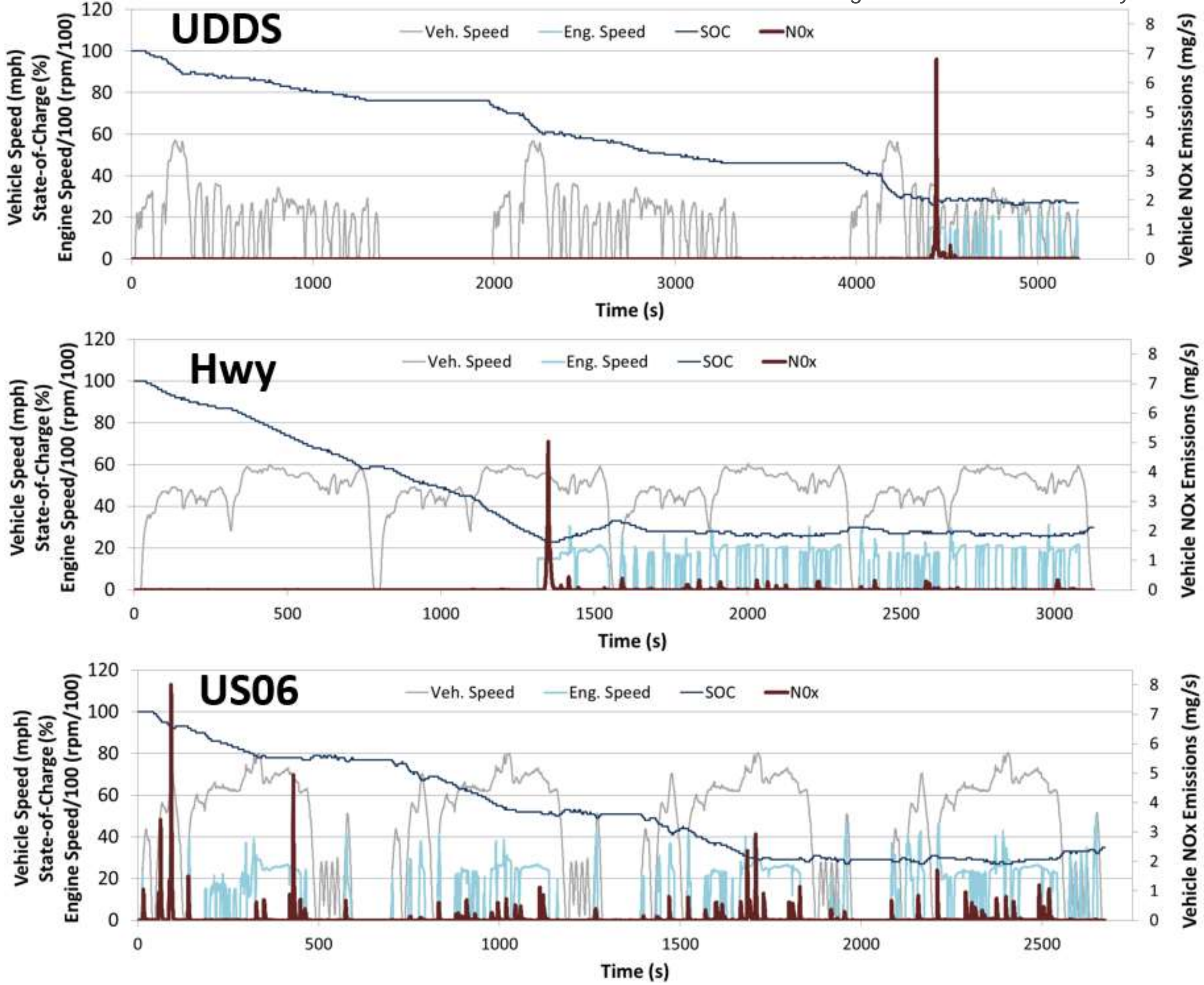
PHEVS

PHEV DESIGN SPACE – ENERGY AND POWER



BLENDED PHEVS: EMISSIONS CONTROL CHALLENGES

Data: Argonne National Laboratory



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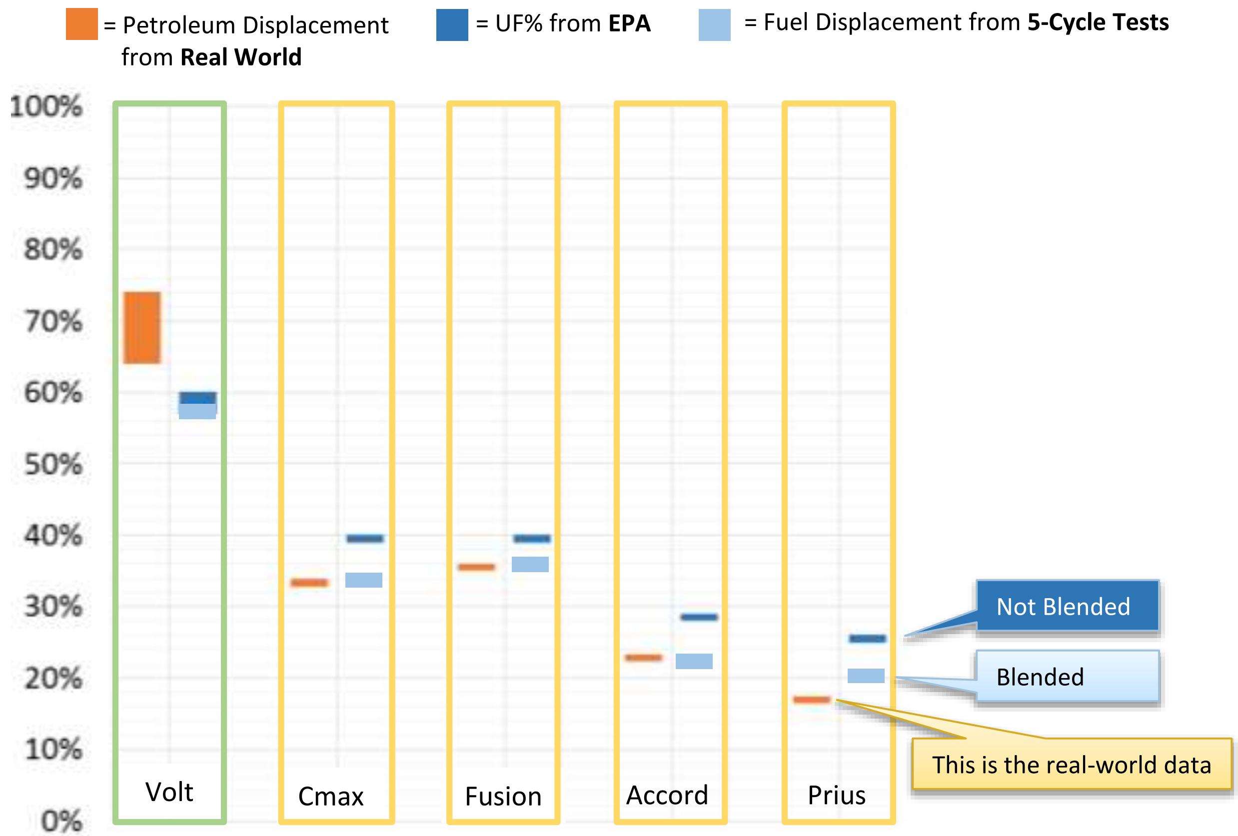
