WORKSHOP
Powertrain Innovations for Connected and Autonomous Vehicles

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US Department of Energy

ARPA-E's energy mandate

- Reduce energy imports.
- Improve the efficiency of energy generation, storage, transmission, distribution and usage.
- Reduce energy-related emissions including CO_2.
- Promote US innovation and hence competitiveness in the energy arena.

  – *A direct match for automotive engine and powertrain efficiency*

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The motivation for new ARPA-E program area

- Target **automotive engine and powertrain technologies** beyond those proposed for 2025.
- Look for substantial fuel consumption and CO_2 emissions reductions beyond those currently expected.
- Take advantage of proposed peripheral or tangential technologies – connectivity and autonomous operation.

  – ARPA-E looks for *transformational technologies* and does not fund incremental improvements.

The Automotive Industry

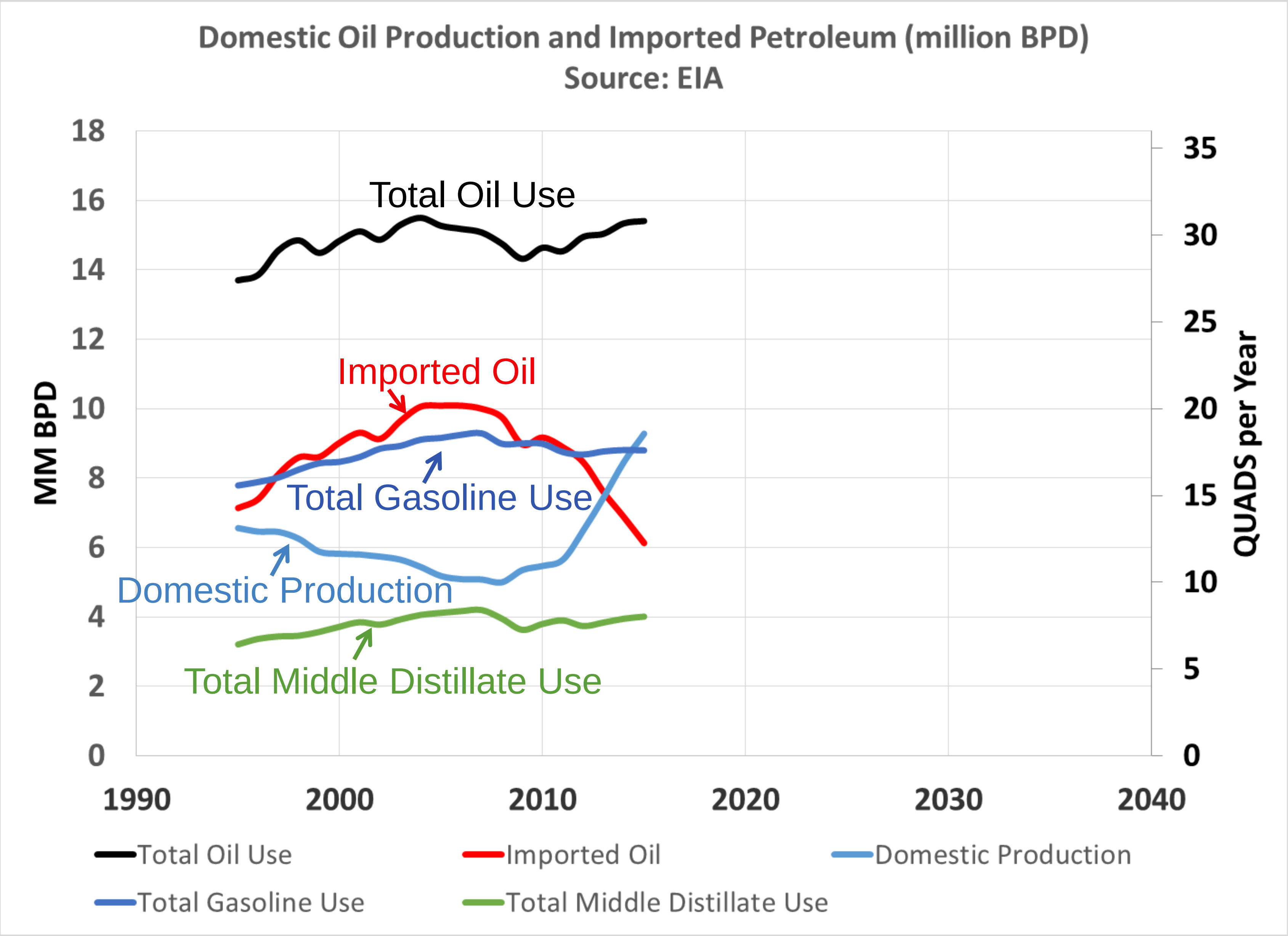
- Is a very mature, conservative industry dominated by
  - Regulation (safety),
  - Regulation (emissions),
  - Customer preferences,
  - While meeting strict cost and price constraints.

  And hence has been considered ripe for disruption – cf. Tesla, Apple, Google…

- The “precautionary principle” has been replaced by the Wild West – “permission-less innovation”.

3 overarching energy trends in the automotive area

- Reduce imported oil and GHGs;
  - 90+% of future vehicles will be either conventional or hybrid vehicles (DOE, EIA, EPA);
- Vehicle connectivity (V2V, V2I, V2X) advances;
- Vehicle autonomy (of varying degrees).



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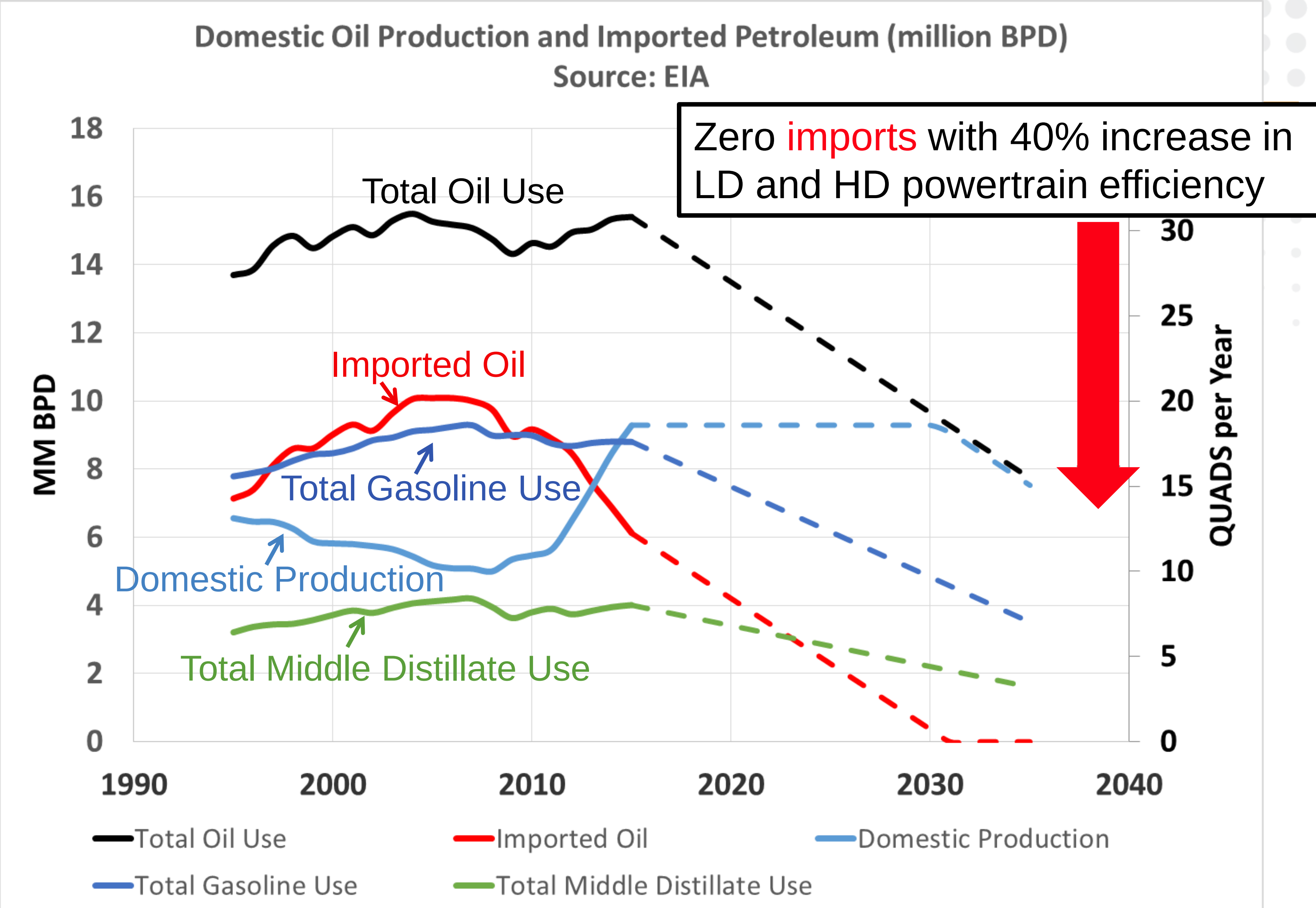

