HIGHLY AUTOMATED VEHICLES – THE IMPLICATIONS FOR ENERGY EFFICIENCY AND FUEL ECONOMY

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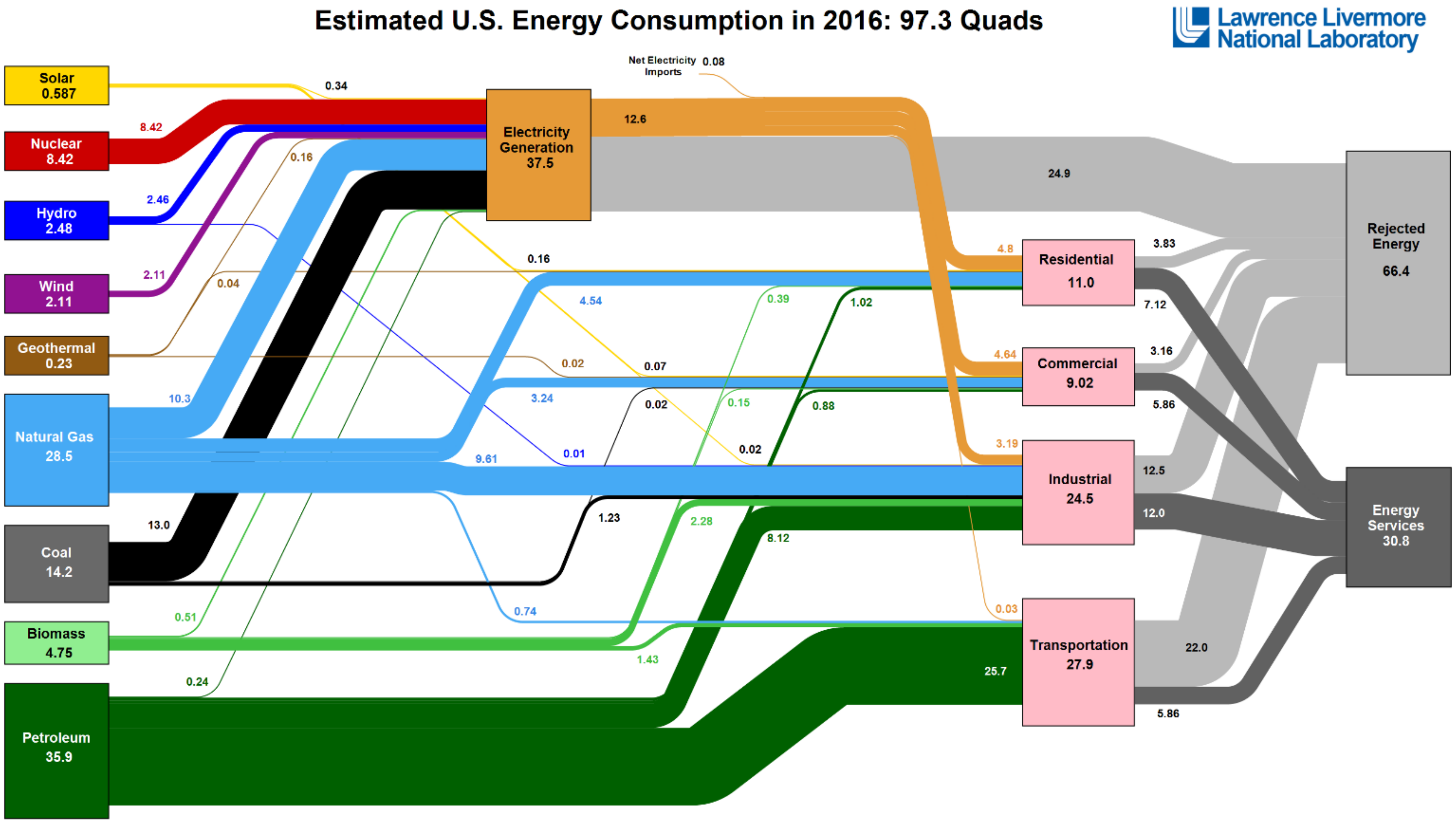
Advanced Research Projects Agency – Energy
US Department of Energy

ENERGY USAGE IN THE UNITED STATES IN 2016



Source: LLNL March, 2017. Data is based on DOE/EIA MER (2016). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes made in mid 2016 to the Energy Information Administration's analysis methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector, and 49% for the industrial sector which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

ARPA-E Mission

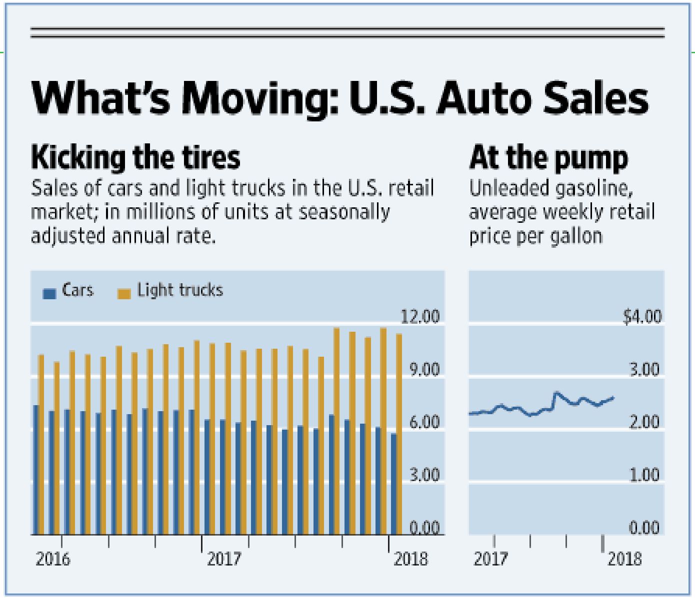
Mission: To overcome long-term and high-risk technological barriers in the development of energy technologies

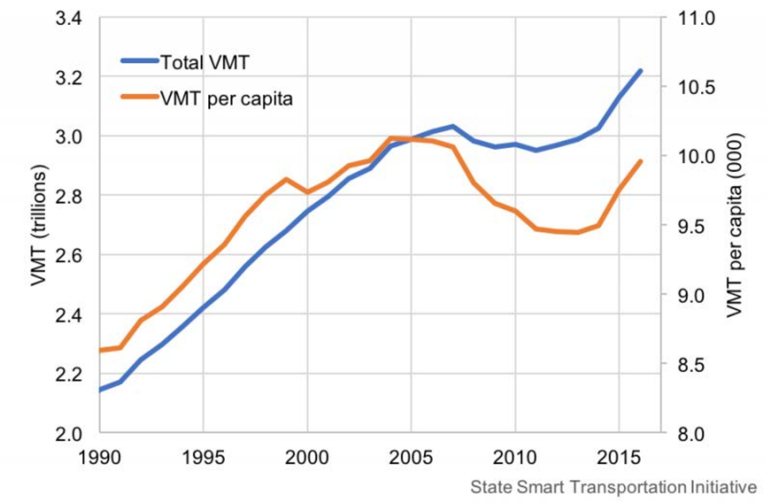
Means:

- Identify and promote revolutionary advances in fundamental and applied sciences
- Translate scientific discoveries and cutting-edge inventions into technological innovations
- Accelerate transformational technological advances in areas that industry by itself is not likely to undertake because of technical and financial uncertainty

Reducing Energy in Automotive Transportation

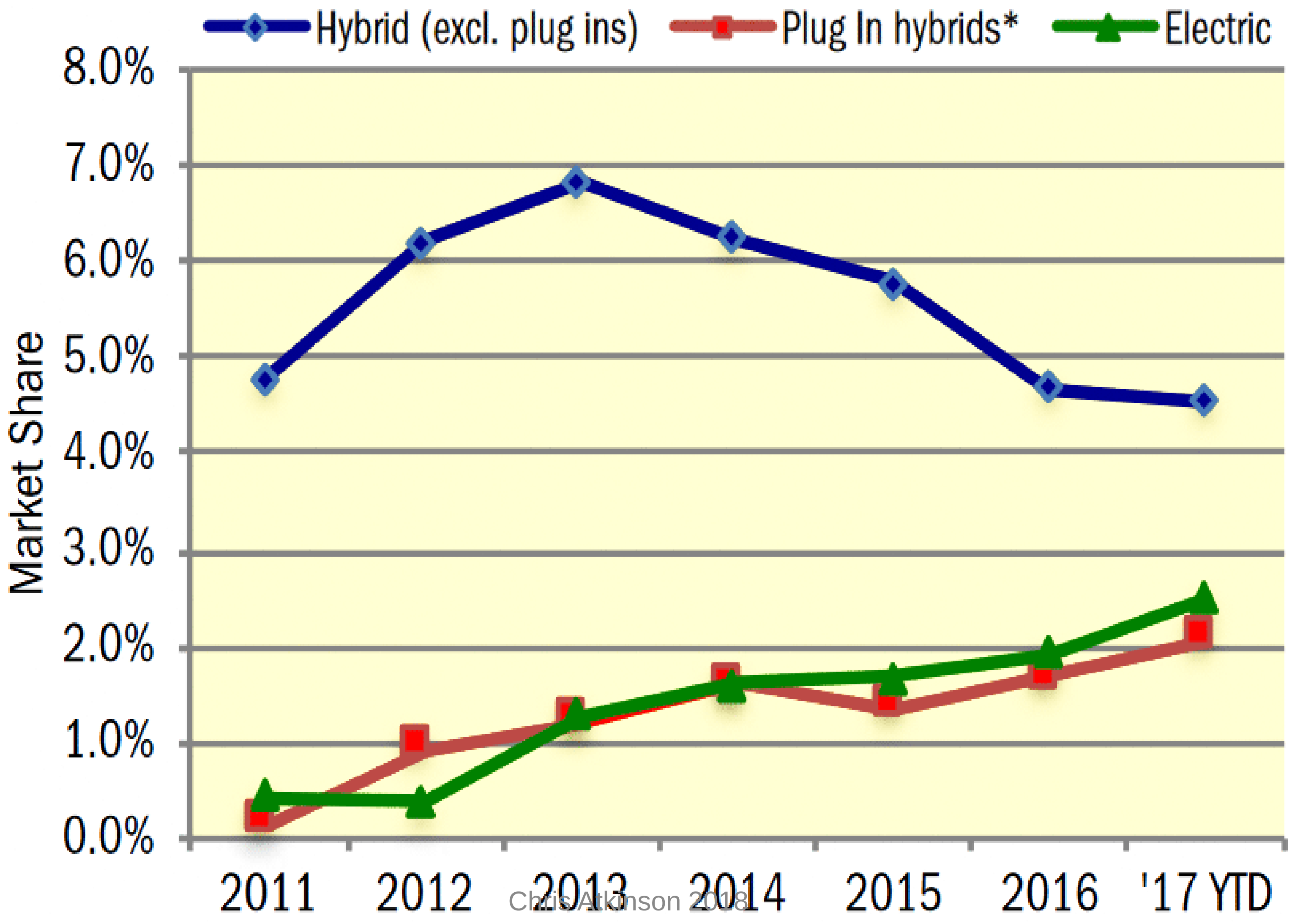
The State of the Automotive Industry Today