BLENDED PHEVS: LOWER % ELECTRIC IN REAL WORLD THAN EREV EREV OR REX

(With same CARB "Equivalent All Electric Range")



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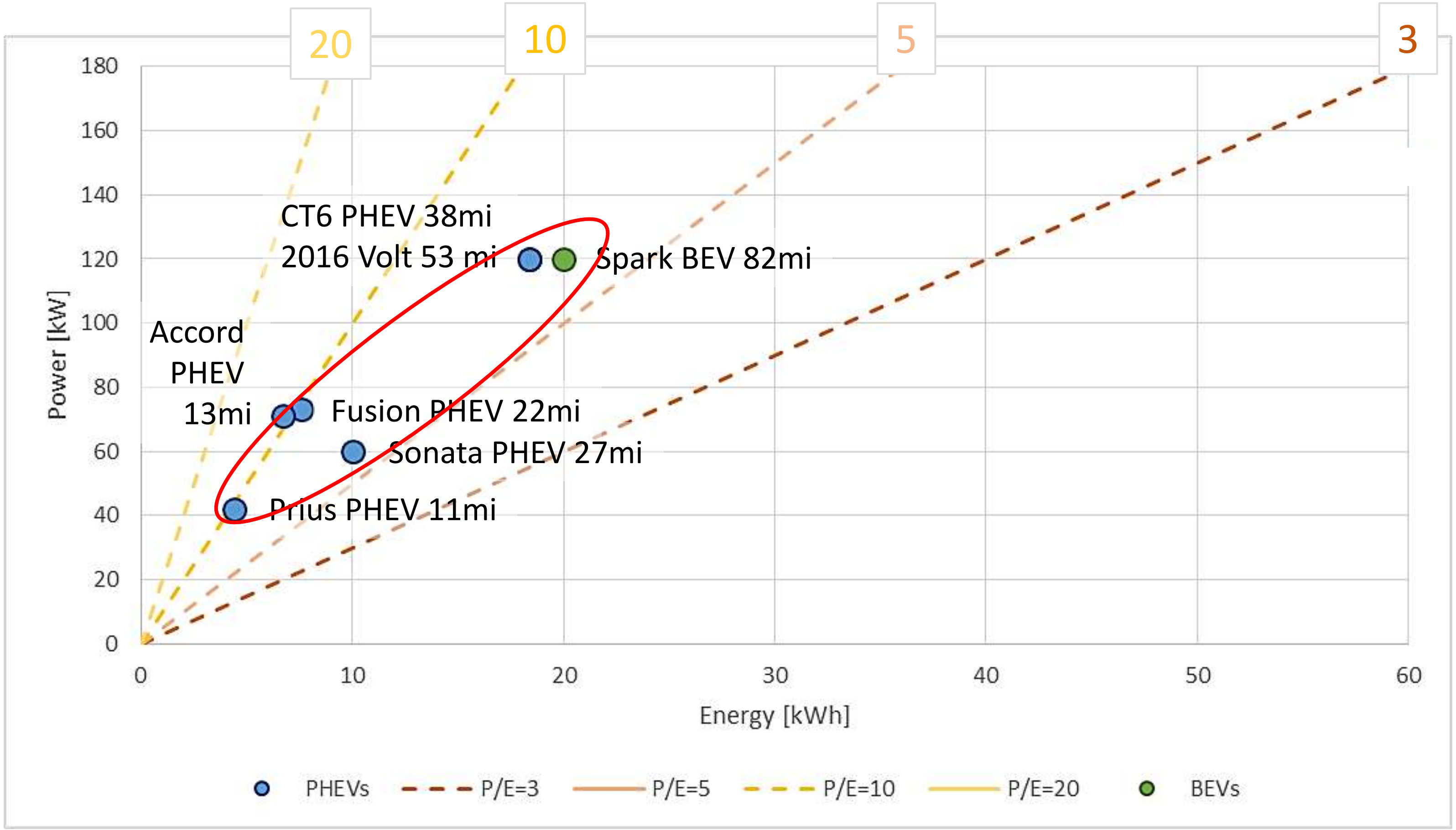
CURRENT POWER/ENERGY BATTERY MAP