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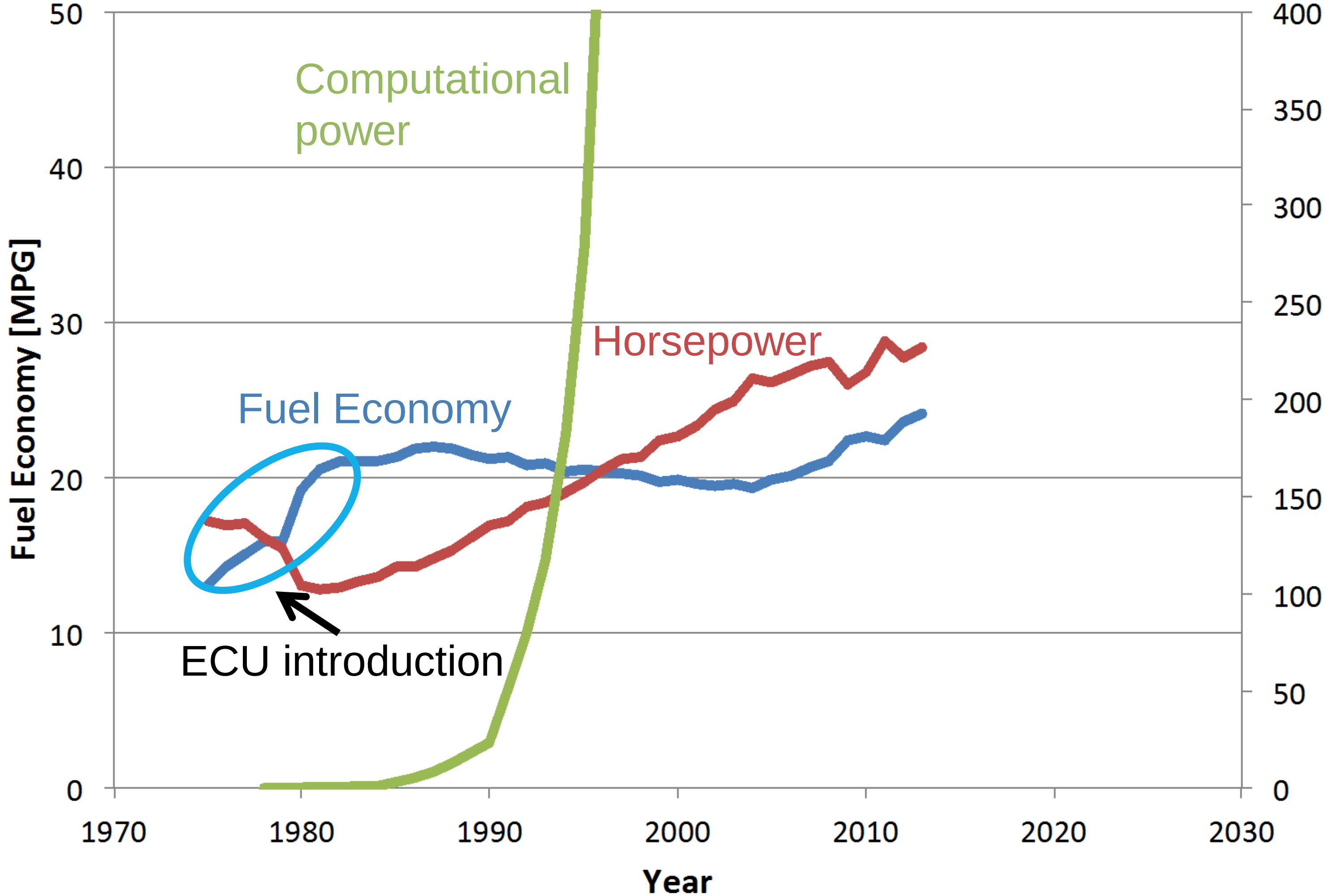
Goal of the workshop