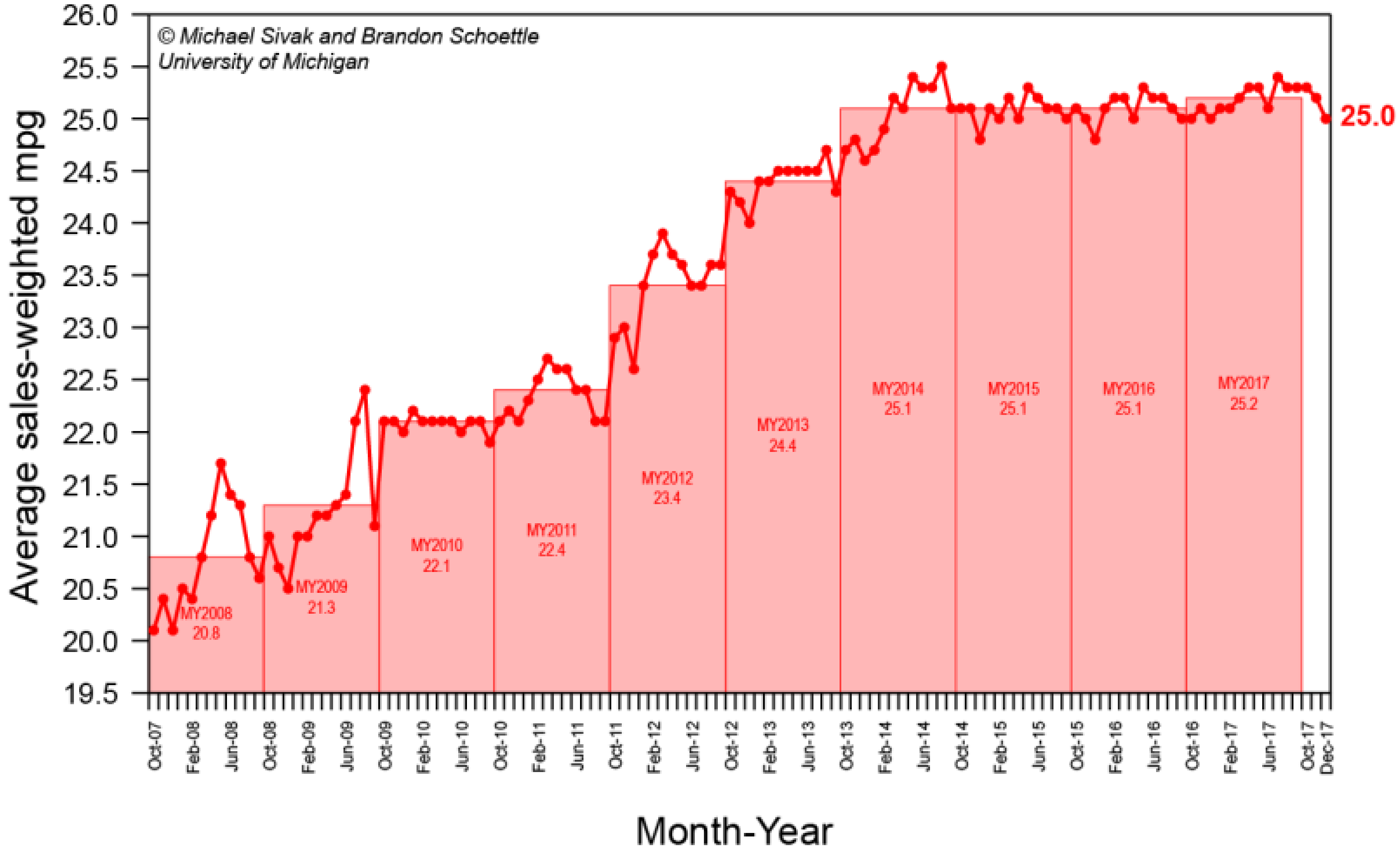


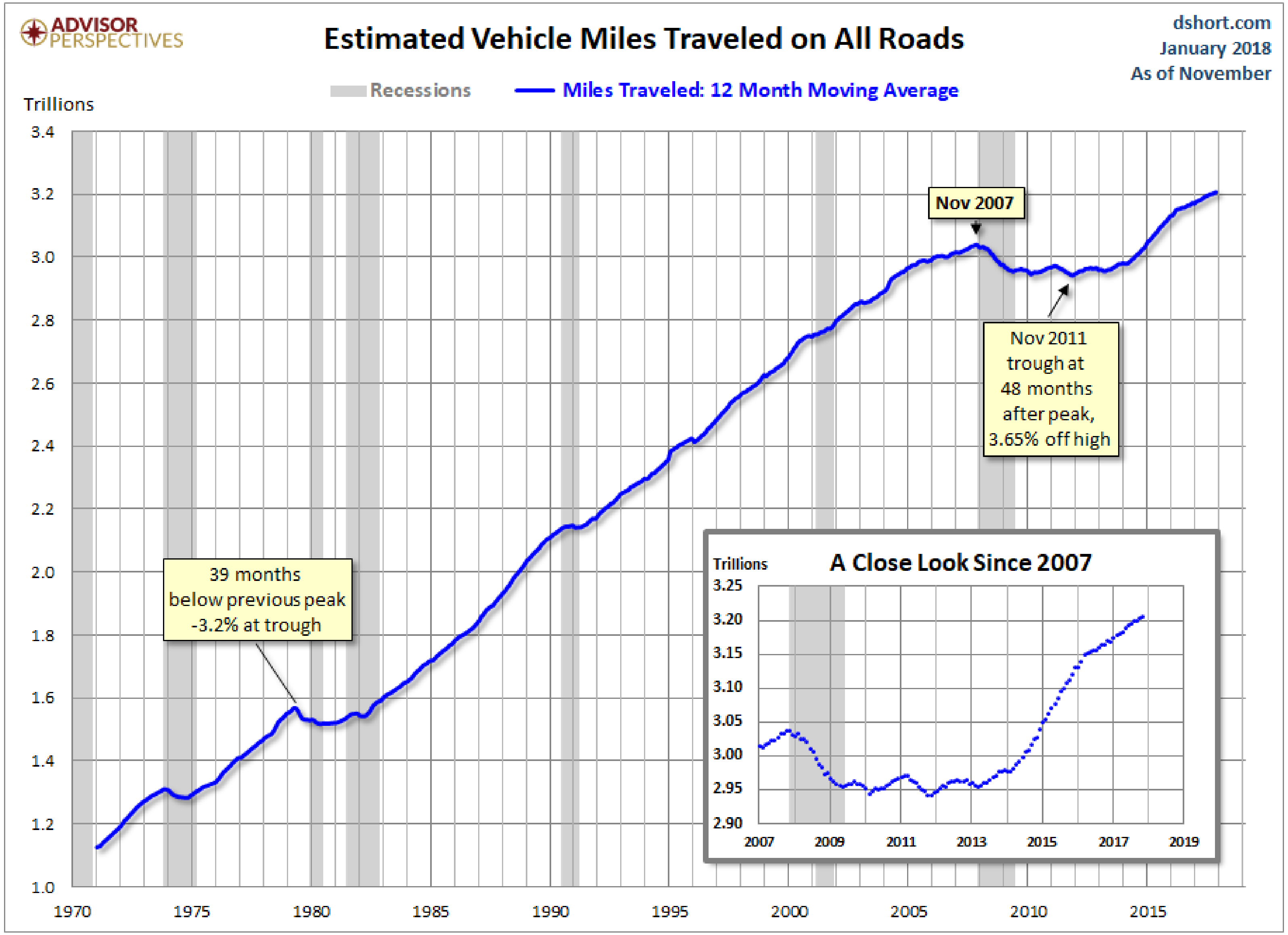
- **Total light-duty vehicle sales** in 2017 were ~17.2 million (at $34k average)
- **Total vehicle fleet** in the US: 190 million cars, 50 million pickup trucks, 12 million heavy-duty (HD) vehicles (trucks, buses).
- **65% of sales** are now pickup trucks, SUVs, crossovers and minivans.
- Average LD vehicle age is now **11.4 years** (Polk).
- LD vehicle fleet takes **10-15+ years** to turn over.
- xEV sales (US, 2017): 1.2% BEVs (including PHEVs), 2.7% HEVs
- Average costs of personal vehicle ownership and operation are **~$0.60/mile**.
- **Heavy-duty** truck sales in 2017 were 290,000 (truck costs are **$3.00+/mile**).

California Market Share



Class 1 & 2 fuel economy has stagnated since 2014 (UMTRI)

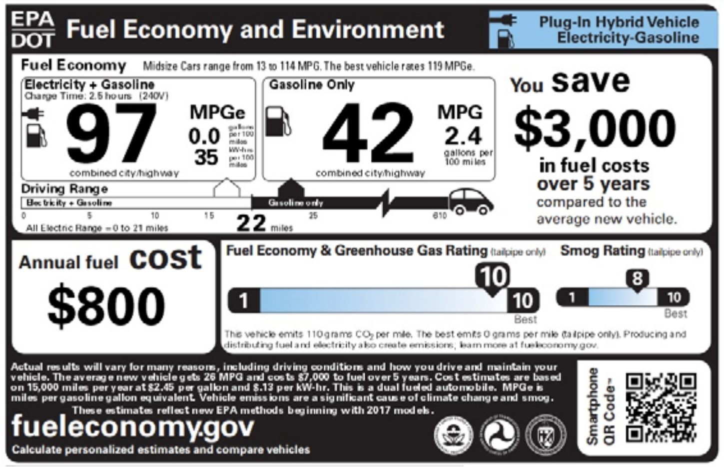



ADVISOR PERSPECTIVES
Estimated Vehicle Miles Traveled on All Roads
dshort.com
January 2018
As of November
Recessions
Miles Traveled: 12 Month Moving Average
Trillions
Nov 2007
Nov 2011 trough at 48 months after peak, 3.65% off high
39 months below previous peak -3.2% at trough
A Close Look Since 2007
Trillions

3 Dominant Trends in Automotive Transportation

Trend 1 – Fuel Economy (or Energy Efficiency)

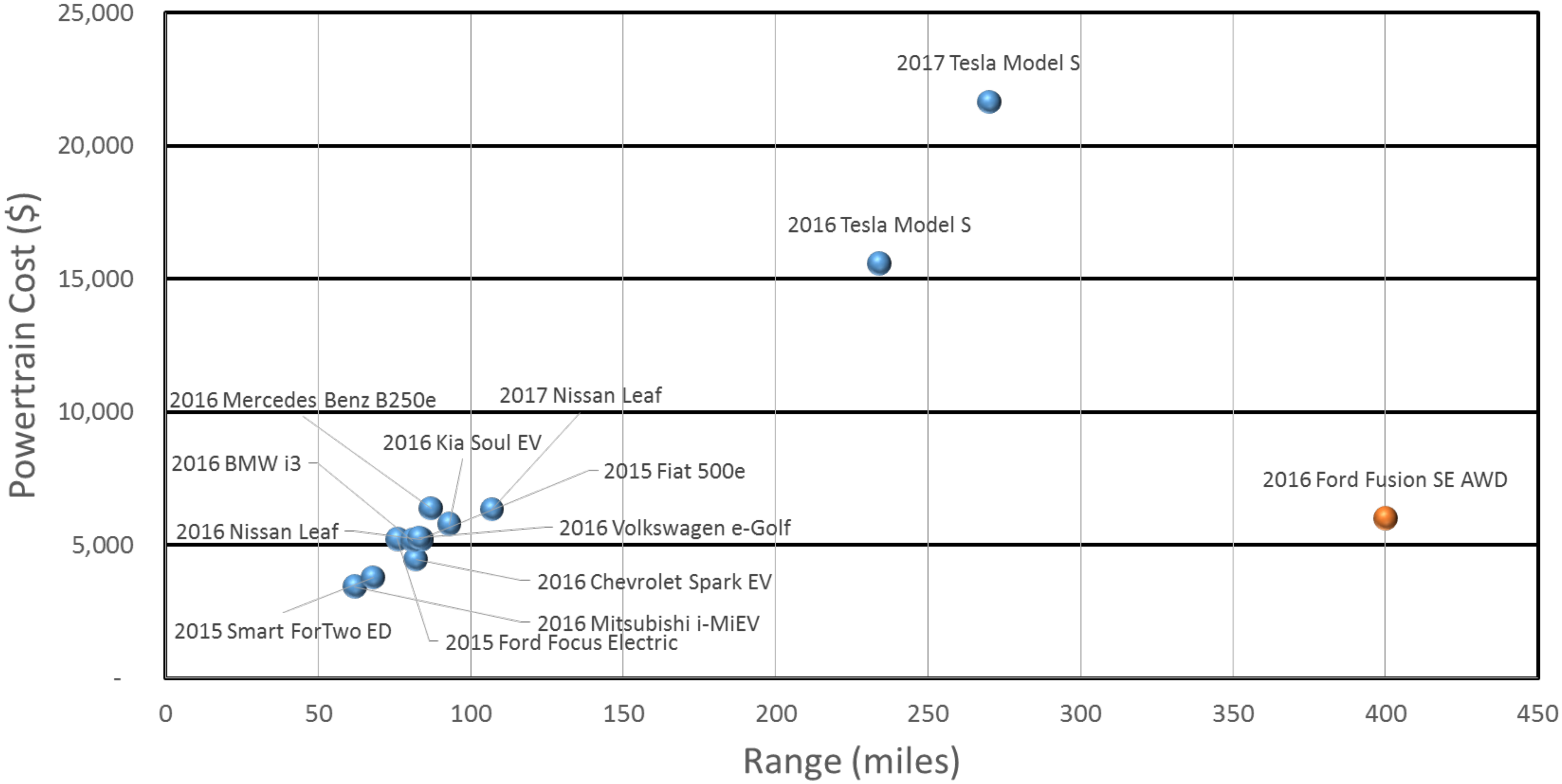
- **Future fuel economy of the light-duty vehicle fleet will be required to be significantly higher than today (54.5 mpg CAFE by 2025).**



- **Heavy-duty** fuel economy regulated by EPA/NHTSA Phase 2 GHG rules.

Fuel efficiency improvements will be achieved by **vehicle light-weighting, reducing aerodynamic drag and tire rolling losses, engine downsizing, boosting, improved transmissions (multispeed, CVT), increased electrification, hybridization, waste energy recovery, and reductions in friction and parasitic losses.**

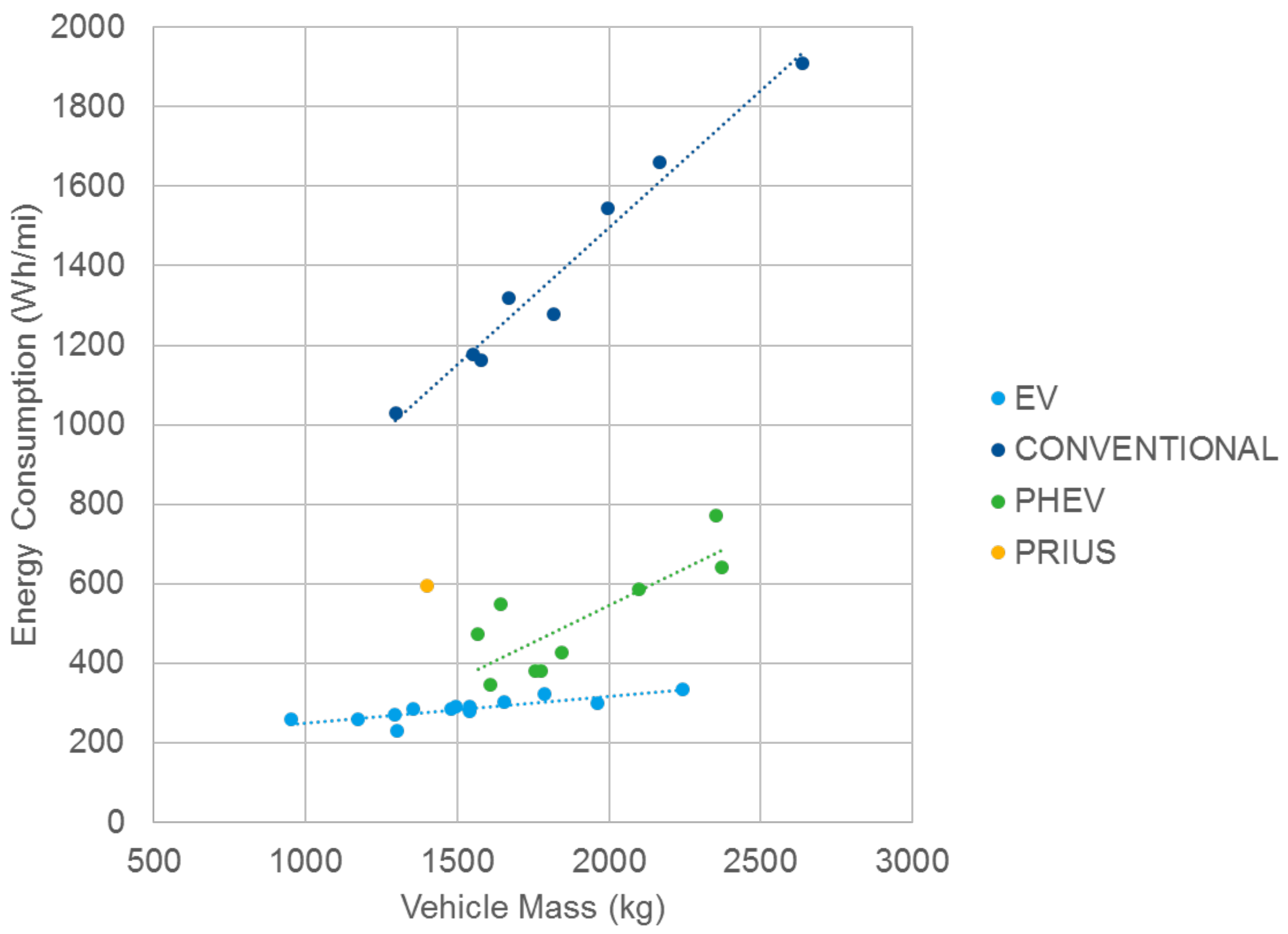
Powertrain Cost (Battery Pack cost $190/kWh, Motor and Power Electronics $8/kW)