- **Current PHEV and BEV P/E ratio is in similar range (6-10)**

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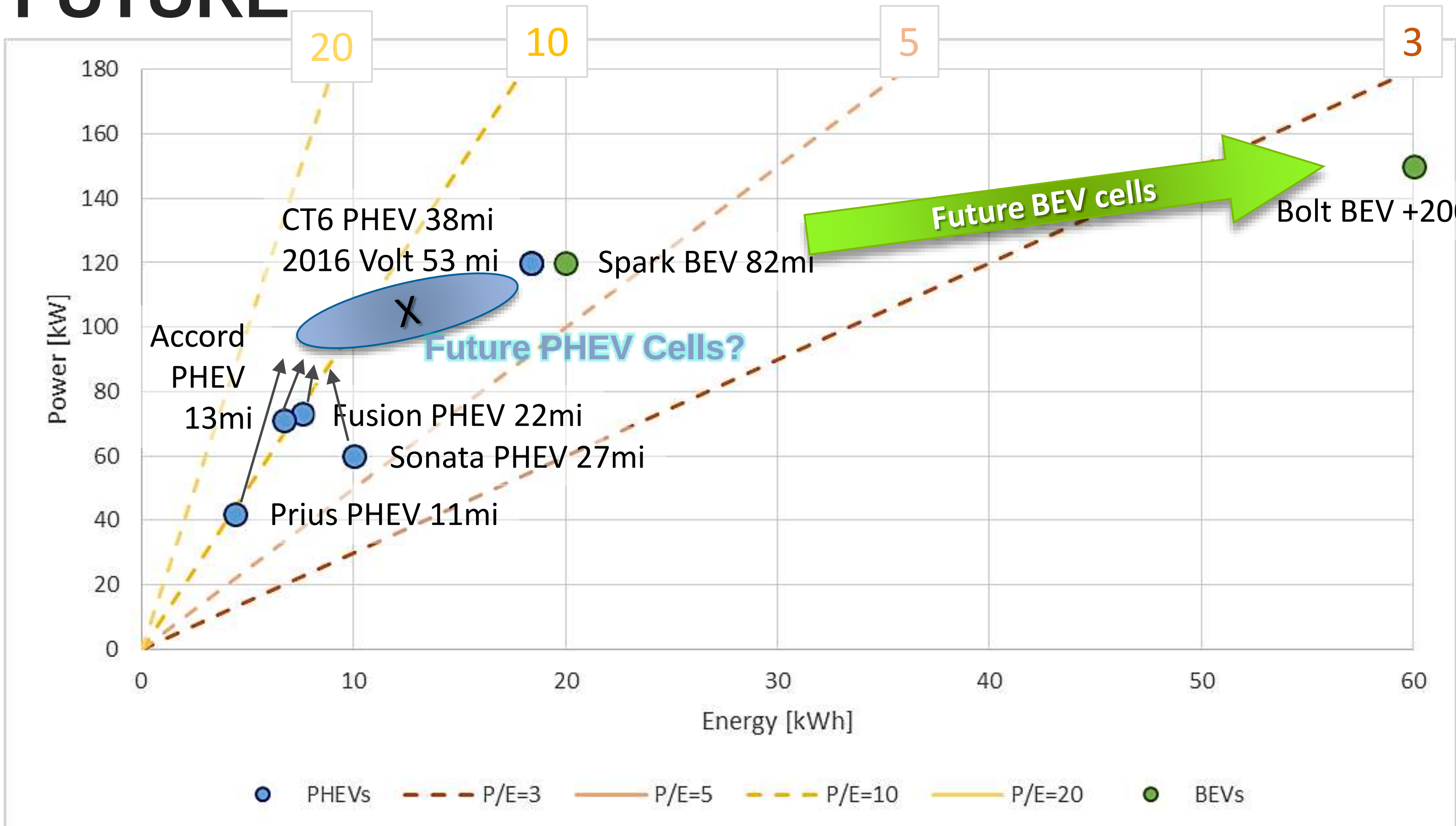
BETTER BATTERIES COULD MEAN ALL EREVS IN FUTURE



Good cost proposition

Could cell design bifurcate to make 25-40 mi EREVs and +200mi BEVs?

Or

Will we continue to see PHEV Range Inflation?