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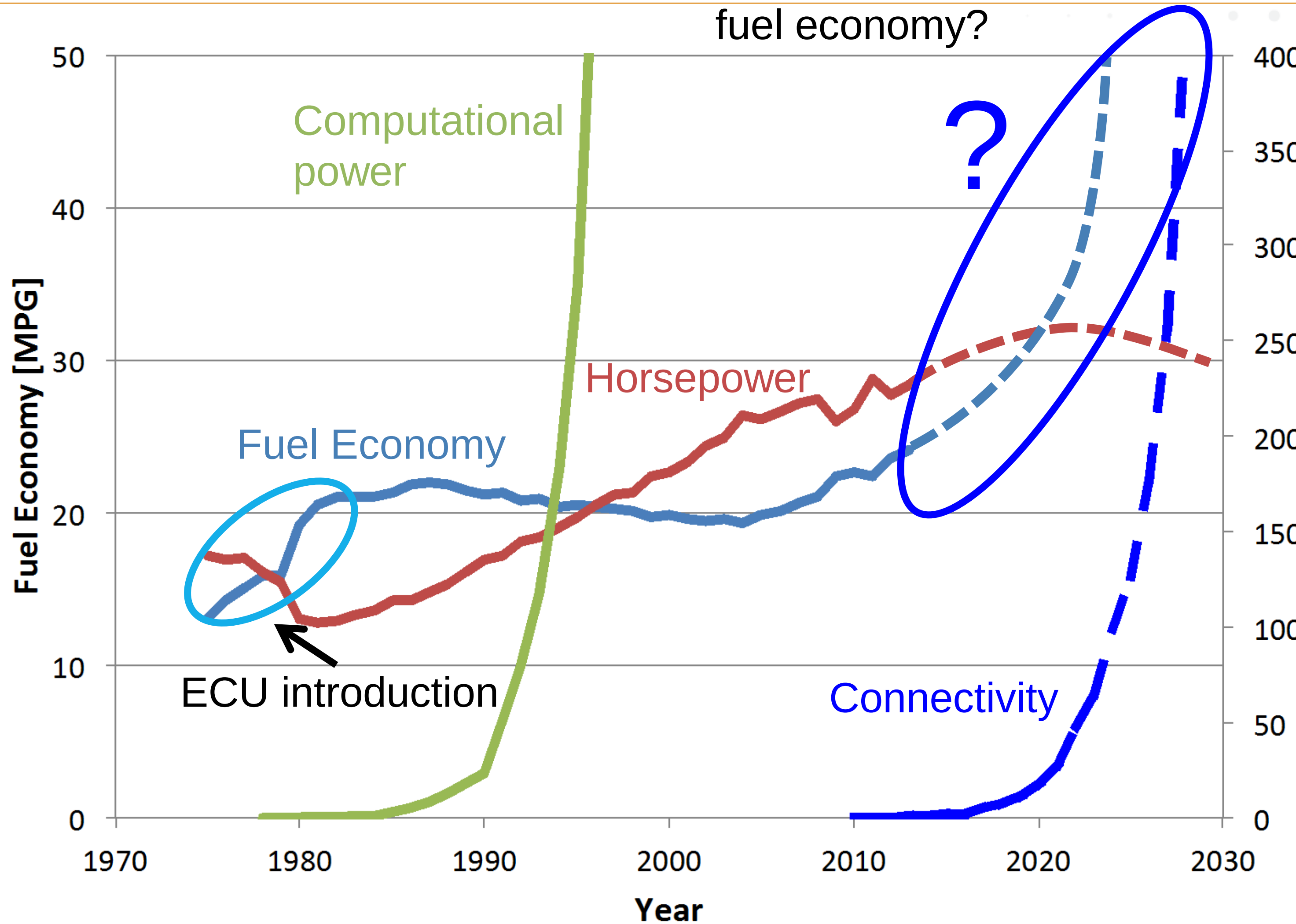
Goal of the workshop

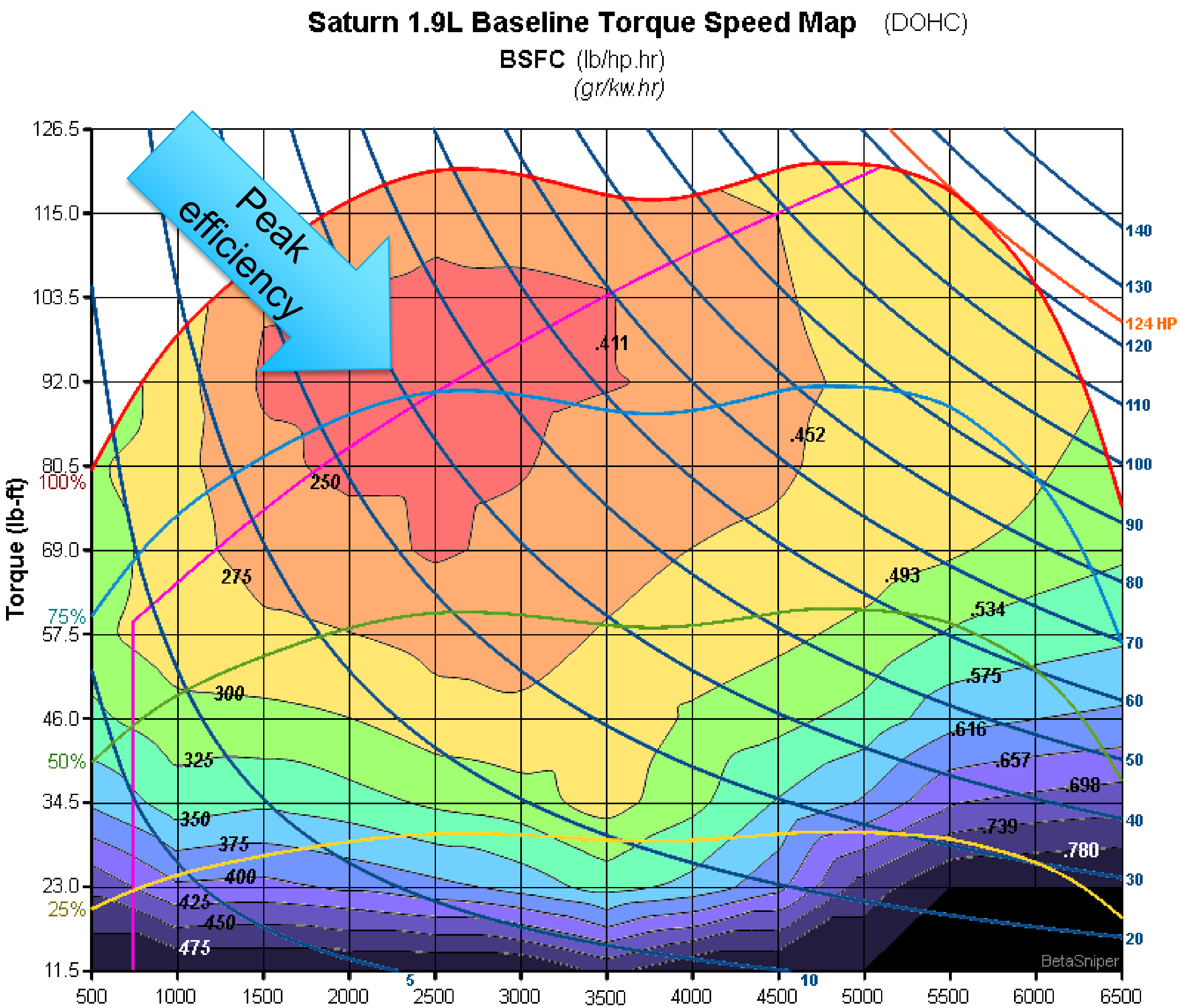
Opportunity to use connectivity & autonomy to increase individual vehicle fuel economy?



State of the Art Peak Engine Efficiency

- SI NA ~38.5% (Toyota Prius)
- CI LD ~42% (VW TDI)
- CI HD ~47% (Cummins and Daimler – without WHR)

Why aren't we there yet?