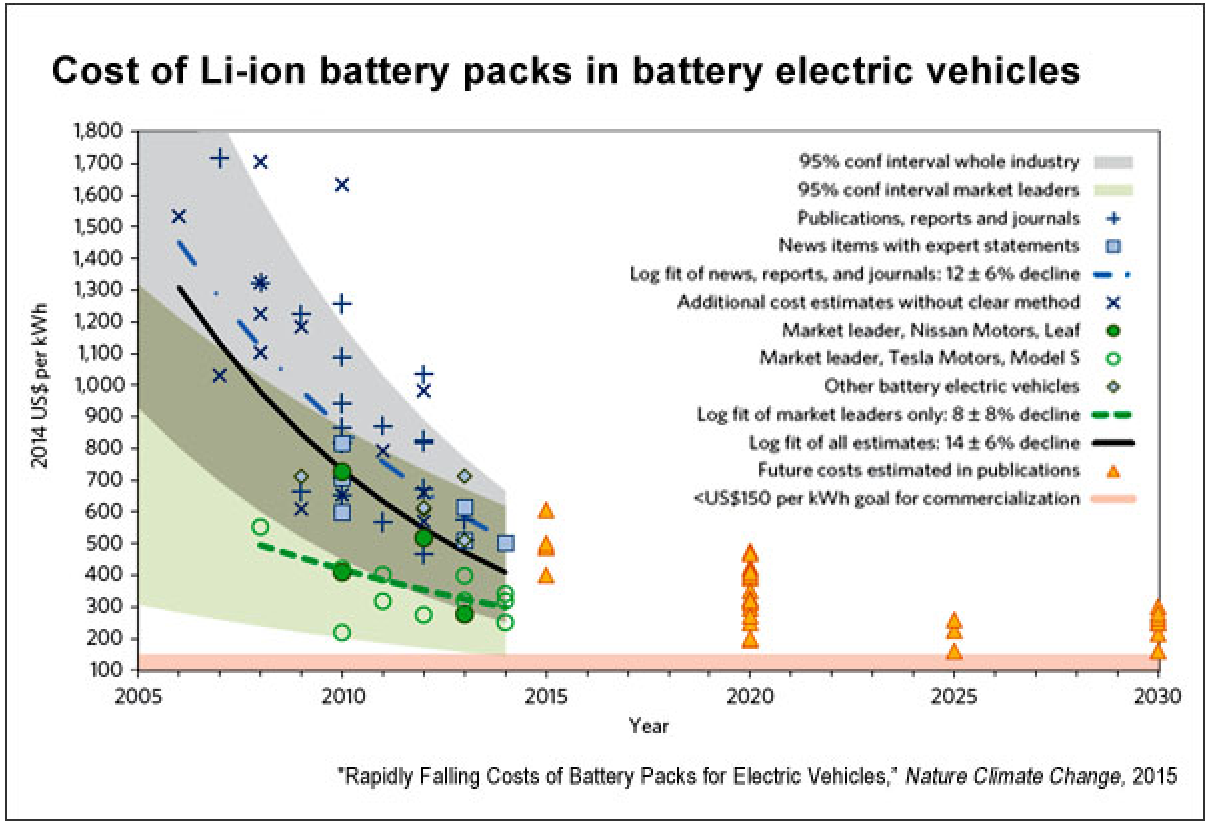


$0.14/mi PT cost over 150k miles.

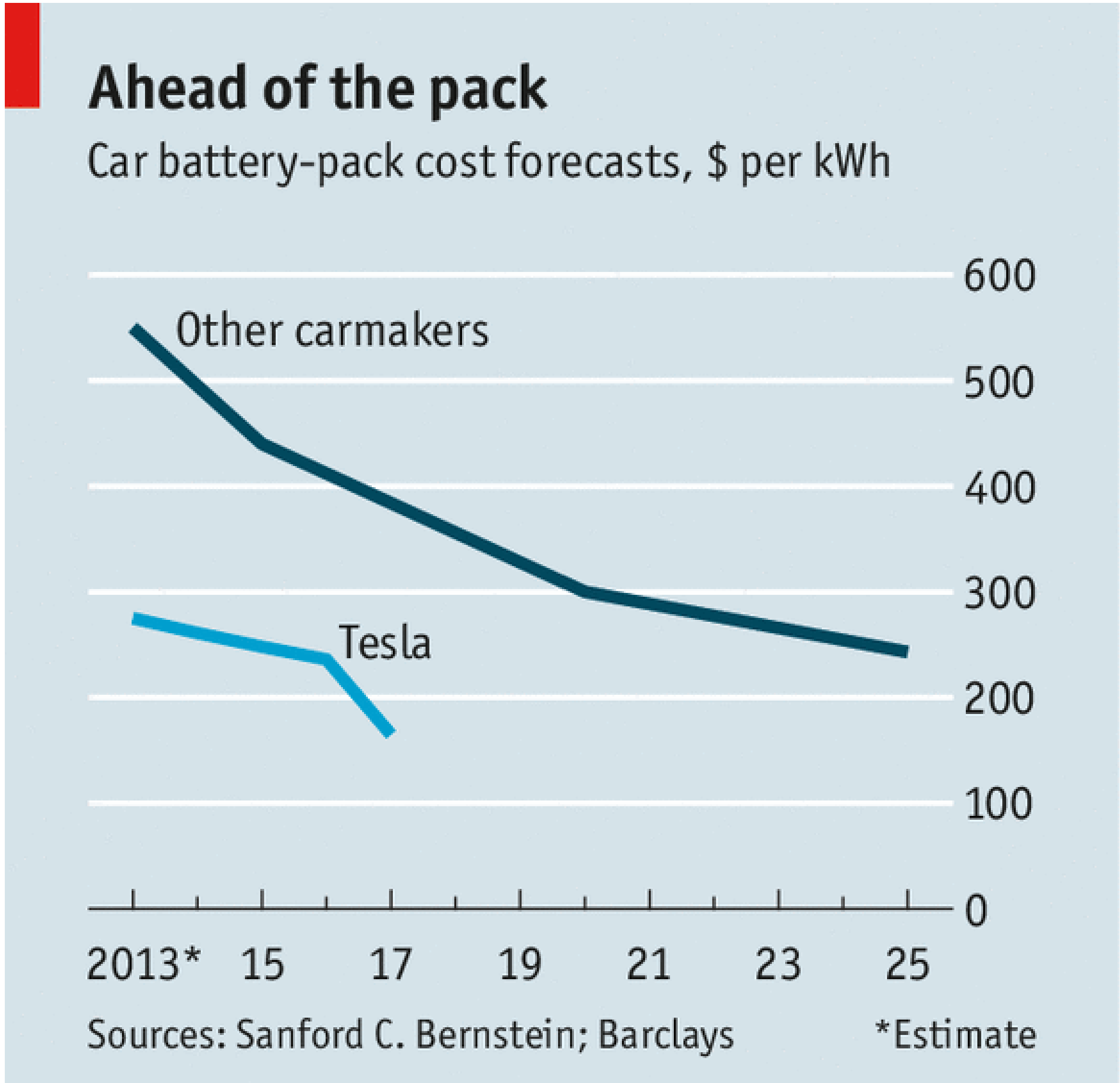
$0.04/mi PT cost over 150k miles.

Energy Consumption (Wh/mi) (Tank-to-Wheels)

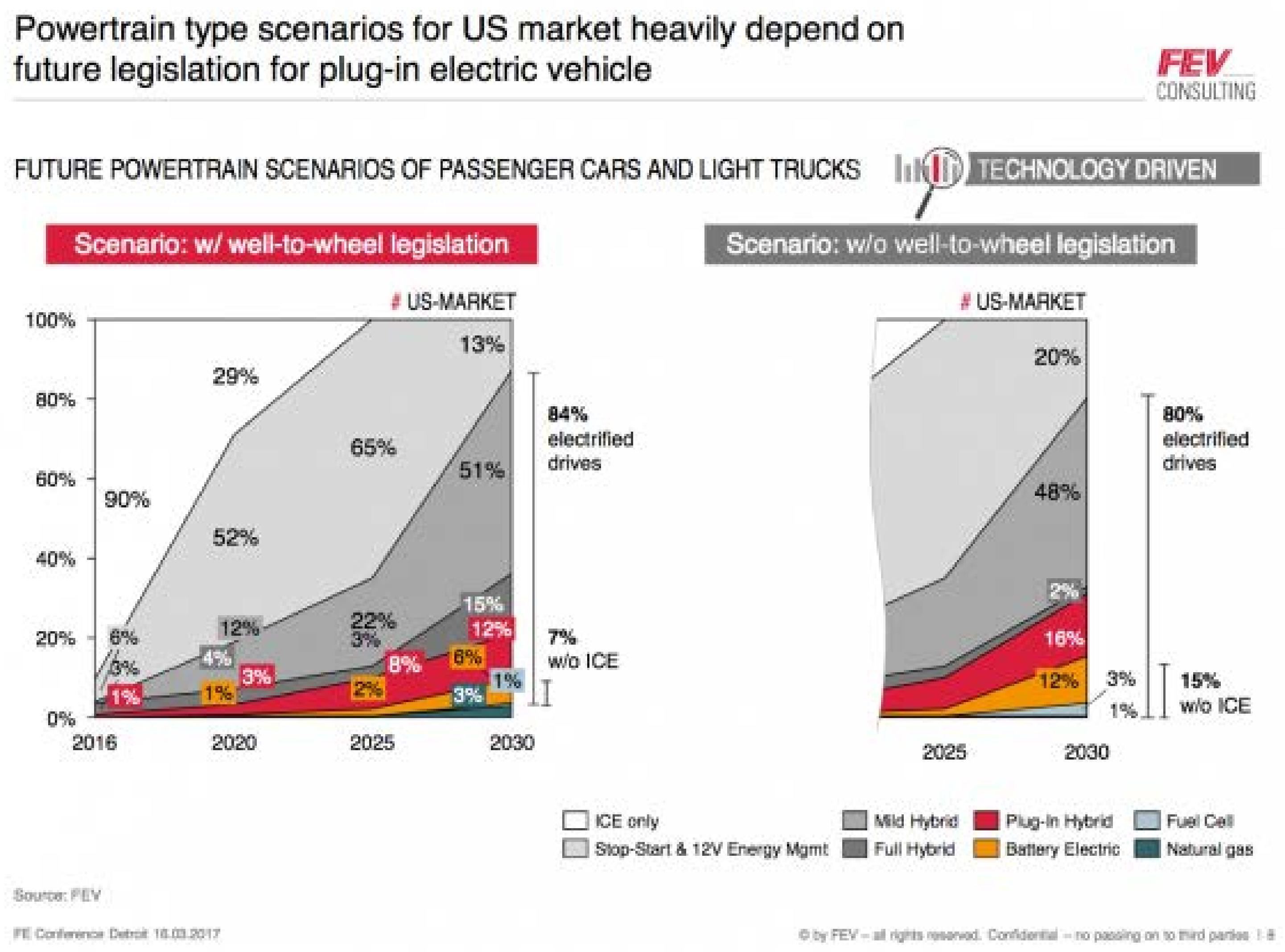




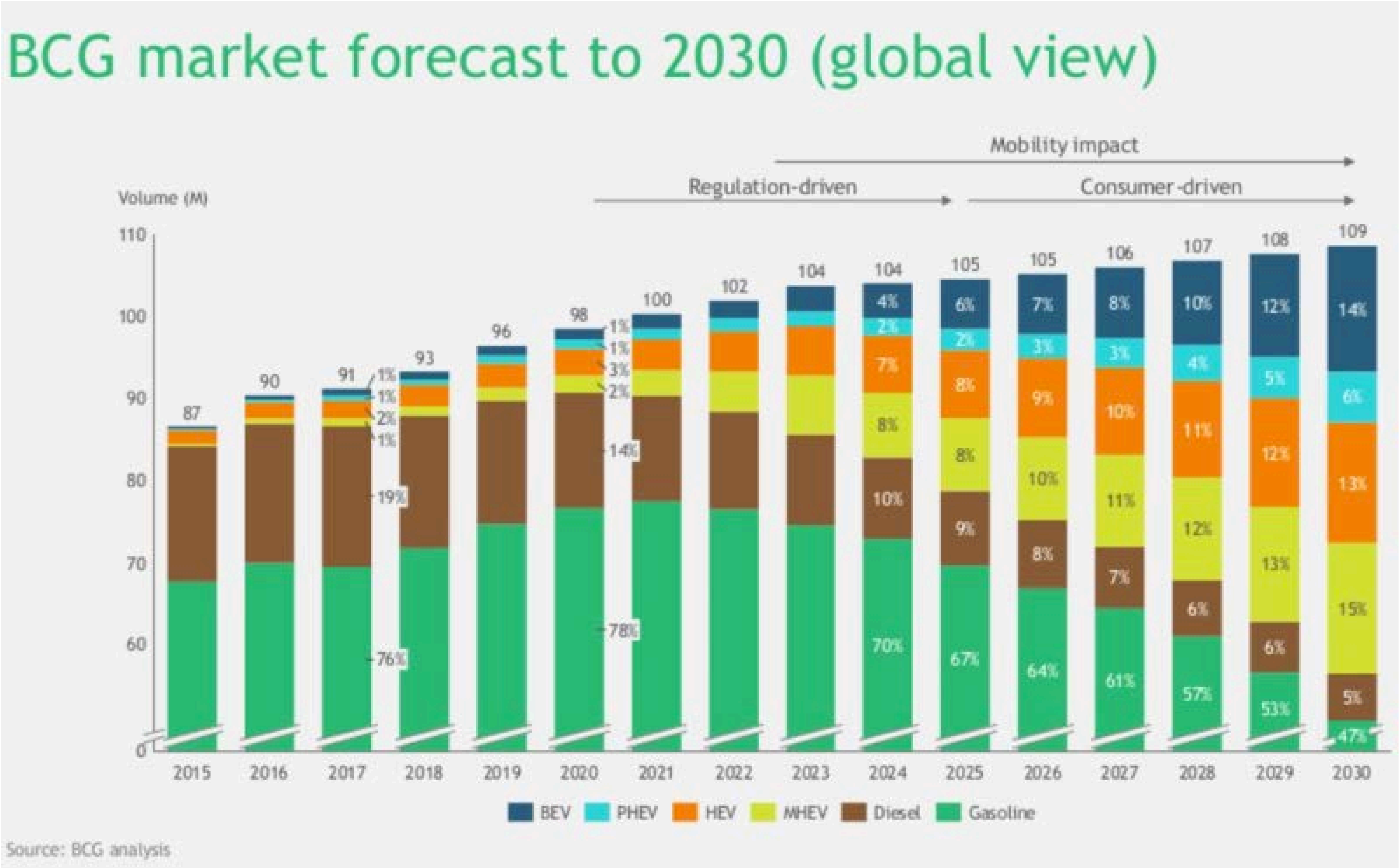
Cost of Li-ion battery packs in battery electric vehicles
2014 US$ per kWh
Year
95% conf interval whole industry
95% conf interval market leaders
Publications, reports and journals
News items with expert statements
Log fit of news, reports, and journals: 12 ± 6% decline
Additional cost estimates without clear method
Market leader, Nissan Motors, Leaf
Market leader, Tesla Motors, Model S
Other battery electric vehicles
Log fit of market leaders only: 8 ± 8% decline
Log fit of all estimates: 14 ± 6% decline
Future costs estimated in publications
<US$150 per kWh goal for commercialization
"Rapidly Falling Costs of Battery Packs for Electric Vehicles," *Nature Climate Change*, 2015