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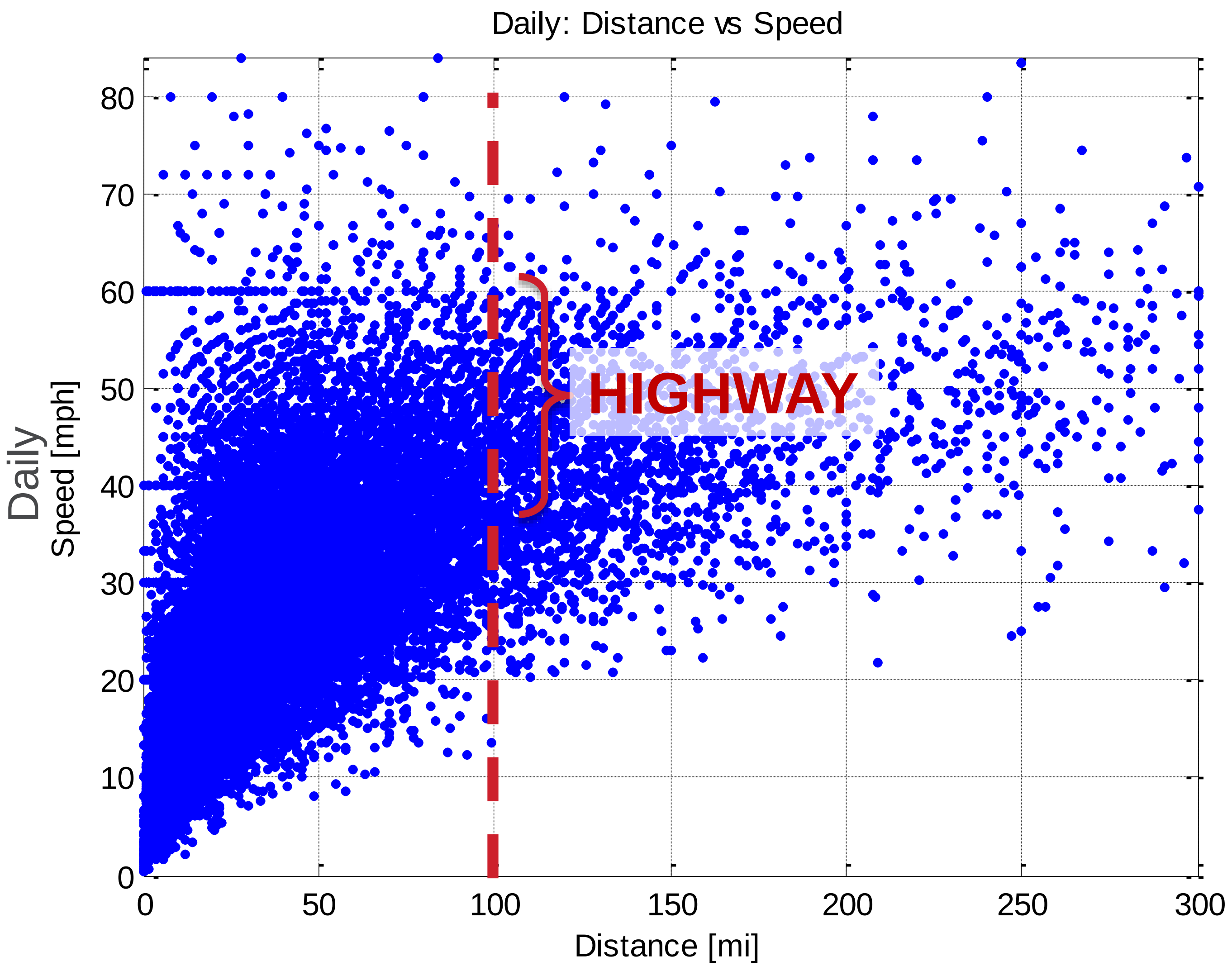
MUCH OF LONG DISTANCE DRIVING IS HIGHWAY DRIVING

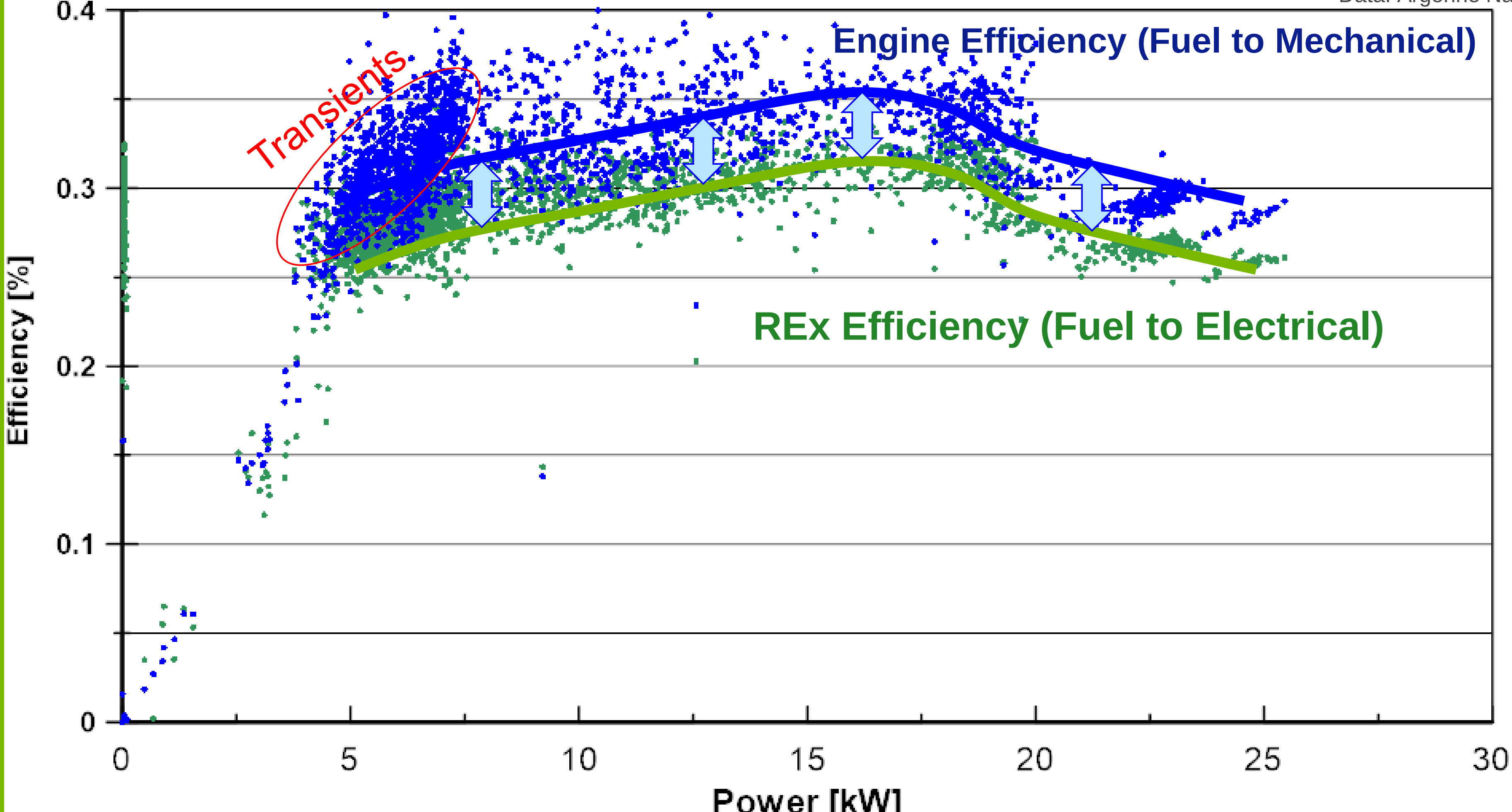
Should REx vehicles (not gasoline limited) have a parallel mode?