Saturn 1.9L Baseline Torque Speed Map (DOHC)
BSFC (lb/hp.hr)
(gr/kw.hr)
Peak efficiency
Torque (lb-ft)
126.5
115.0
103.5
92.0
80.5
100%
69.0
75%
57.5
46.0
50%
34.5
23.0
25%
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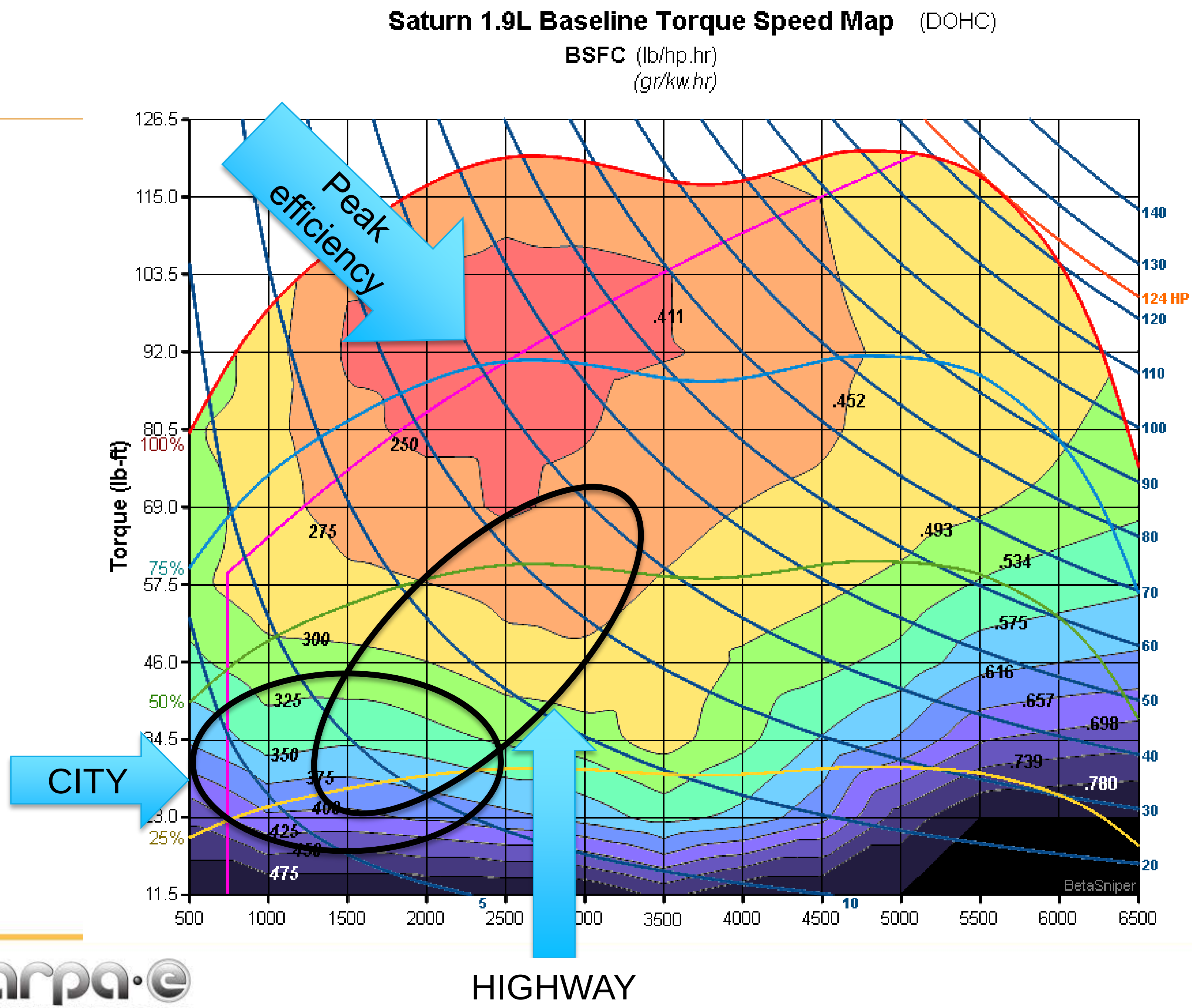
BetaSniper