Ahead of the pack
Car battery-pack cost forecasts, $ per kWh
Other carmakers
Tesla
600
500
400
300
200
100
0
2013* 15 17 19 21 23 25
Sources: Sanford C. Bernstein; Barclays
*Estimate



2017: HEVs – 2.7%, BEVs – 1.2%



Boston Consulting Group, 2017

Predictions of IC Engine Penetration – post 2030

- **Optimistic – IEA, DOE, EPA, IEAE, most OEMs, many suppliers**
- **Pessimistic – various advocacy groups, China, India, Norway**
- **Many OEMs and organizations confuse “electrification” and “hybridization”**
- **IC Engine Penetration Predictions range from 0% to 80% or more**
- **The most probable outcome – engines dominate in HD (difficult to fully electrify; mild hybridization probable); HEVs dominate in LD (mild to 48V to moderate to strong) – can also include PHEVs.**
- **So, an educated guess would be:**

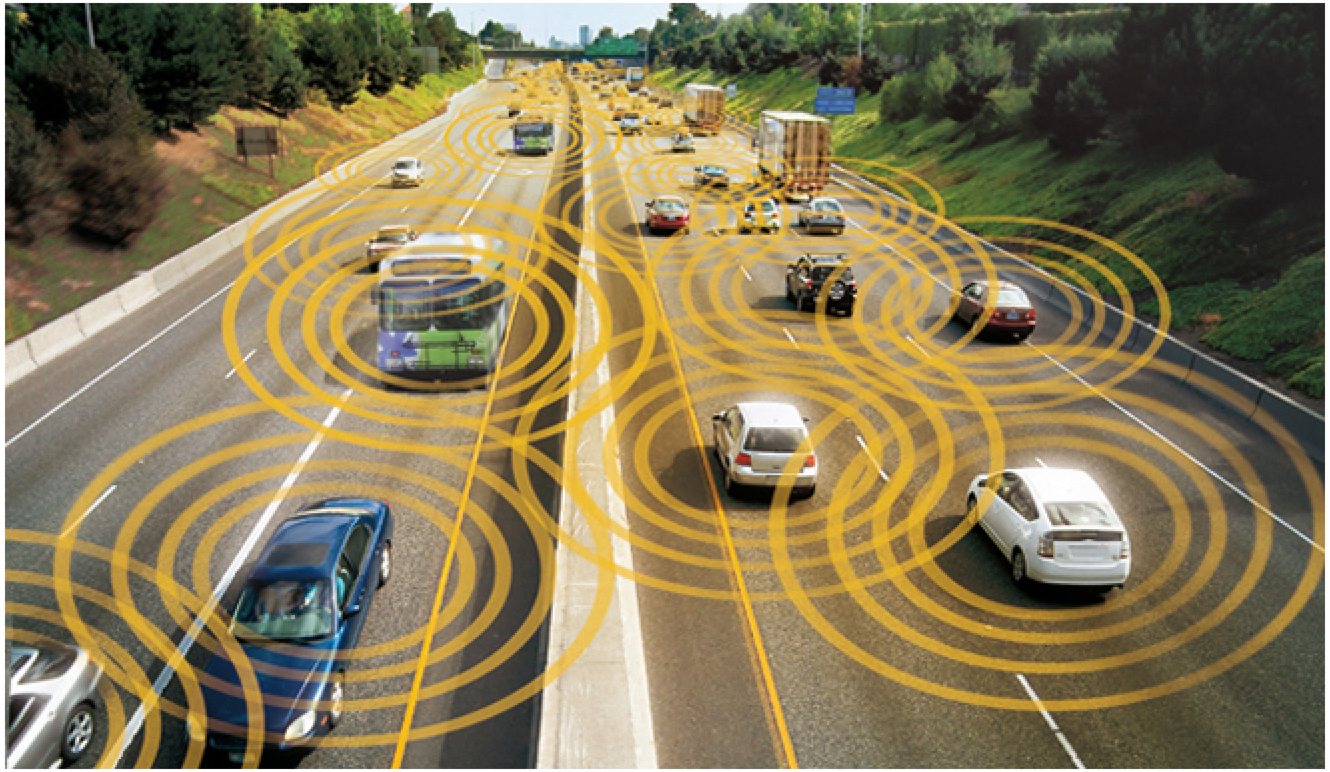
  80% engines (including HEVs & PHEVs) in LD & MD in North America in 2030; close to 100% for HD;

  60% in Europe; 20% in China; 90% in ROW.

  →**80 - 100M engines per year in 2030**

Trend 2 – Vehicle Connectivity

- Future vehicles will utilize greater levels of connectivity – V2V, V2I, V2X – this trend has been driven primarily by road traffic safety considerations.



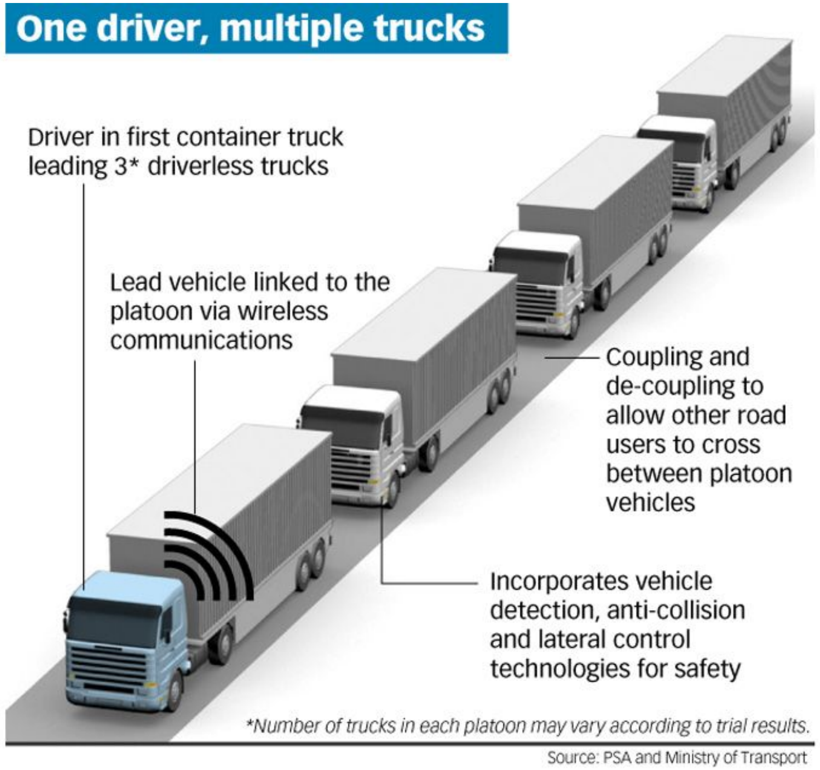
Trend 3 – Vehicle Automation

- **Future vehicles will display greater levels of automation – from L0 (no automation) to L1&L2 advanced driver assistance systems (ADAS) to L3&L4 automation (automated operation with a driver present) and L5 (highly automated or full automation – no driver required).**

Automation attractive for safety considerations, and for removing the (cost of) the driver.

Connectivity and Automation can reduce energy usage

- **Facilitates collaborative vehicle behavior (requires V2V communication)**
  - *Platooning, congestion mitigation, CACC*
- **Facilitates interaction with infrastructure (requires V2I communication)**
  - *SPaT – signal phase and timing*
  - *Eco-approach and departure*
- **Facilitates congestion mitigation (requires V2X, cellular, satellite communication)**
  - *Eco-routing*

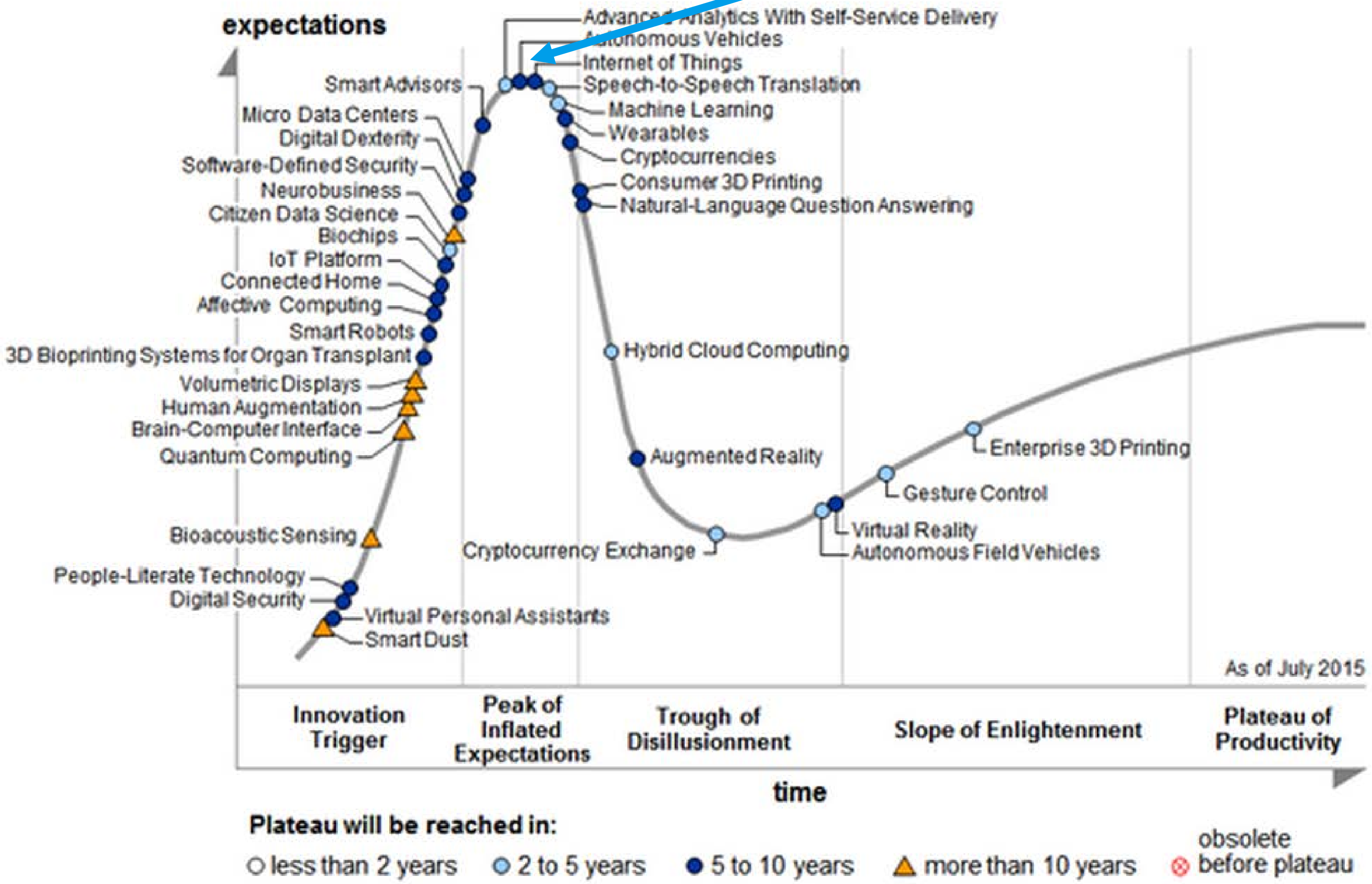


Connectivity and Automation – Effects on Powertrain Control

- **For the first time, powertrain control will have full future predictive capabilities – a point of inflection**
- **Vehicles and powertrains will know (on multiple timescales) what their future power demand will be**
- **Especially useful for hybrid powertrains due to multiple sources and sinks of energy and power**
- **Will allow for the use of a whole new class of high efficiency, poor transient response engines**
  - Alternative architectures
  - Reconfigurable architectures
  - Alternative combustion regimes
  - Range extender-specific engines