EFFICIENCY OF REX ENGINE

Engine Efficiency: gain 5 percent points higher if avoid series path

Data: Argonne Nationa



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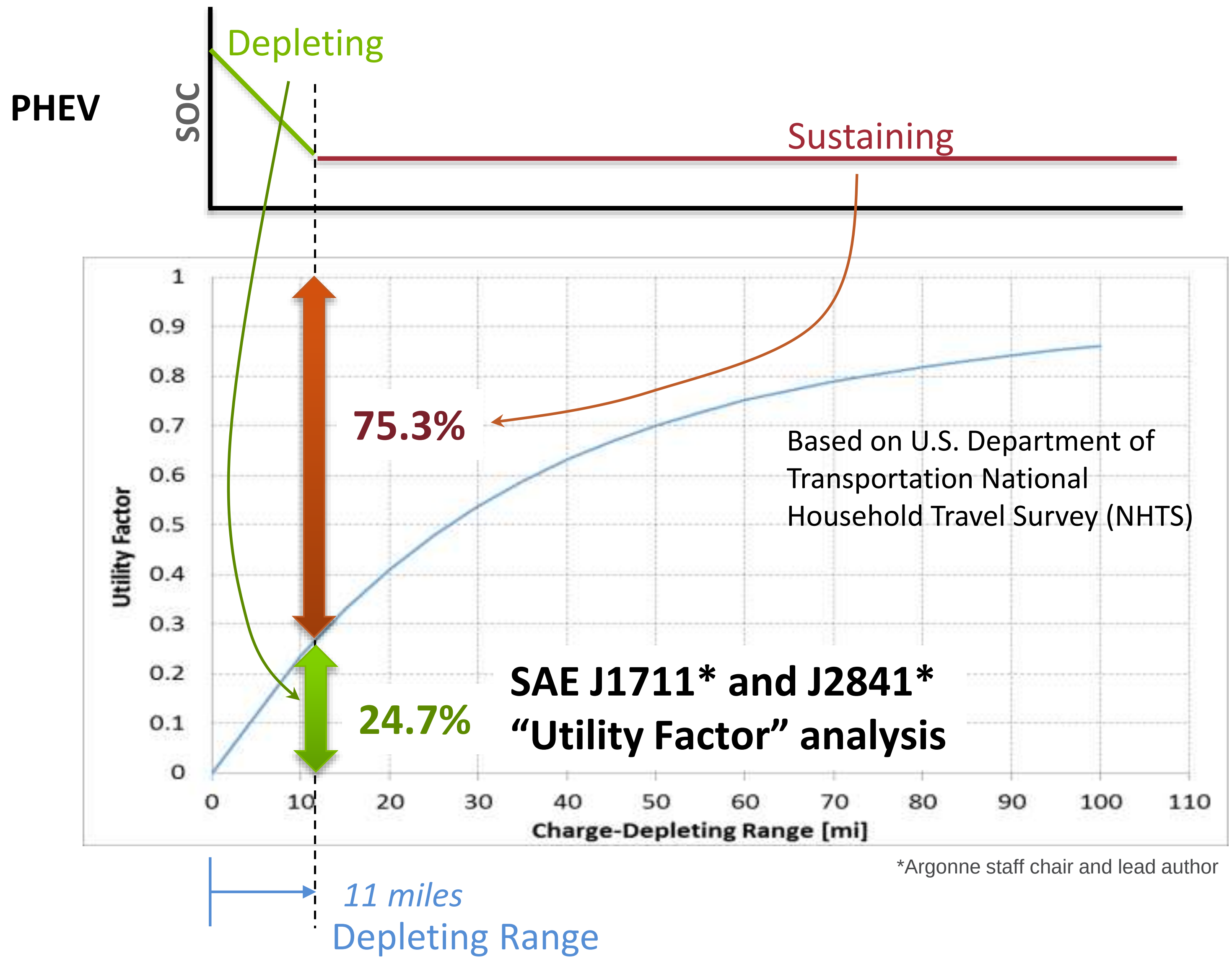