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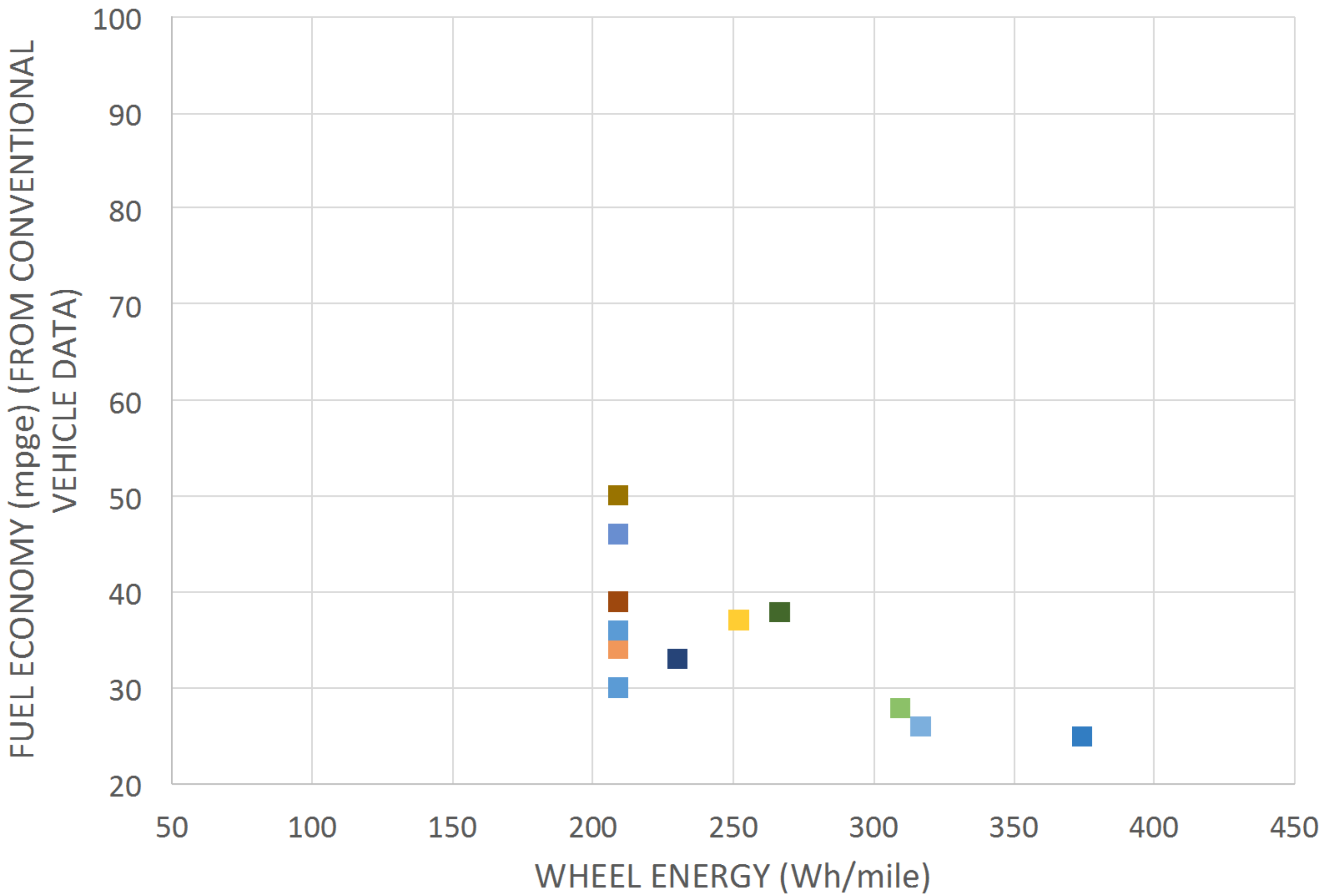
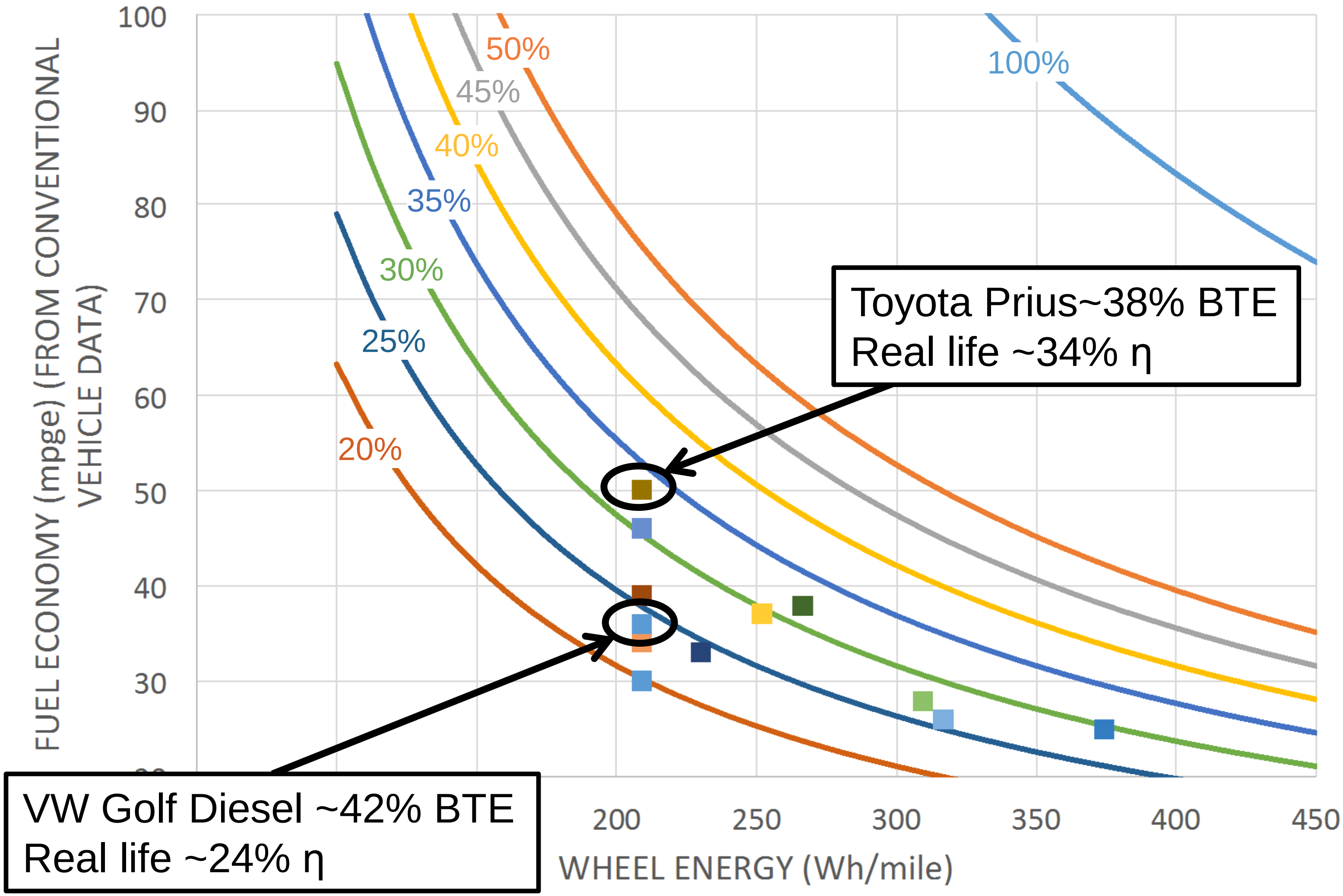
Peak efficiency
CITY
HIGHWAY

Advancements in peak engine efficiency



Advancements in peak engine efficiency



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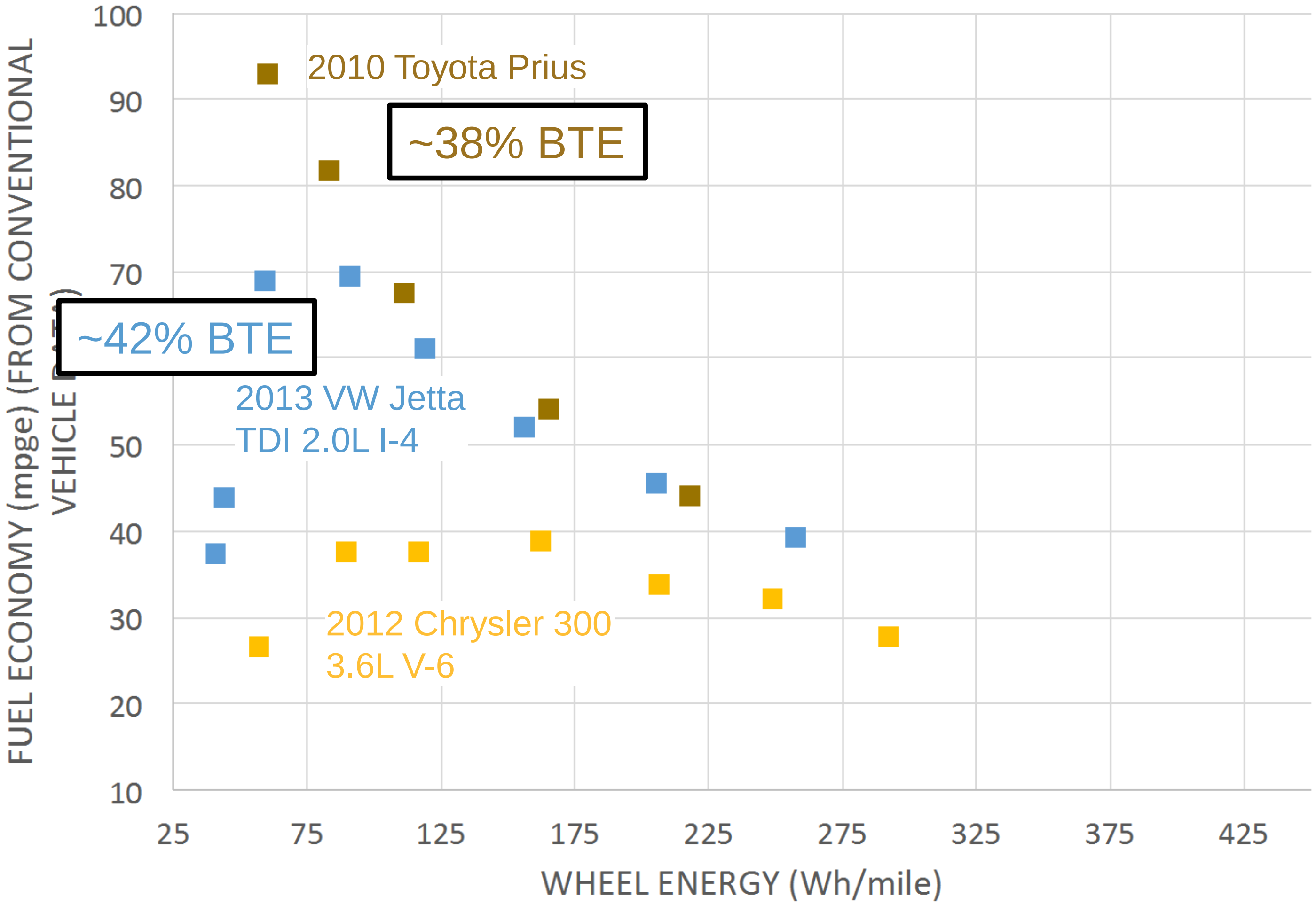
Advancements in peak engine efficiency