Highly Automated Vehicles

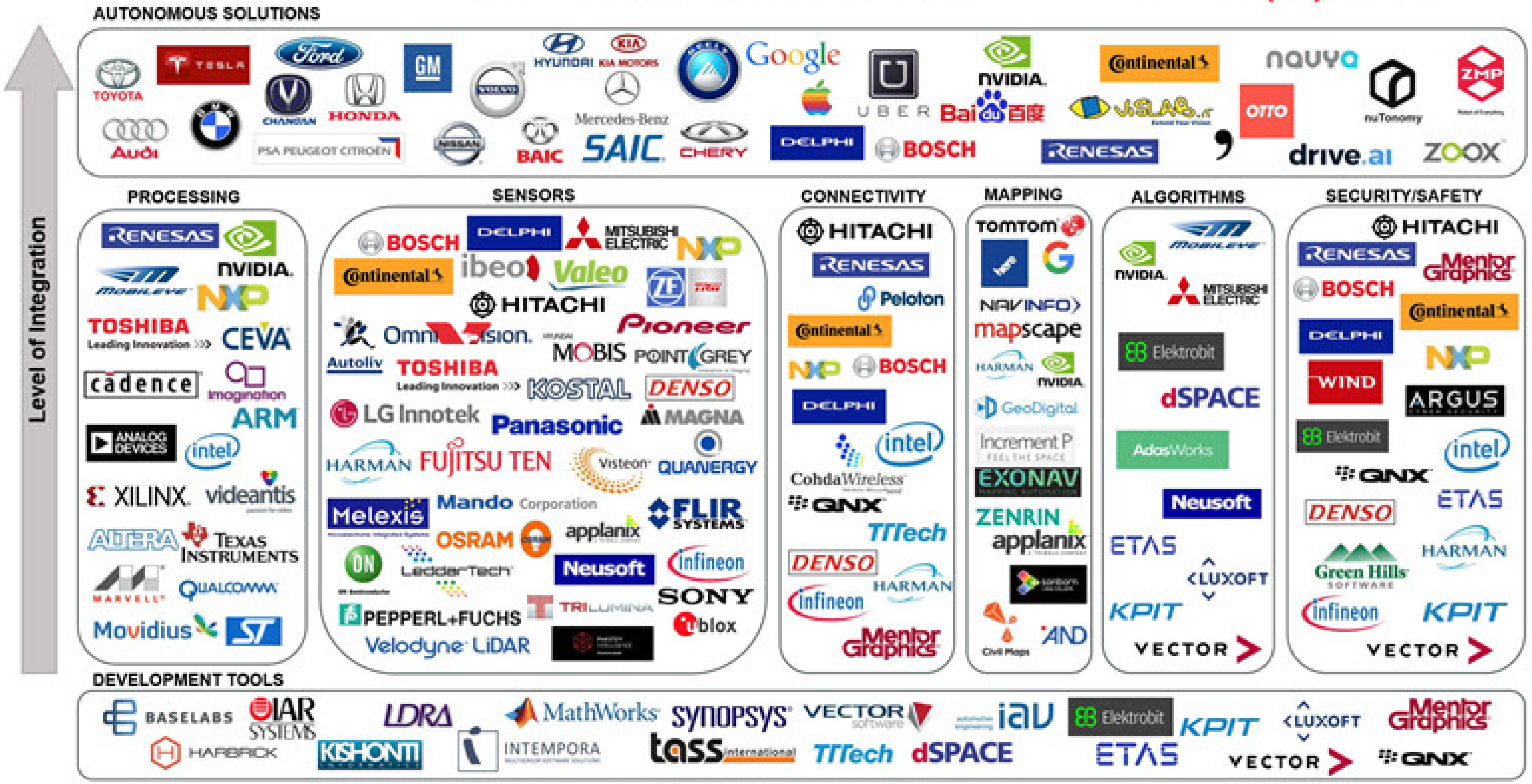
Figure 1. Hype Cycle for Emerging Technologies, 2015



Gartner, 2015

The Building Blocks of Autonomy

Prepared by VISION SYSTEMS INTELLIGENCE



Highly Automated Vehicles – some energy myths

- **All HAVs will be battery electric vehicles (BEVs).**
  No, not necessarily – they will probably be hybrid electric vehicles (HEVs or PHEVs) due to their electrical system requirements (up to 15 kWe for prototypes; 5 kWe for production vehicles). The converse is probably true – that automation facilitates the adoption of BEVs.
- **HAVs will lead to an increase in ride-sharing and/or vehicle-sharing.**
  No, Jevon's Paradox teaches us that making something easier to use, or cheaper to use, leads us to use more.
  The differences between ride-hailing (Uber), ride-sharing (UberPool), car-sharing (Car2Go, Zipcar) are significant from an energy utilization perspective.
- **HAVs will be cheaper to operate.**
  No reason to believe this – massive increase in complexity and hence cost.
- **HAVs will lead to a reduction in energy usage.**
  - No reason to believe this.
  - Urban and suburban sprawl.
  - Driving by proxy.

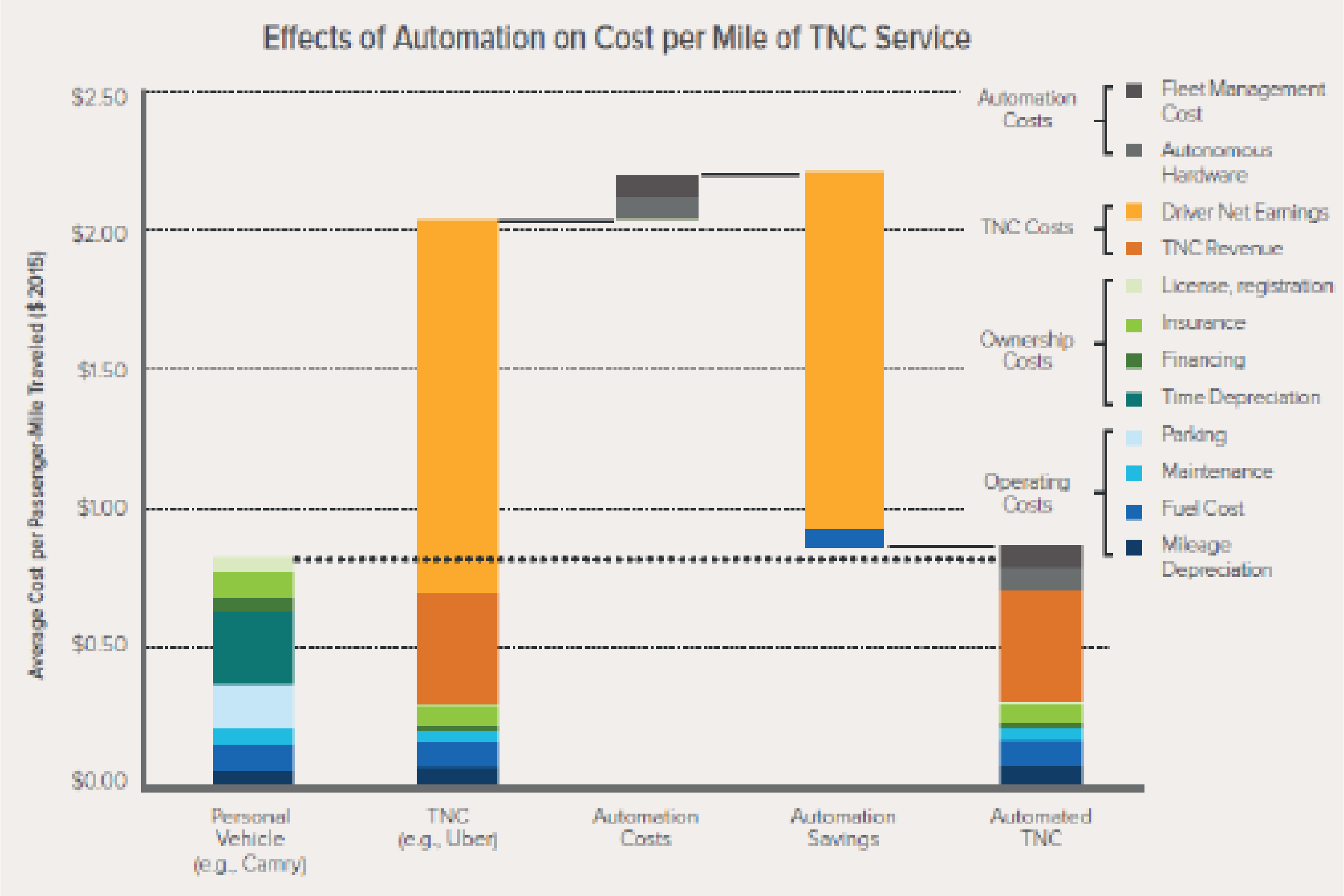


Figure 18: Effects of automation on cost-per-mile of transportation network company service[38]

Rocky Mountain Institute, 2016

Gonder et al., NREL 2016

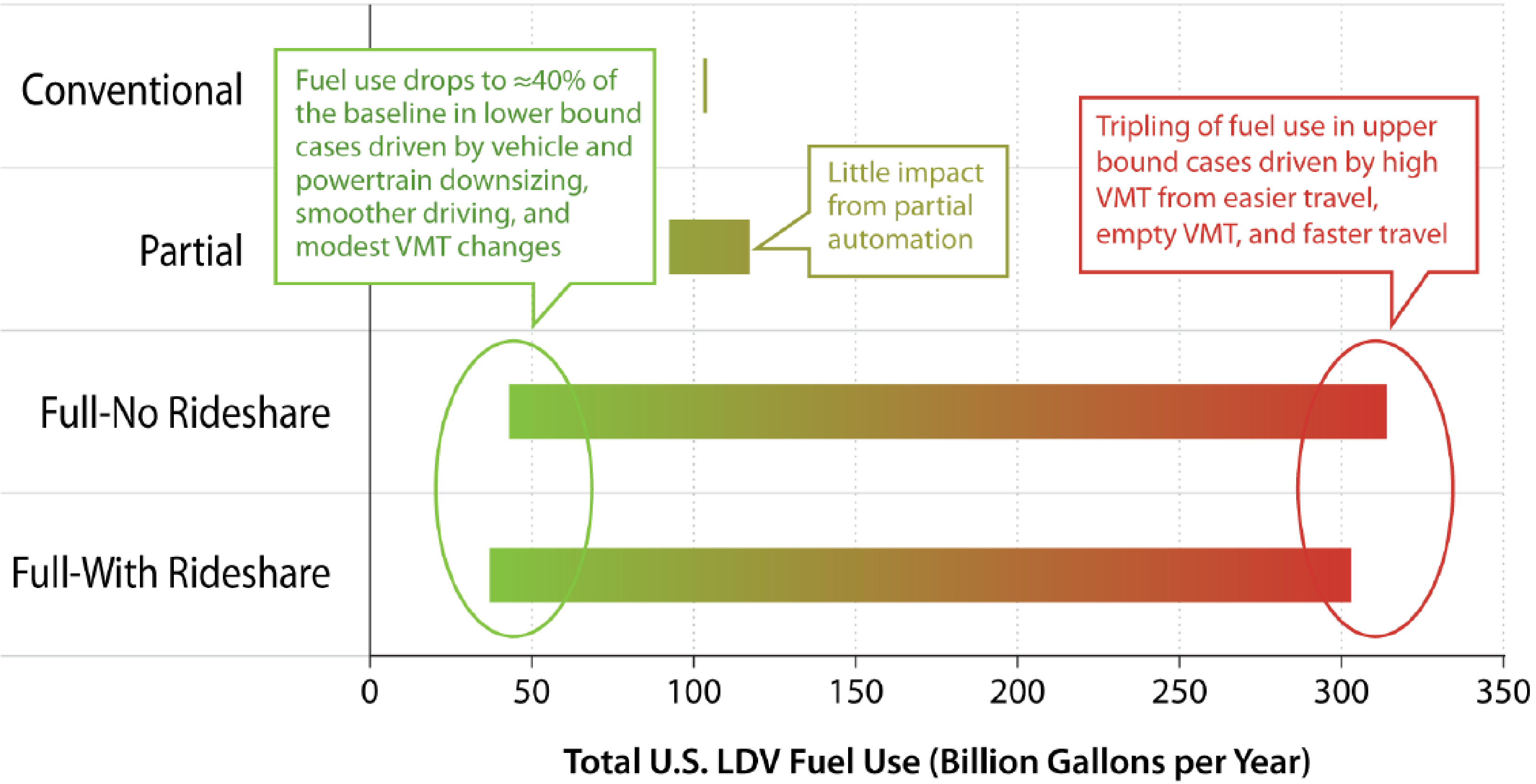


Figure ES-2. Estimated bounds on total U.S. LDV fuel use per year under the base (Conventional) and three CAV scenarios, based on the study's synthesis approach from CAV feature impact ranges reported in existing literature

What are the implications for future energy usage?

  - Liquid fuels (petroleum, biofuels) will persist due to large legacy fleet, cost, energy density, range, refueling infrastructure, ease of refueling
- Potential for halving fuel use with constant VMT is real with HEVs and PHEVs
  - BEVs will make inroads – currently 1.2% of new vehicle sales; 10-20% quite reasonable by 2030 or beyond (average daily driving range is <60 miles; 99th percentile is 400 miles)
- Li-ion to 2030 – what is beyond Li-ion?
- Present $250/kWh at 75 kWh per vehicle is $18,750 (compared to a conventional powertrain cost of ~$5,000)
- 2 million BEVs per year (~12% of 2016 sales) requires 4 Gigafactories' output.
- At $150/kWh, 1 GF = $5.6B per year
- If whole US vehicle fleet was BEV, 3.2T miles would take ~30% of US annual electricity production
- A Class 8 tractor-trailer (SuperTruck) would travel 50 miles on 100 kWh (typical travel duration can be 400-500 mi/day) – would need 1,000 kWh of storage.

Replacing dependence on imported oil with imported minerals?

What is ARPA-E doing about this?

- Next generation engines.
- Next generation hybrids.
- Next generation propulsion systems.
- NEXTCAR.