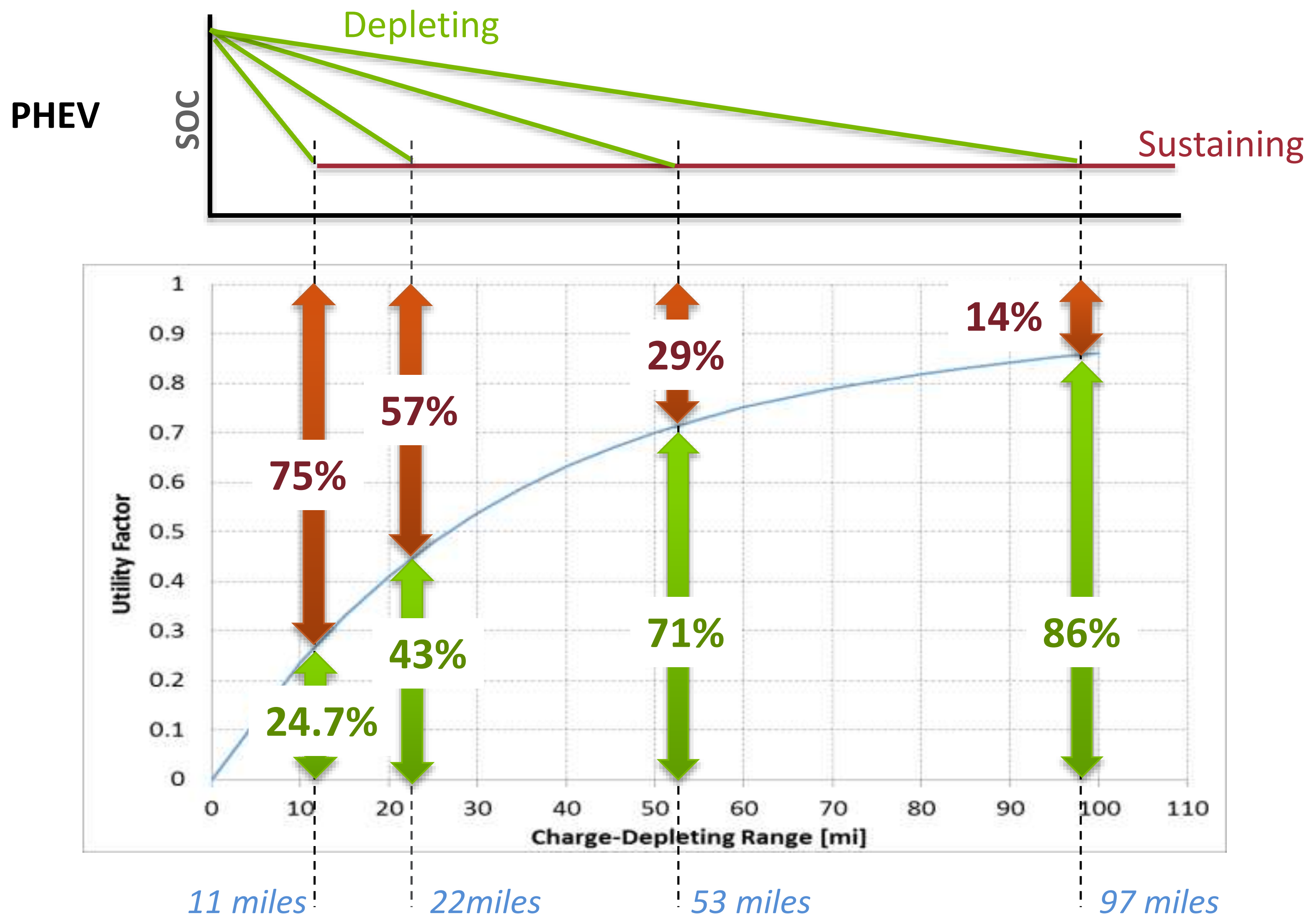
UTILITY OF EREV/REX ENGINE (distance weighted)



*Argonne staff chair and lead author

UTILITY OF EREV/REX ENGINE (distance weighted)