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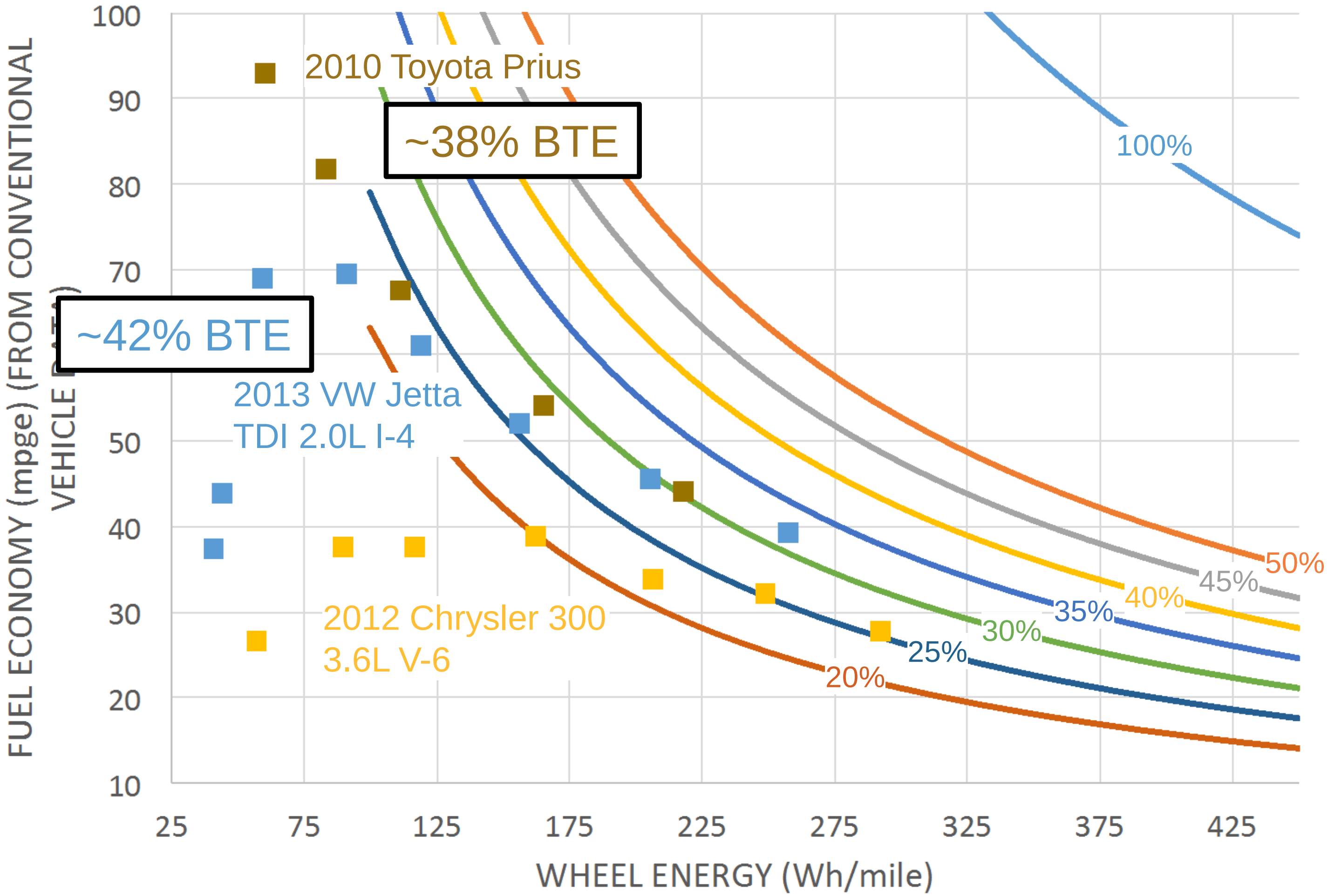
Advancements in peak engine efficiency



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WORKSHOP Topic Areas

- **A – Reducing fuel consumption by improving powertrain control through connectivity.**
- **B – Improving future autonomous vehicle fuel efficiency via new engine and powertrain technologies.**

Reducing Fuel Consumption through Connectivity

Advanced Information and Communication Technologies (ICT)

Vehicle Connectivity + Autonomous Driving = EVs?

Vehicle Connectivity + Autonomous Driving = EVs?

Not if 90+% of vehicles will continue to be conventionally powered or hybrids, even after 2030.

(*cf.* DOE, NAS/NAE, EPA, EIA)

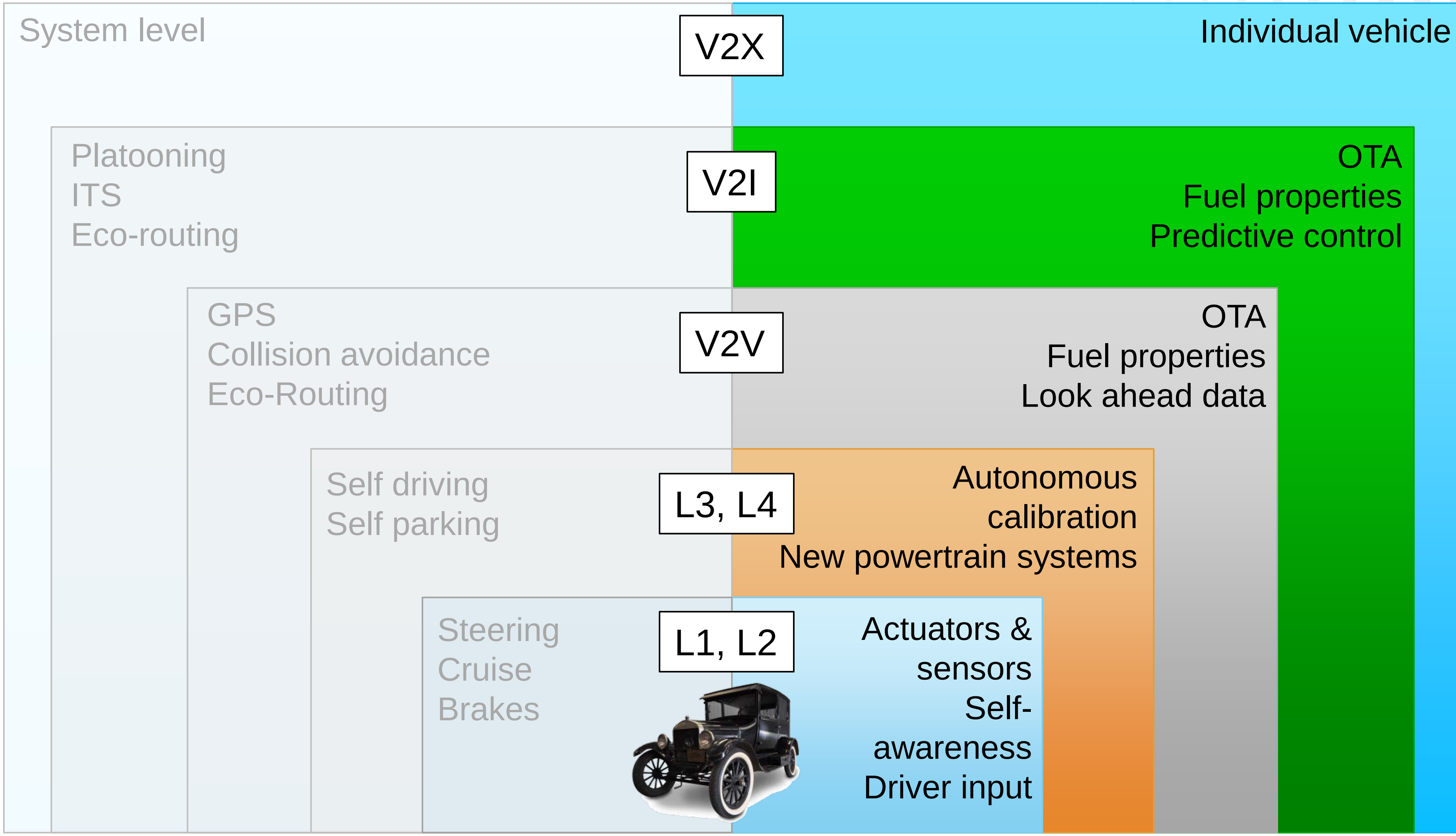
Vehicle Connectivity is a secular trend.