ENGINE PROJECTS – OPEN 2015 - $14M

- **Achates Power Inc. - *Gasoline Compression Ignition Medium Duty Multicylinder Opposed Piston Engine Development (with Delphi, Argonne National Laboratory), $9M, 2016-2019***
- **Cummins Inc. - *Efficient Knock Suppression in Spark Ignited Engines, $3M, 2016-2019***
- **University of Michigan - *Split Micro-Hybrid Boosting Enabling Highly Diluted Combustion (with Eaton Corp.), $2M, 2016-2019***

Opposed Piston Gasoline Compression Ignition

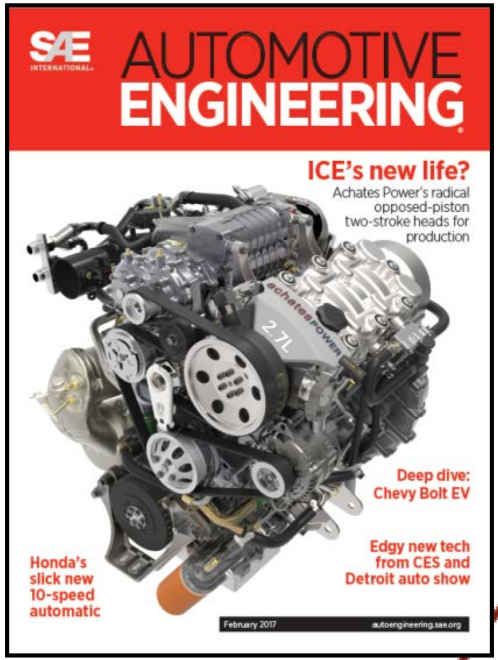
ARPA-E DE-AR0000657 OPEN 2015 ~$9M

Program:

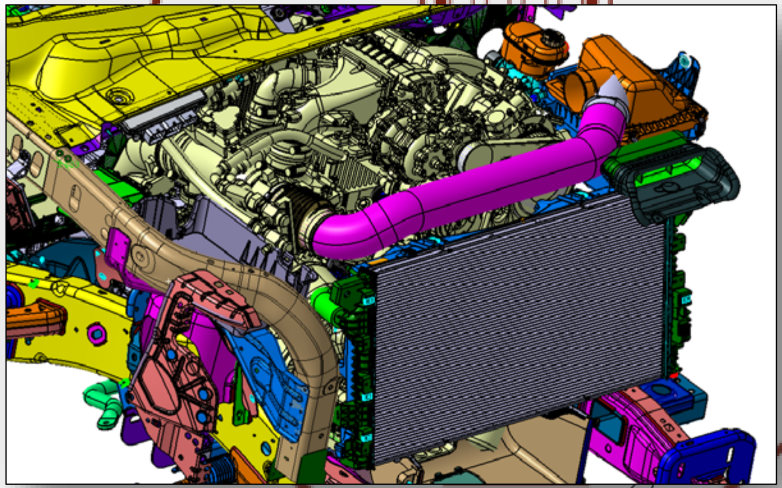
- Developing an opposed-piston gasoline compression ignition engine for light duty trucks
- In partnership with Argonne National Laboratory and Delphi Automotive
- 2.7L I3, 270hp, 650Nm
- Engine design complete early 2017
- First prototypes by end of 2017
- 2025 CAFE compliant, Tier 3, LEV III, Euro 6
- **Up to 50% efficiency improvement over conventional gasoline engine over transient operation**

Derivative project:

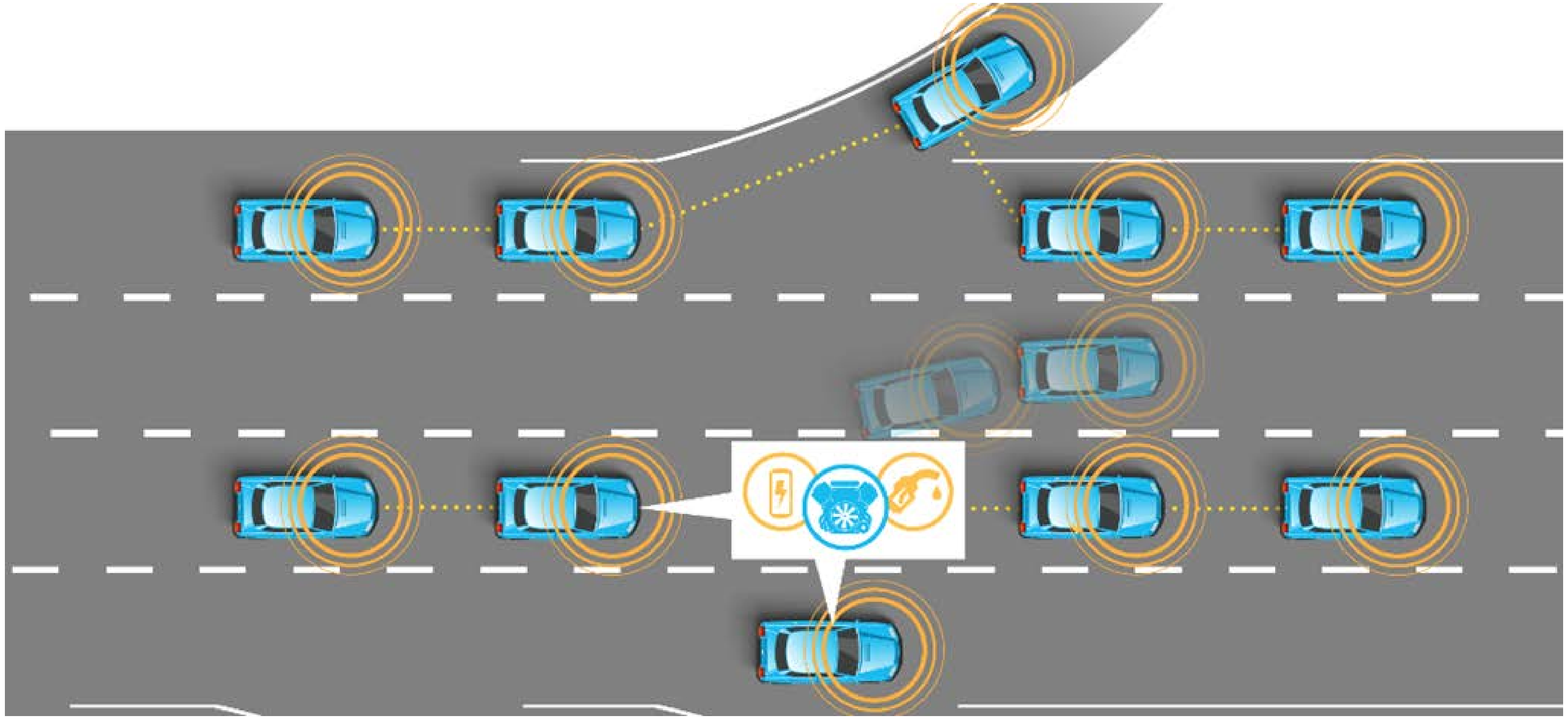
- Vehicle demonstration
- NAIAS main show floor display Jan 2018
- Ride & Drive in 2018



Ford F-150



NEXTCAR Motivation

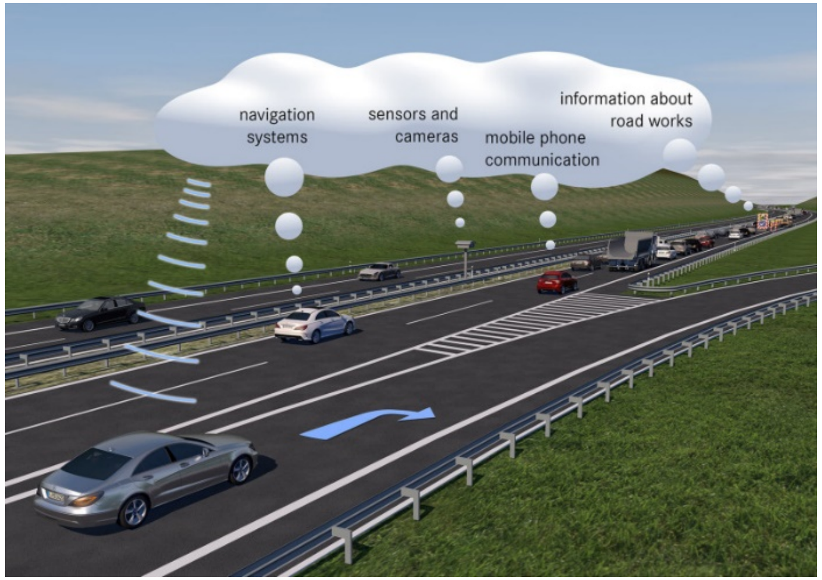


Facilitating energy efficient operation through connectivity and automation

by bringing together experts in powertrains, vehicle dynamics, controls and optimization, and transportation systems.

NEXTCAR Motivation

- **What if a vehicle had perfect information about**
  - Its route and topography
  - Environmental conditions
  - Traffic conditions
  - Traffic behavior
  - Condition of its powertrain and aftertreatment systems (if any)
  - The quality of its fuel
  - ……and everything else?
- **And it cooperates with all the vehicles around it in order to reduce its energy consumption**
- **With perfect control and optimization**



Source: Daimler

→ while platooning, employing speed harmonization for congestion mitigation, eco-approach and departure from traffic signals, as well as a single vehicle driving alone, and all other real-world driving scenarios….

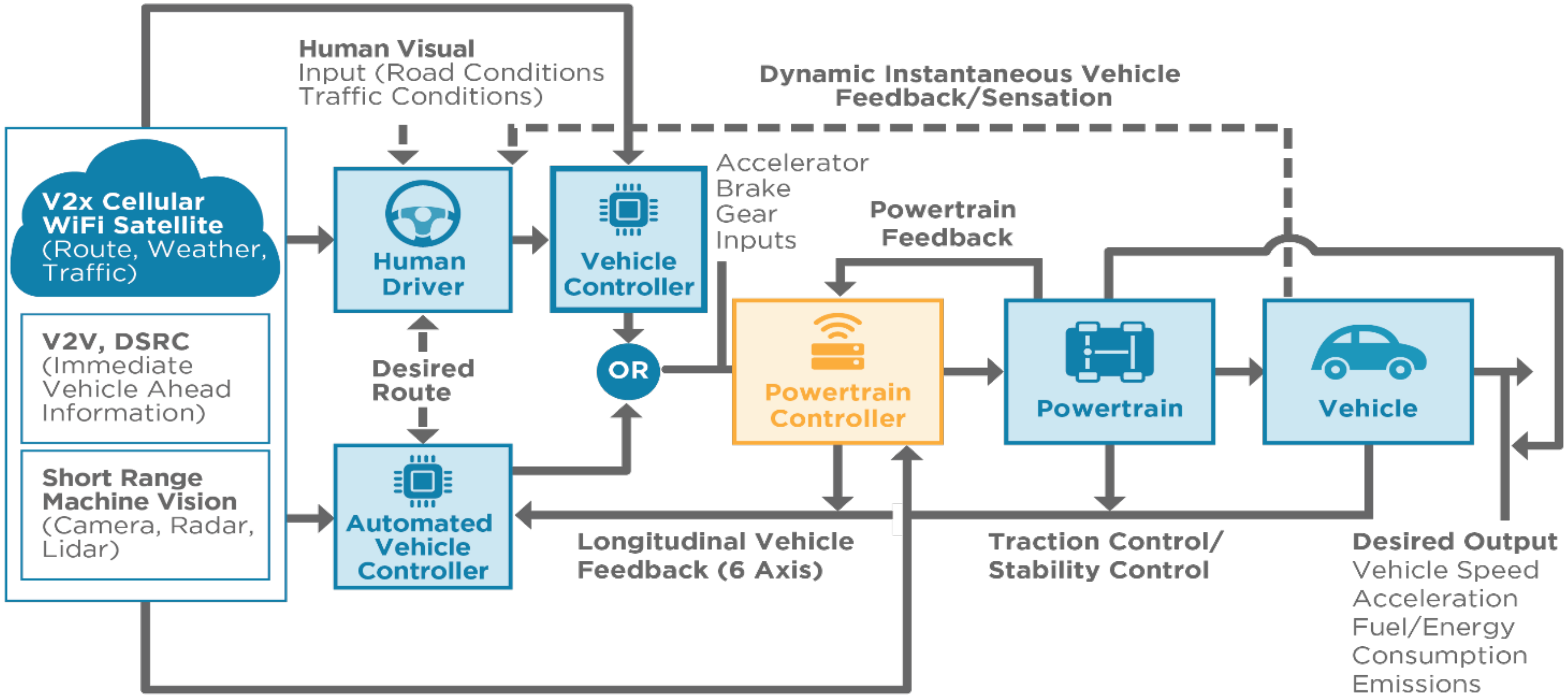
NEXTCAR Motivation

Reduce the energy consumption of all future vehicles by an additional 20% through the use of connectivity and automation,

- **in any vehicle application,**
- **in an energy and fuel agnostic fashion,**
- **while meeting future exhaust emissions regulations, as well as customer acceptability requirements (including acceleration, range, utility, driveability etc.),**

with a $50/% energy consumption reduction target.

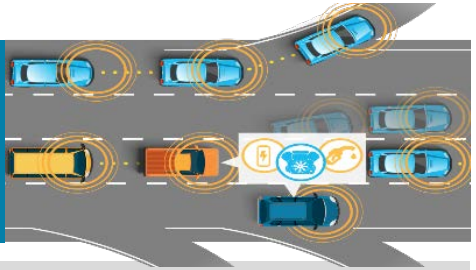
Future Powertrain and Vehicle Control



NEXTCAR, ARPA-E 2016

NEXTCAR

NEXT-Generation Energy Technologies for Connected and Automated on-Road vehicles



Mission

The ARPA-E NEXTCAR Program will fund the development of new and emerging vehicle dynamic and powertrain control technologies (VD&PT) that reduce the energy consumption of future Light-Duty (LD), Medium-Duty (MD) and Heavy-Duty (HD) on-road vehicles through the use of connectivity and vehicle automation.

Program Director	Dr. Chris Atkinson
Total Investment	$35 Million over 3 years

Goals

Energy Consumption: 20% reduction over a 2016 or 2017 baseline vehicle.

Emissions: No degradation relative to baseline vehicle.

Utility: Must meet current Federal vehicle safety, regulatory and customer performance requirements.

Customer Acceptability: Technology should be transparent to the driver.

Incremental System Cost: $1,000 for LD vehicle, $2,000 for MD vehicle and $3,000 for HD vehicle.

Potential Impact

Energy Consumption Reduction: 4.4 quads/year

CO_2 Emissions: 0.3 GT/year

NEXTCAR Projects – 2017-2020

- **General Motors - InfoRich VD&PT Controls *(Carnegie Mellon U, NREL)***
- **Michigan Technological University - Hybrid Electric Vehicle Platooning Control *(GM)***
- **Ohio State University - Engine Cylinder Optimization in Connected Vehicles *(Delphi, Tula Technologies)***
- **Pennsylvania State University - Fuel Efficiency through Co-Optimization *(Volvo Trucks)***
- **Purdue University - Connected and Automated Class 8 Trucks *(Cummins, Peterbilt)***
- **Southwest Research Institute (SwRI) - Vehicle Model Predictive Control *(Toyota, UM)***
- **University of California, Berkeley - Predictive Data-Driven Automotive Control *(Hyundai of America)***
- **University of California, Riverside - Efficient Plug-In Hybrid Electric Buses *(US Hybrid)***
- **University of Delaware - Optimized Vehicles through Connectivity *(Bosch, BU)***
- **University of Michigan - Integrated Vehicle Power & Thermal Management *(PNNL)***
- **University of Minnesota - Optimized Delivery Vehicles *(Workhorse)***

Beyond NEXTCAR – HAVs will *eventually* demonstrate far higher energy efficiency (decades hence – beyond 2040-2050?)