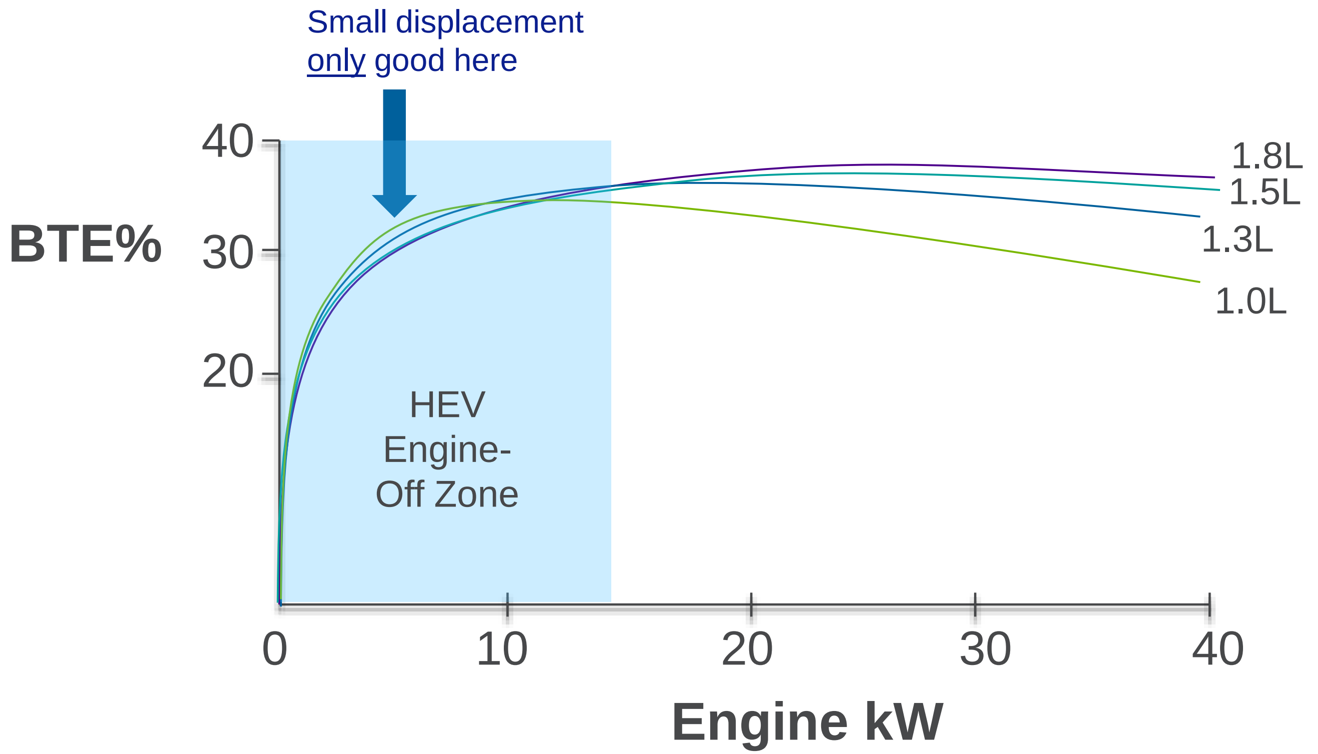
HEV CONFIGURATIONS

HEV OPERATION & EFFICIENCY

PHEVS

HEV ENGINES (SPEED ROUND)

TOO MUCH DOWNSIZING IN FULL HYBRID CAN BE DETRIMENTAL



Gen 1 Prius **1.5**L → **46** MPG
Gen 2 Prius **1.8**L → **50** MPG

ENGINE EFFICIENCY

How High Can It Go?

- Atkinson hybrid engines currently at ~40% BTE

- Toyota roadmap for 45%

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Engine Technologies for Achieving 45% Thermal Efficiency of S.I. Engine

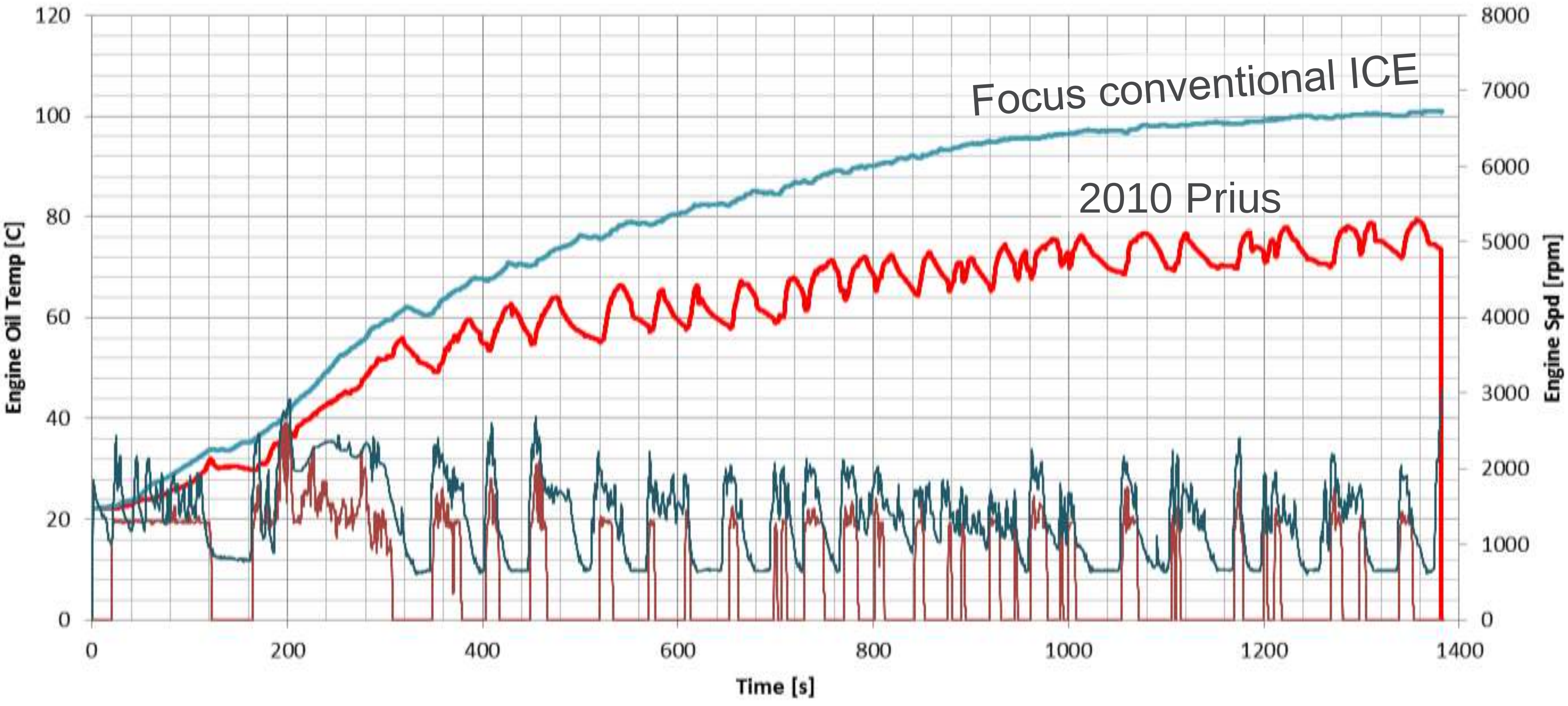
Koichi Nakata, Shinichiro Nogawa, Daishi Takahashi, Yasushi Yoshihara, Atsunori Kumagai, and Tetsushi Suzuki
Toyota Motor Corporation

