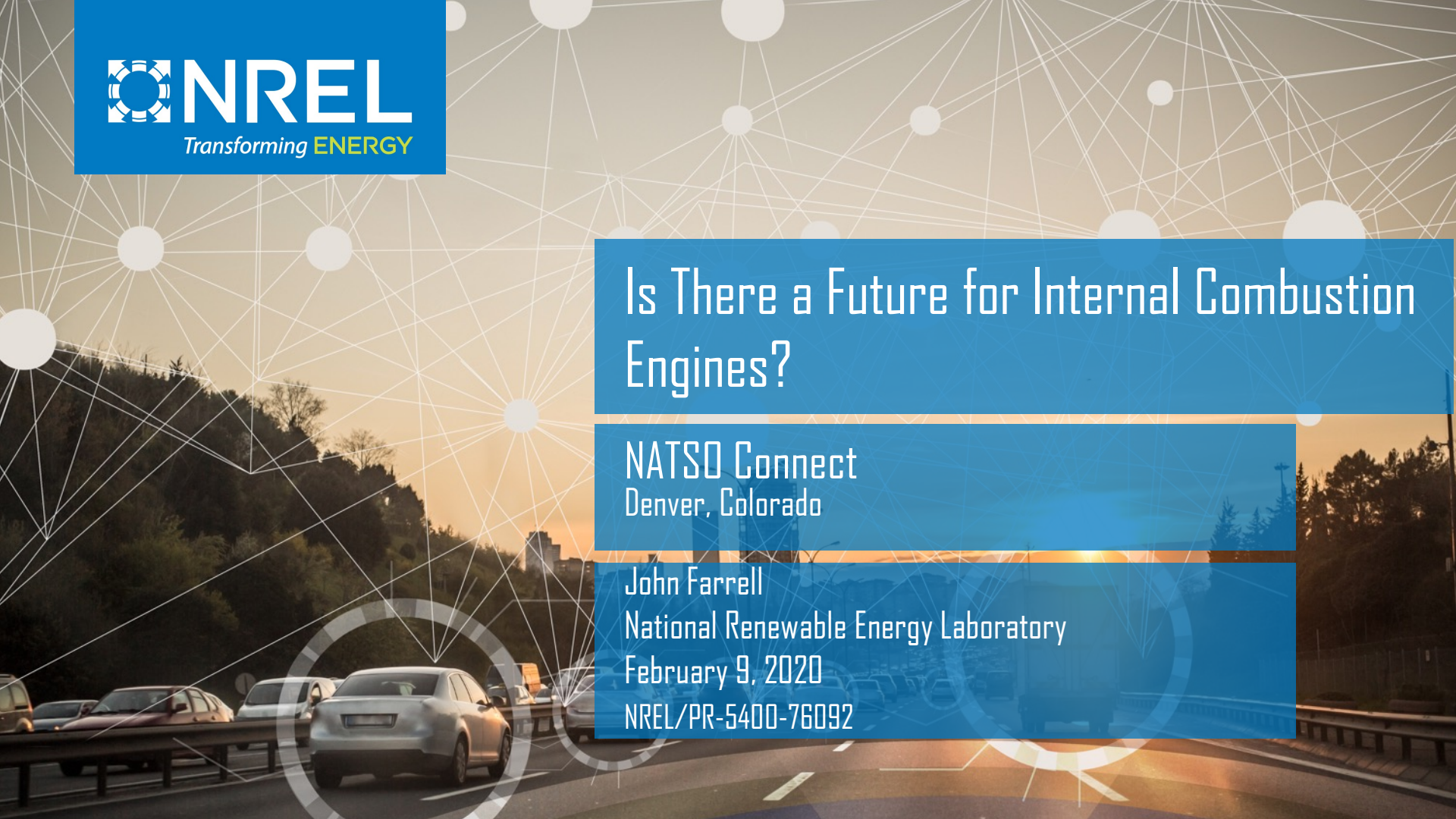
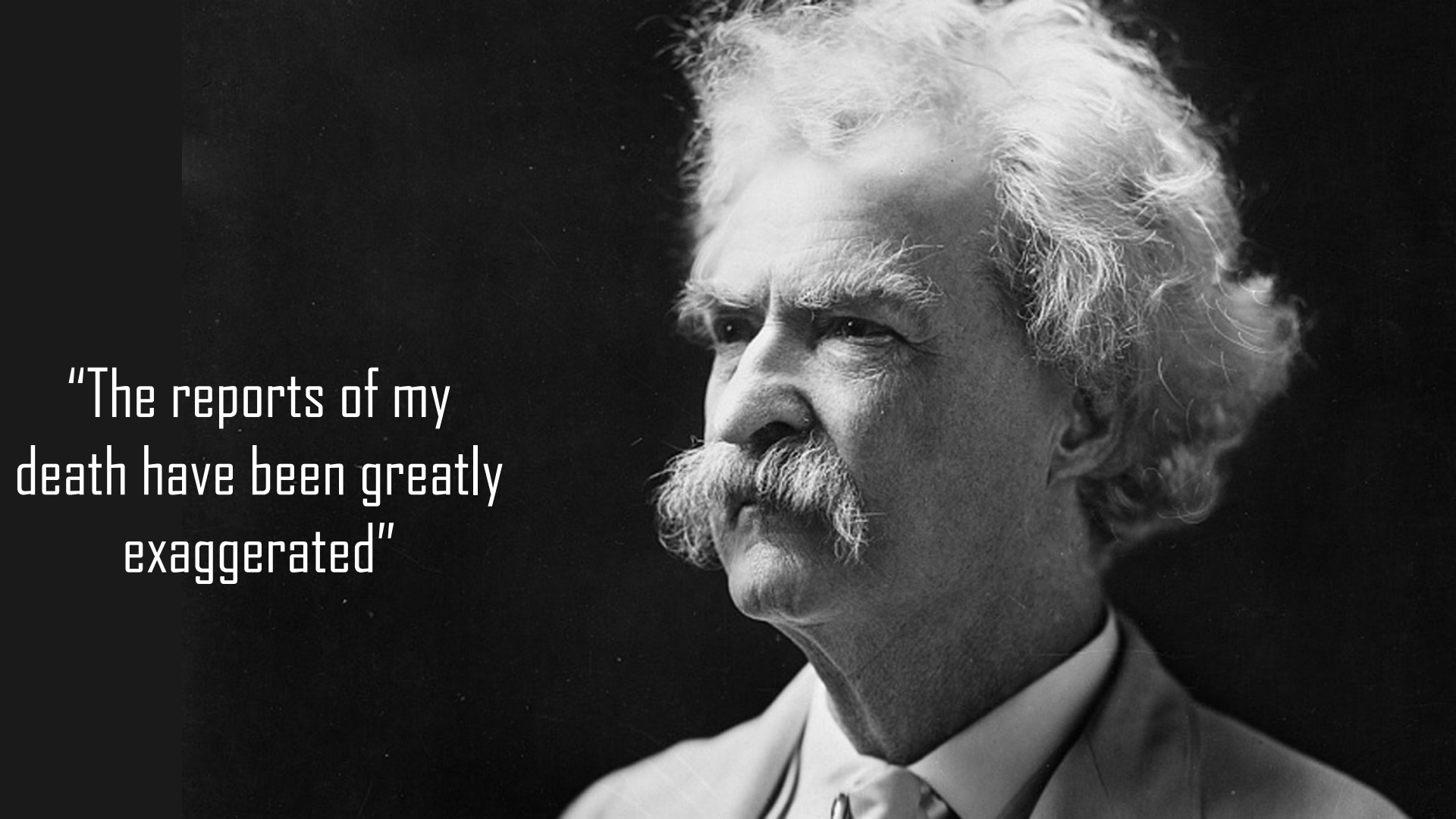