- Vehicles will become increasingly connected, to each other (V2V), to the infrastructure (V2I), and to the "cloud" (V2X).
- Vehicles will display increasing degrees of autonomy in their operation –
  - Advanced driver assistance systems
  - Semi-autonomous
  - Fully autonomous

Connected vehicles – V2V, V2I, V2X

DENSO, 2015

What are the enabling opportunities for increasing individual vehicle fuel efficiency?



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Future fuel efficiency potential with V2X?

On an individual vehicle basis

- Real-time optimization of powertrain control – on-board or off-board.
  - What can be done with 1000x real-time computational capability?
  - What can be done with more knowledge and information?
  - Supercomputer in the cloud?
  - OTA updates of engine control and calibration?
  - Bespoke, fully customized individual vehicle calibration optimization?

What are the fuel efficiency margins due to…

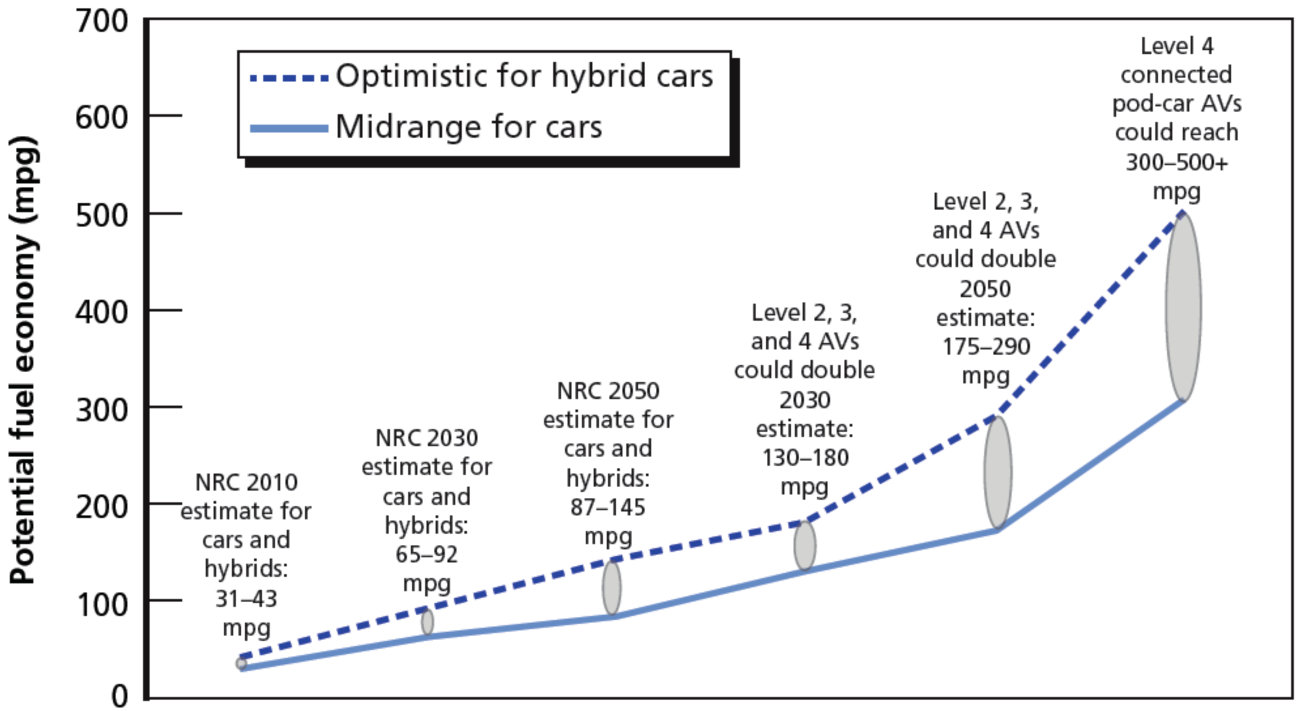
- Variations in fuel composition.
- Engineering and emissions margins.
- Variation in actuators and sensors, and ageing.
- Environmental conditions.
- Off-cycle operation.
- Driver behavior.

Future potential with Vehicle Autonomy?

- Advanced driver assistance systems vs. semi-autonomous vs. fully autonomous vehicles.
- Autonomous EVs offer little potential for efficiency improvement over non-autonomous EVs – aerodynamics, weight and cabin loads dominate.
- Autonomous engine-powered vehicles offer significant potential for efficiency improvements.
  - Reduction in driver's expectation of performance
  - Removing the driver from the loop

Future potential with Vehicle Autonomy?

Figure 2.6
Range of Potential Fuel Economy Improvements for Conventional, Hybrid, and Autonomous Cars



SOURCES: Analysis using data from NRC, 2013a; Folsom, 2012.

RAND *RR443-2.6*

Autonomous Vehicle Technology – A Guide for Policymakers – Anderson et al., RAND Corporation, 2014

CHANGING WHAT'S POSSIBLE

Improving Future Vehicle Fuel Efficiency via New Engine and Powertrain Technologies

Possible technology solutions

- Progression of **existing** technologies –
  - downsizing and boosting, (or upsizing and NA)
  - ultra-lean operation facilitated by new boost, fueling and ignition systems,
  - dilution with air or EGR
  - variable (high) compression ratio engines,
  - Otto and Diesel cycle convergence,
  - very high compression engines with knock mitigation,
  - LTC, dual fuel or reactivity controlled combustion,
  - friction, pumping loss and auxiliary load reduction,
  - thermal loss reductions (reduced surface area available for heat transfer),
  - stop/start,
  - waste heat recovery, hybridization and direct energy recovery systems.