  – Homogeneous lean burn w/cooled EGR
  – Boosted (better if e-driven supercharger?)

- What new engine concepts specifically for HEVs?
  – Reduced operating range
  – Slower transients, controlled, long warmup time
  – Integrated HVAC

HYBRID ENGINE THERMAL CONDITIONS DIFFERENT

- Hybrid engines spend considerable time OFF.
- Cylinder, head/port temperatures, fueling strategies different
- Catalyst temp management strategies different



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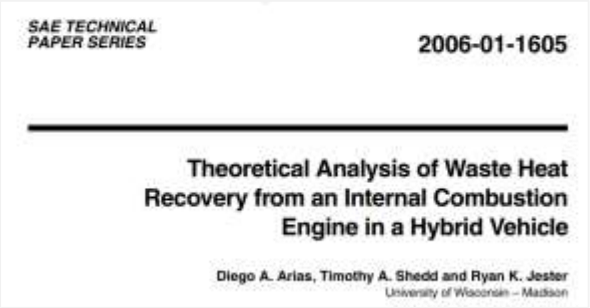
RECOVERING WASTE HEAT FOR ELECTRIC POWER IN HEVS

- HEV easy integration of electricity generated from waste heat cycle
  - But less waste heat available

- Clean sheet engine?
  - Exhaust and coolant flow/temp optimized for best heat-power cycle
  - Backpressure
  - New coolant fluids

- Other Heat Management
  - Integrated HVAC? Heat exchanger-muffler?
  - Better warmup
  - Better integration with Aero
    - Reduced air stagnation in front grill heat exchangers

Argonne – UW study



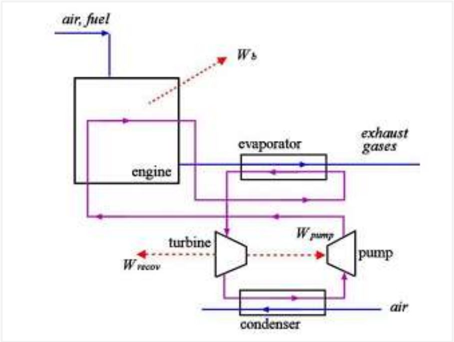
SAE TECHNICAL PAPER SERIES

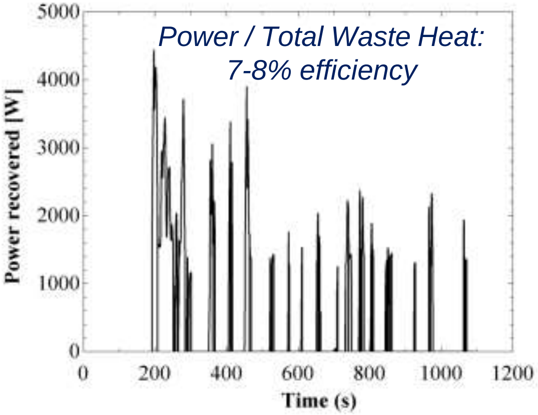
2006-01-1605

Theoretical Analysis of Waste Heat Recovery from an Internal Combustion Engine in a Hybrid Vehicle

Diego A. Arias, Timothy A. Shedd and Ryan K. Jester

University of Wisconsin – Madison





Added power based on 2004 Prius data

OTHER STUFF

- High hybridization = no fuel enrichment, low emissions <u>all</u> the time
- Next gen HEVs with unusual packaging requirements (Toyota “1/x”)
- Can we exploit greatly reduced transient requirements? Turbo design, intake air temp controls etc.
- Light electric boosting (electric turbo)
- Best advanced powertrain for Ride Share Vehicles?
  - Fuel and maintenance costs favor electricity usage. Gasoline refueling requires people.
  - BEVs? Must spend time not earning money to be on charge (peak hours limitations)
  - EREVs (w/ wireless charging)? Engine size requirements? Range requirements?
    - **Someone needs to study how much range is needed for autonomous ride share EREVs. This can fed into what type of engine is best.**

CONCLUSION / SUMMARY

- Configuration now less important
- Improved batteries and e-motor tech has benefitted engine cycle efficiency
- Engine with peaky efficiency island possible with modern HEV tech
- Still many unknowns for how PHEVs are used in future
- Opportunities for more integrated thermal management and heat recovery?
- BTE of 45% within reach
- "50-55%" could mean clean-sheet approach to engine + HEV powertrain