Is There a Future for Internal Combustion Engines?

NATSO Connect
Denver, Colorado

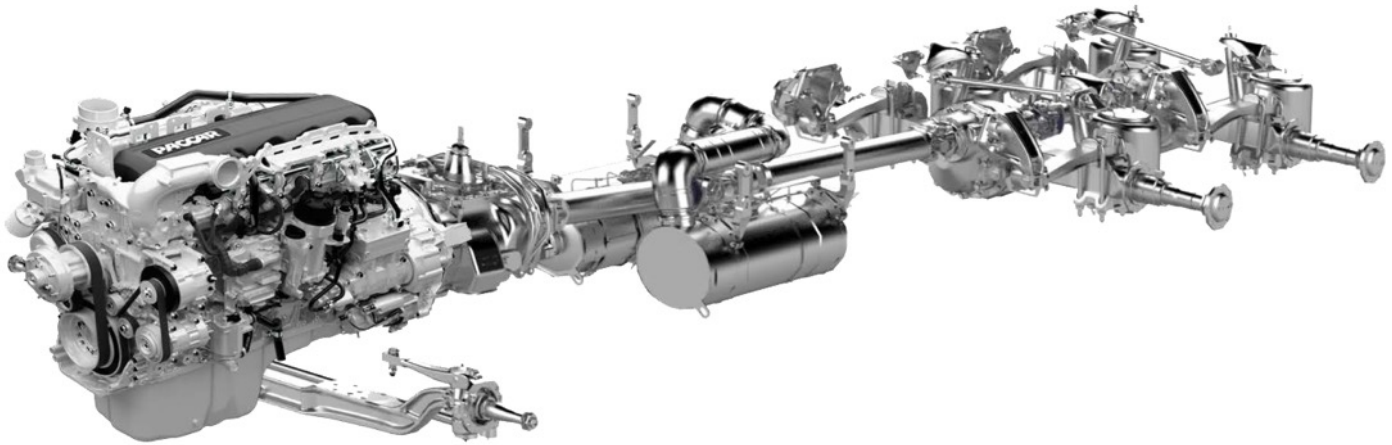
John Farrell
National Renewable Energy Laboratory
February 9, 2020
NREL/PR-5400-76092