- **Intrinsically safe vehicles "won't crash".**
- **Significant reductions in vehicle mass possible due to reduction in safety equipment required.**
- **Large weight de-compounding effects, also allowing for the use of lighter materials – CF, plastics, light metals?**
- **Opportunity for xEVs? Reduced energy storage requirements for same vehicle range.**
- **Automated vehicles will have more/less opportunity for recharging?**
- ***Is this the application that BEVs have been waiting for?***

The Probable Pathway to 2030 and Beyond

- **Vehicle powertrain technology – more electrification, hybridization, downsizing, waste energy recovery, 48V systems?**
- **Vehicle structures – vehicle downsizing, weight reduction, more use of light-weight materials.**
- **Vehicle ownership – how will the 84 month ownership cycle be reconciled with 1-2 year product cycles?**
- **Ride-sharing, car-sharing – new ownership and usage models.**
- **OEMs – the center of gravity of the high-technology components of the vehicle has shifted to suppliers both old (Bosch, DENSO, Continental, Delphi) and new (Mobileye, NVIDIA).**
- **ADAS systems will proliferate, leading to L3 automation (such as the Tesla Autopilot) being essentially standard.**
- **L5 automation requires or facilitates new vehicle architectures (full electrification?) but will probably be slow in penetrating the full market.**
- **Regulations? One of the big unknowns.**
- **The implication for energy usage – energy usage in the LD fleet will almost certainly be reduced by 2030 and beyond (due to ongoing fleet turnover). After that timeframe, it is not clear.**

How hard can it be to develop a HAV?

Quite tough, actually.

Automated Driving Rule Set (Atkinson, 2017)

There are only (roughly) 10 rules of driving required for Automated Vehicle operation:

- **Keep right, keep to the road, avoid on-coming traffic and stay centered within the driving lane.**
- **Travel at the minimum of {the speed limit; the prevailing traffic speed; an appropriately safe speed dictated by road conditions, traffic and environmental conditions}.**
- **Stop when required by traffic signals, traffic signs, traffic officers (or other humans), stationary traffic ahead or obstacles or (substantial) debris in the road.**
- **Maintain a safe following distance (and do not follow too closely or run into vehicles ahead).**
- **Come to a stop, stand or park only when safe and appropriate to do so and in a manner that will not impede traffic.**
- **Adjust speed and merge in turn into traffic with suitable vehicle-to-vehicle clearances at ramps, stops and merges.**
- **Take turns at unregulated stops or merges.**
- **Avoid obstacles (stationary and moving) with sufficient clearance to allow for directional changes (pedestrians, other road users, animals, debris, road repairs etc.)**
- **Pass only where safe and do not obstruct or impede other (oncoming) traffic.**
- **Drive defensively and predictively, and not selfishly (use common sense, be alert, be predictive and not merely reactive).**

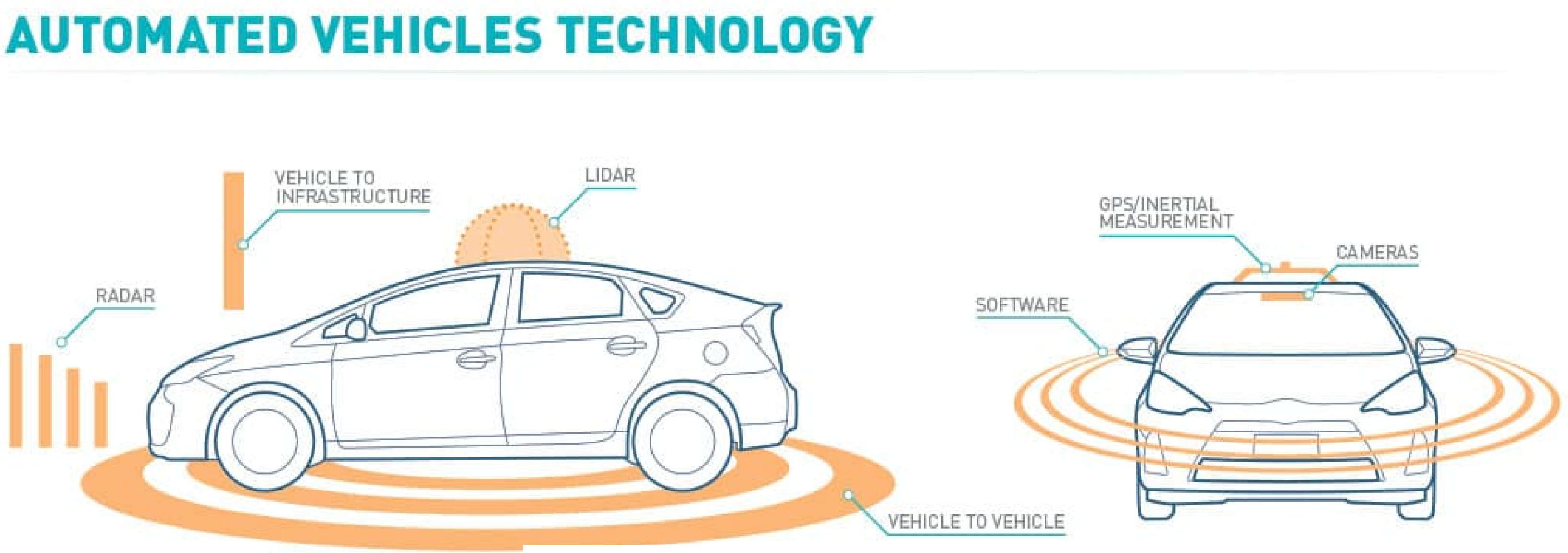
Vehicle Automation (Atkinson, 2017)

Fully automated driving (L3-L5) requires a vehicle automation system to have the following characteristics:

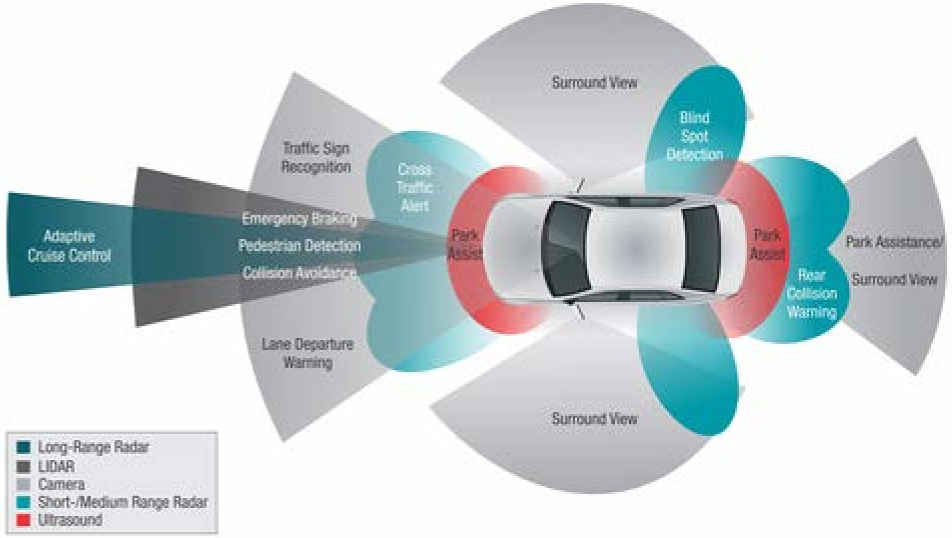
- **Mapping ("refer") – refer to pre-developed 3D maps of fixed features, together with overlays of temporary or moving obstacles (SLAM – 'simultaneous localization and mapping'). *Where is the vehicle going, and where is the vehicle in the driving lane?***
- **Machine vision ("see") – inputs from multiple sensors including cameras, radar, LIDAR, acoustics/ultrasonics to sense proximity, localization, displacement and velocity of vehicles, obstacles, lane markings, roadway surface etc. *What threats are there around the vehicle?***
- **Sensor and data fusion ("reorganize") – fuse inputs and data from machine vision and mapping (on and off-board) to create a comprehensive visual 'map'. *Create a visual map of position, trajectory and potential threats.***
- **Connectivity ("integrate") – access additional information or data from off-board the vehicle and to coordinate with other vehicles. *Coordinate with the infrastructure and other surrounding vehicles.***
- **Decision making ("think") – computation, cognitive reasoning and decision-making. *Decide on the best next action.***
- **AI ("decide and learn") – artificial intelligence (of which 'deep learning' is a part) allows for learning and adaptation. *Learn and adapt to new, unseen situations.***
- **Automation ("respond") – control the vehicle in a safe and predictable fashion. *Respond and control.***

100 million LOC at $100/LOC = $10B to develop

Automated Vehicle Sensing



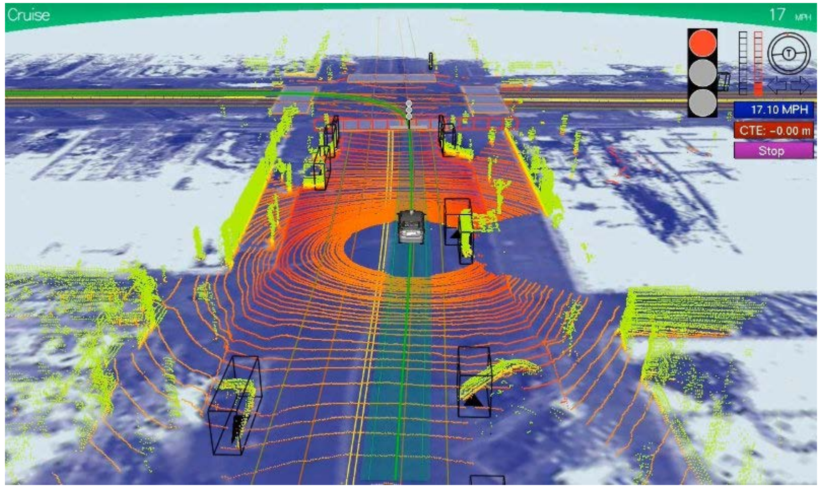
RADAR ~100m+ ~$1k
Camera ~50m ~$100-200
LIDAR ~50m ~$10k-100k
Ultrasonics ~5-10m ~$100



Visual Processing

- **At 70mph, we require 3s look-ahead, < ~1.00s response time and substantial braking performance.**
- **For forward vision, consider a 10m x 4m zone at 90m**
- **For lateral vision, consider a 60m x 4m zone at 5m (x2)**
- **Roughly 500 m^2 with 10 pixel per 0.1m resolution = 5 Mpixel**
- **At 300 Hz, that requires visual processing of 1.5 Gpixel/s**
- ***What about threat identification? Does an automated system need to identify a threat to recognize it?***