- New engine **architectures** – such as
  - free piston engines,
  - split-cycle engines,
  - entirely new thermodynamic and combustion cycles.

- New **engines and powertrain operating systems** –
  - variable displacement engines, or
  - intermittent operation engines,
  - Integration with electric machines or other hybrid systems.

Any new powertrain technology has to be comparable to or better than the baseline in:

Criterion	Explanation
Power	Power density (or energy density including the fuel/energy storage capacity) ⇒ Customer acceptance
Efficiency	Fuel economy (over real-world dynamic driving) ⇒ Regulation
Emissions	Regulated criteria pollutants (and now CO_2) ⇒ Regulation
Cost	Total cost of ownership (including capex and fuel cost)
Reliability	Mean time between failures, maintainability
Utility	Acceleration, driveability, NVH, cold start, off-cycle operation, ease of use, transparency to the user, and acceptable range
Fuel acceptability	Use a readily available fuel or energy source.

An Automotive Industry Comparison

	Mid-size Conventional	Mid-size Hybrid	Tesla Model S	Tesla:Mid-size
Power (hp)	240	200+	500	2.0X
Emissions (Tailpipe)	ULEV	ULEV	ZEV	0.0X
Cost ($)	$32,000	$35,000	$95,000	3.0X
Range (mi)	540	540	265	0.5X
Refueling Rate (MW)	20	20/0.01	0.02	0.001X
Sales Volume (per yr)	2,500,000	250,000	20,000	0.01X

What do we hope to learn from the Workshop?

- What opportunities are there to leverage connectivity and/or autonomous operation to increase individual powertrain efficiency?
- What is the perceived trajectory of future powertrain hardware and/or controls development and is there an opportunity to change the learning curve with targeted funding?
- How do we optimize powertrain efficiency for any driving cycle given perfect information?
- How much powertrain efficiency is currently “left on the table”? Can that be reclaimed using connectivity i.e. perfect information?

THURSDAY, MAY 14	

	gram Director Dr. Chris Atkinson

FRIDAY, MAY 15	

	son

Breakout Questions

Breakout 1 – The information, connectivity and controls side of fuel efficiency

- How would you use connectivity to enhance the fuel efficiency of any powertrain? What information would you collect or use? What would you do with that information? What would having any and/or all information offer you from a fuel efficiency perspective? (both on vehicle and V2X information)
- In a world with connected vehicles and advanced computational capability, what new opportunities exist to co-optimize the powertrain (engine and transmission or hybrid system) for maximum efficiency?
- What additional sensors (real or virtual), or actuators, would you want in a future powertrain? How would these help increase vehicle efficiency?

Breakout 1 continued…

- (From a controls standpoint) What are the unique opportunities for increasing powertrain efficiency for either conventional or hybrid vehicles using connectivity? How do we need to change controls to incorporate new information facilitated by connectivity?
- How do the opportunities differ for light and heavy-duty vehicles? Are there any unique opportunities for light-duty or heavy-duty?

Breakout 2 – Powertrain hardware innovations

- Engines today are designed with performance, emissions, fuel efficiency, customer acceptability, cost, reliability, range and manufacturability in mind (amongst other factors). Imagine an ideal scenario where thermodynamics is the only constraint on engine efficiency. What would this engine look like? What fuel would it use <u>(noting that we are fuel agnostic)</u>? Which of the constraints mentioned could you relax and why?
- What is (are) the main limiting factor(s) to increasing powertrain efficiency? What new opportunities exist to co-optimize the powertrain (engine and transmission or hybrid system) for maximum efficiency assuming connectivity?

Breakout 2 continued…

- If you take the driver out of the loop with respect to vehicle and powertrain control, as well as the driver's expectation for performance, how would you re-design the powertrain for fuel efficiency? What are the opportunities besides "right-sizing" the powertrain?
- How would perfect virtual/real sensors help increase powertrain efficiency?
- Are we limited by the physics or chemistry of sensing or actuating? How can we improve this?

Other brainstorming questions

- What opportunities are there in engine calibration for additional efficiency?
  - Sensors for fuel identification
  - Sensors for after treatment behavior/degradation
  - Sensors for emissions being produced for real time optimization of combustion
  - Sensors for passenger loading and monitoring – feed back for engine calibration or hvac settings. Is there a benefit to having smaller aux components (coolant pump, hvac fans) and more of them and using them in a binary, discretized fashion as opposed to a single larger device?
  - What is the effect of dynamic ECU calibration as opposed to static maps?
  - Physical sensors vs virtual sensors?

- What opportunities are there with removing the driver’s right foot from the vehicle control?
  - Smoother driving
  - Predictive grades in the road and change of engine operation
  - Cylinder deactivation for higher BSFC operation (less switching between on/off)
  - Modified/variable engine/transmission calibration for higher efficiency (along the lines of lower power performance of the vehicle)
  - Weather (humidity, temperature and altitude)

- What other sensors or measurements would enable high efficiency? How many sensors are required and can you have too many? What would you want to measure?

Guide for Workshop Moderators: The "Do's" and "Don't's" for Discussion

DO talk about..

- Powertrain hardware & control
- Fuel injection strategies
- Hybrid controls
- How to *use* sensors, eg fuel identification, exhaust aftertreatment, emissions for real time optimization of combustion, passenger loading and monitoring
- Dynamic ECU calibration vs. static maps
- Optimized cylinder deactivation
- Modified/variable engine/transmission calibration for higher efficiency
- Opportunities with taking the driver out of the loop
- Autonomous calibration
- Predictive control
- Vehicle-to-cloud

DON'T talk about..

- Improving anything that is a non-powertrain technology
- Platooning
- Eco-routing
- Traffic signal synchronization
- Information Technology Services (ITS)
- Collision avoidance
- Developing sensors that enable connectivity / autonomy
- Car sharing
- Lightweight materials for the vehicle
- Battery chemistries
- Fuel development (eg "low carbon fuels", electo-fuels, etc)
- Self-driving / parking
- Adaptive cruise control
- Vehicle dynamics (e.g. aerodynamic drag, tire rolling resistance)
- Brakes

Connected/Autonomous Vehicles

- With partial and/or full integration of vehicle connectivity/autonomy (assume that the infrastructure and technology exist):
  - What are the efficiency improvement opportunities for conventional powertrains?
  - What are the efficiency improvement opportunities for HEVs?
  - What are the efficiency improvement opportunities for EVs?
  - How would you redesign your powertrain or what will the powertrain look like in such a case?

Powertrain Improvements

- Imagine a situation where powertrain computational capability (memory & microprocessor power) is not a limitation anymore.
  - What are the opportunities for optimal powertrain control and calibration?
  - Will this have an impact on powertrain/engine design?
  - What impact will it have on the way in which vehicles or engines are calibrated and optimized?
- With V2X and conventional vehicles with some degree of on-board energy storage, what type of new control strategies could be used for maximizing fuel efficiency?

Powertrain Innovations

- Imagine a situation where you could redesign the engine without cost constraints (but keeping in mind the other 6 metrics)
  - What conventional powertrain improvements can be leveraged (heat transfer, friction, downsizing etc.) for typical transient driving conditions?
  - What fuel/s and combustion strategies will be used?
  - What exhaust energy recovery strategies can be adopted?
  - How will future engine and powertrain architectures look for HEVs?

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