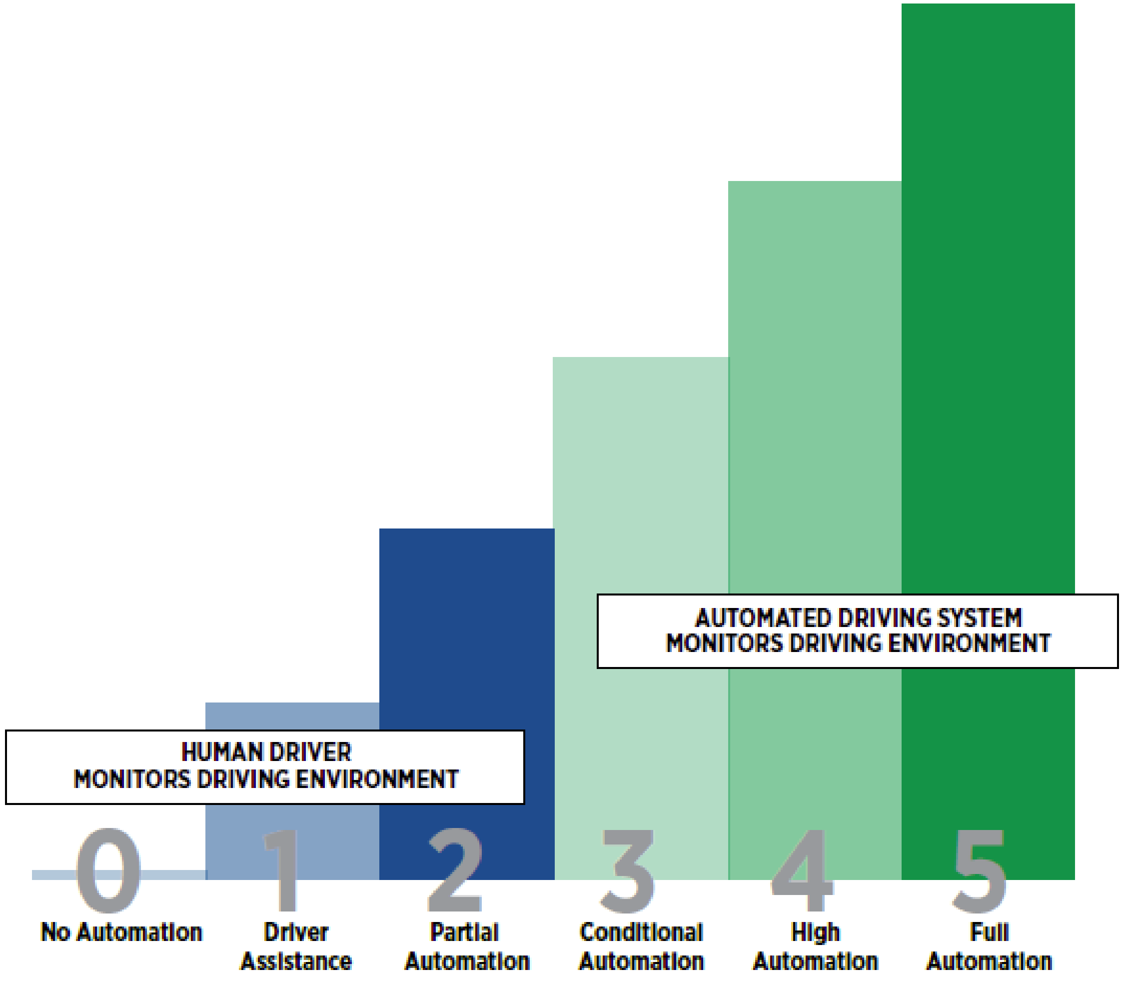
LIDAR – active vision



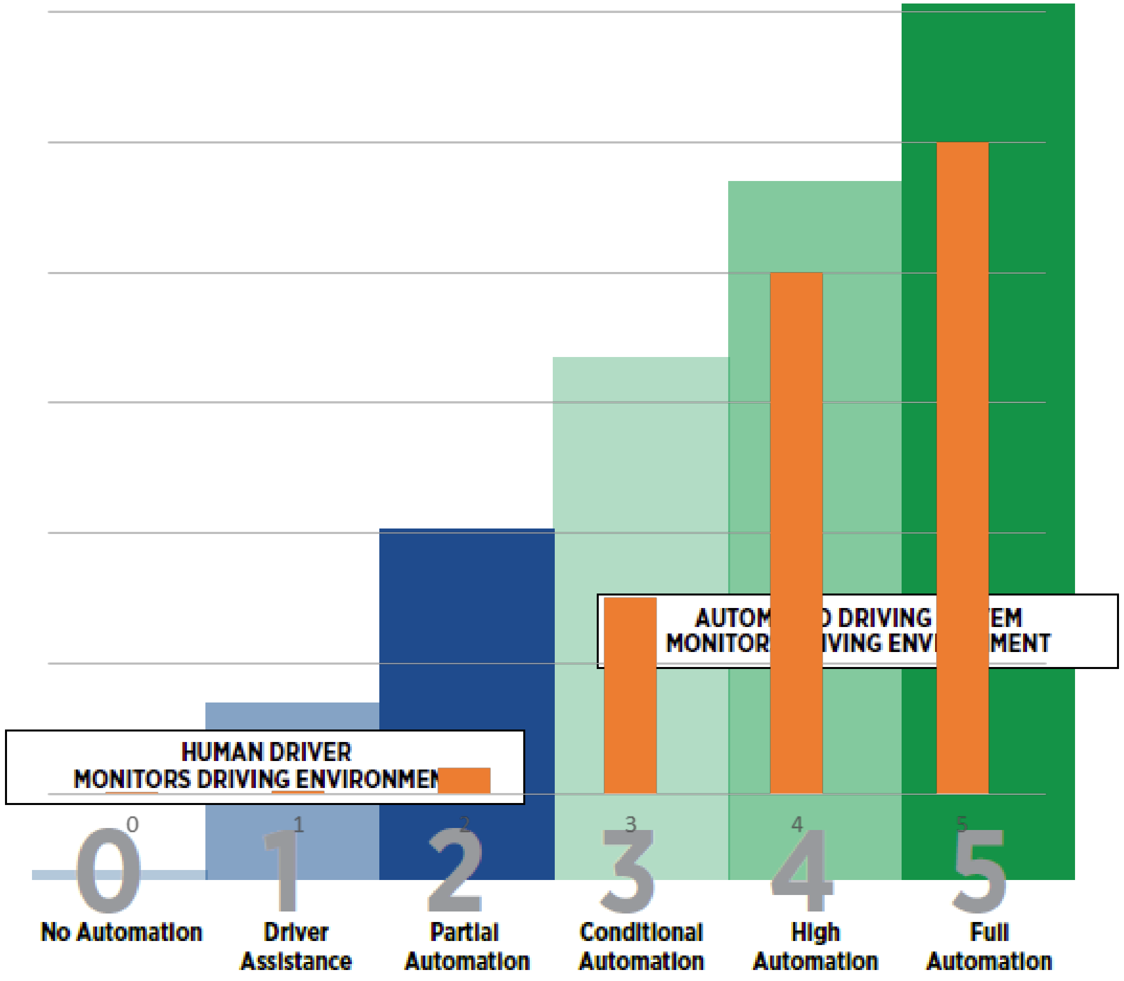
Testing and Validation Required

- **In 2015, 35,092 fatalities in the US over 3.2T VMT – 94% caused by humans,10% known to be caused by distraction.**
- **So, the “average human driver” experiences a fatal accident every ~100M miles.**
- **To be 10x safer, a CAV would have to have the experience of 1,000M miles of driving.**
- **At 70mph, that is 1,630 years of driving around the clock.**
- **At $2.00/mile cost for a vehicle and driver, that is $2B of testing for a new sensor, algorithm, sub-system, vehicle etc.**
- ***Clearly we need accelerated testing, simulation, validation and some smart thinking.***

SAE Levels of Vehicle Automation

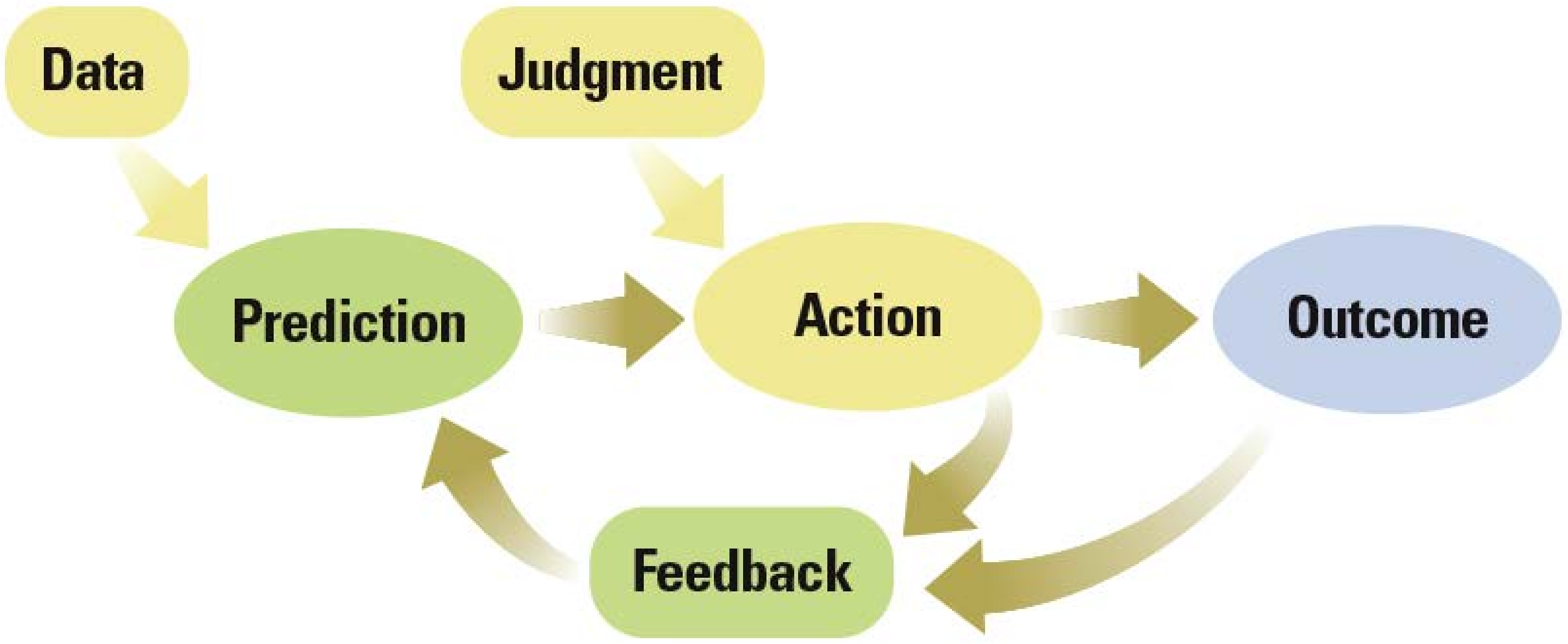


SAE Levels of Vehicle Automation



LEVEL OF EFFORT AND TESTING REQUIRED

Machine Learning



Agrawal, Gans and Goldfarb 2017

What powertrain technologies will drive the future?

- Hybrid architectures – regenerative braking energy capture; series hybrids; parallel hybrids; multi-mode hybrids (and plug-ins).
- xEVs
- FCEVs
- High efficiency engines – 50% brake thermal efficiency engines exist – compression ignition, waste energy recovery
- *New engine architectures – free piston, linear engines; split-cycle engines…..*
- *New combustion modes – low temperature combustion; reactivity controlled combustion; ultra-lean; knock resistant……*

How do we best reduce energy in the “inefficient interim” term?

Clearly one answer is more efficient hybrids, and engines or fuel cells.

Requirements for commercial success

Any new powertrain technology should 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 Energy efficiency
Emissions	Regulated criteria pollutants (and CO_2) ⇒ Regulation
Cost	Total cost of ownership (including capex and energy cost)
Reliability	Mean time between failures, maintainability
Utility	Acceleration, driveability, NVH, cold or off-cycle operation, ease of use, transparency to the user, refueling, and acceptable range
Fuel acceptability	Use a readily available fuel or energy source.

Conclusions

- The IC engine will persist for decades to come (mainly in hybrid configurations but also as a standalone propulsion system, especially in trucks).
- The implication for energy usage – we need to reduce automotive transportation energy significantly by increasing engine and propulsion efficiency.
- Connectivity and automation represent a point of inflection for engine design, and for vehicle control, as for the first time propulsion control can be forward-looking and predictive and not merely reactive.
- ARPA-E has invested over $80 million in engine technologies, $300 million in battery technology and power electronics, and $500 million in transportation-related projects since 2007; and anticipates continuing to do so.
- Future engines may utilize entirely new (old) architectures, with energy recovery, electrification and hybridization built in.

Dr. Chris Atkinson

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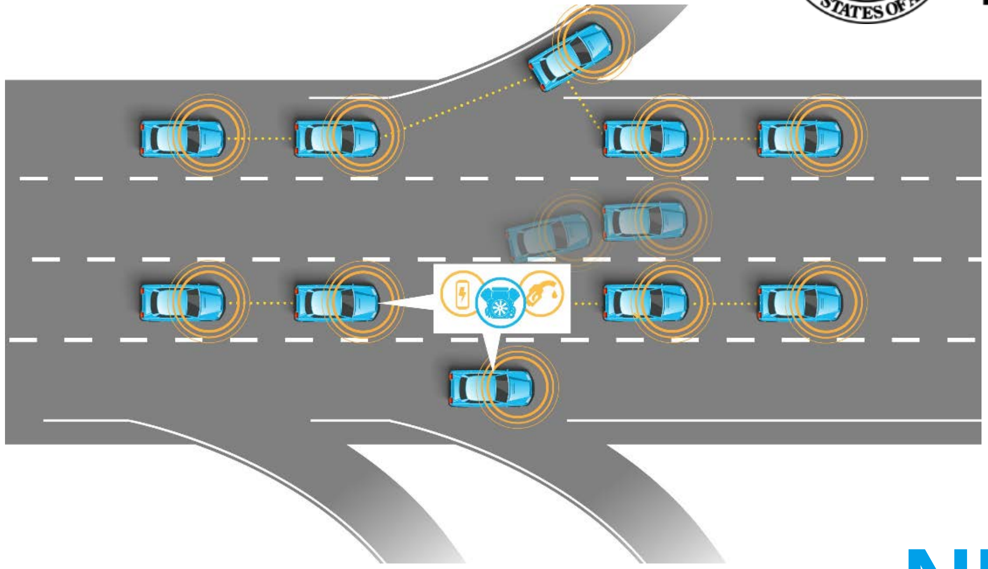
Advanced Research Projects Agency – Energy

US Department of Energy



NEXTCAR

An Application of Machine Learning in Powertrain Control

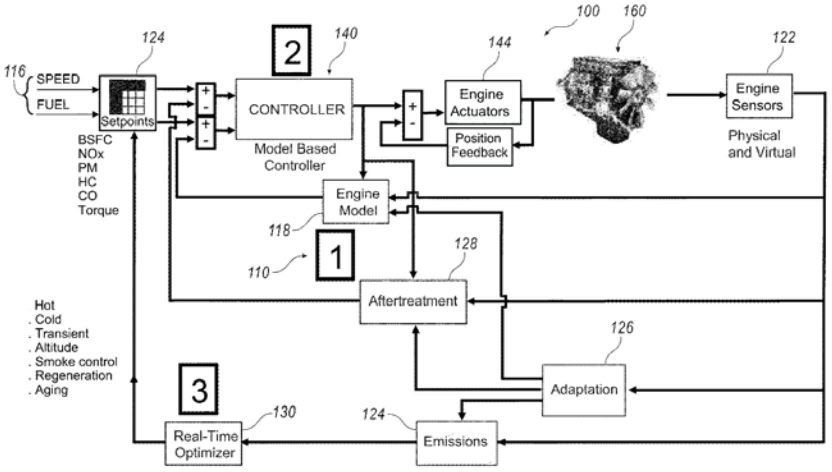


FIG. 1

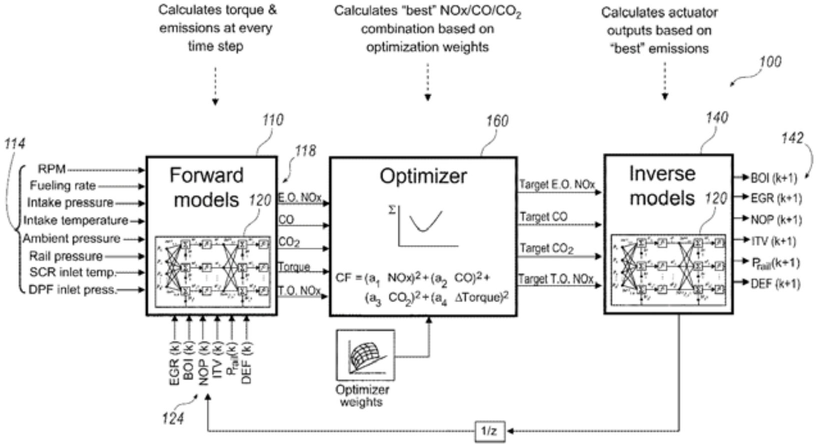


FIG. 2

Model-based optimized engine control

US 20110264353 A1

Atkinson, Allain and Kropp. Assigned to Daimler AG.

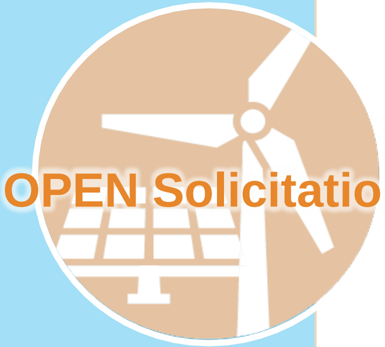
Focused and OPEN Programs

Focused programs prioritize R&D topics by their potential to make a significant difference in ARPA-E’s mission space.

- Size of the potential impact
- Technical opportunities for transformation
- Portfolio of projects with different approaches

OPEN programs support the development of potentially disruptive new technologies across the full spectrum of energy applications.

- Complement focused programs
- Support innovative “one off” projects
- Provide a “snapshot” of energy R&D
- OPENs have occurred in 2009, 2012, 2015 and now 2018



ARPA-E Recruitment Opportunities

Want to work at ARPA-E? There may be a role for you!

Program Director

- ✓ Program development
- ✓ Active project management
- ✓ Thought leadership
- ✓ Explore new technical areas

Technology-to-Market Advisor

- ✓ Business development
- ✓ Technical marketing
- ✓ Techno-economic analyses
- ✓ Stakeholder outreach

Fellow

- ✓ Independent energy technology development
- ✓ Program Director support
- ✓ Organizational support

If you are interested in applying or learning more, please email ***arpa-e-jobs@hq.doe.gov****.*