"The reports of my death have been greatly exaggerated"


"The reports of my (impending demise) have been greatly exaggerated"

Key Takeaway Messages

1. Significant work is still underway focused on improving ICE efficiency and emissions…



… but each successive improvement increases vehicle cost and complexity

Image: Steve Ciatti, PACCAR, SAE HEICE Symposium 2019

Key Takeaway Messages

2. Electrification is the 800 lb gorilla in the (board) room – for both passenger and commercial vehicles

Electric vehicles are still (really) expensive, but can be cheaper to operate, and battery prices continue to fall

Key Takeaway Messages

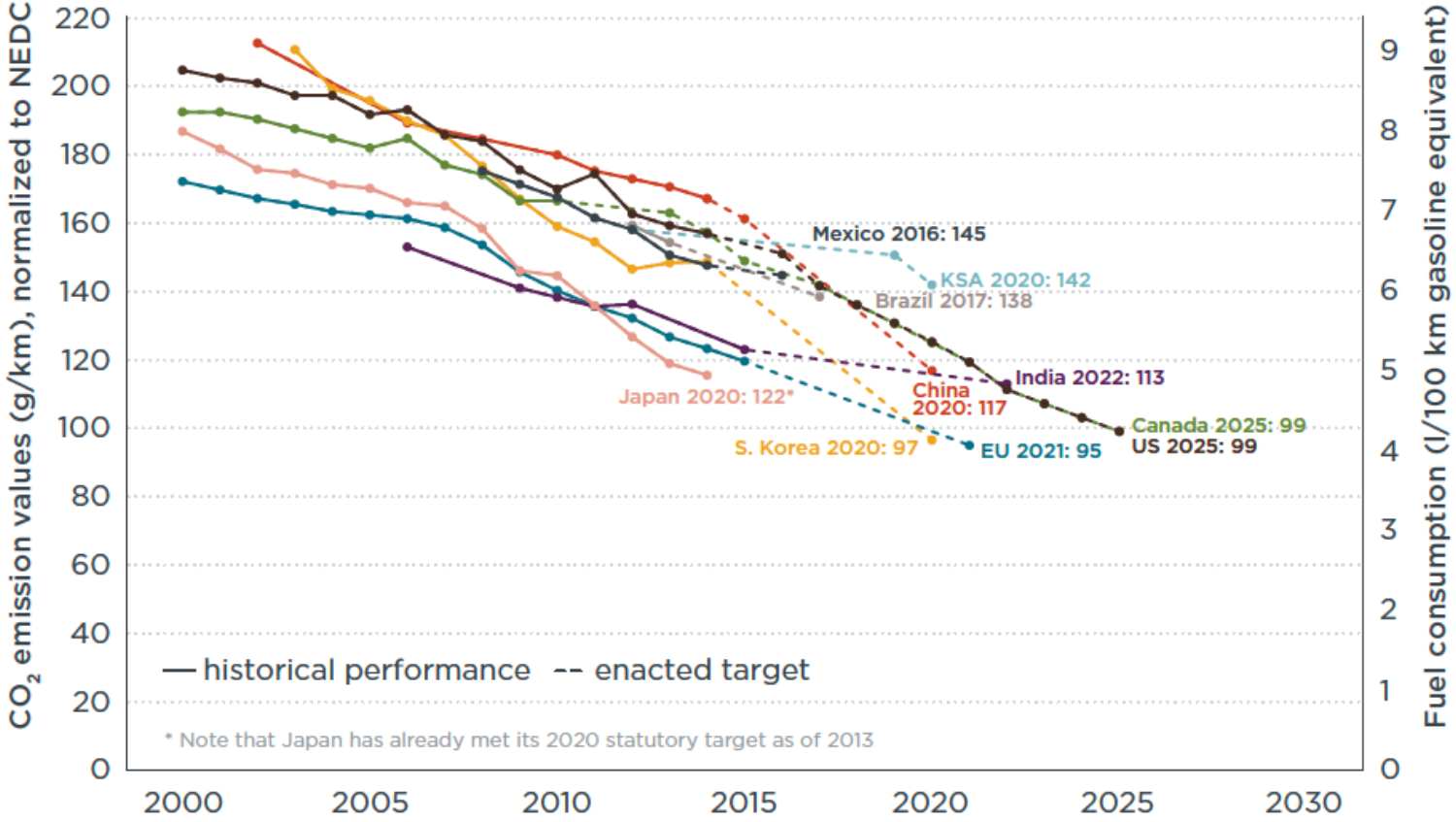
3. e-fuels won't save the day...

... for a while at least, and likely not without a lot of help

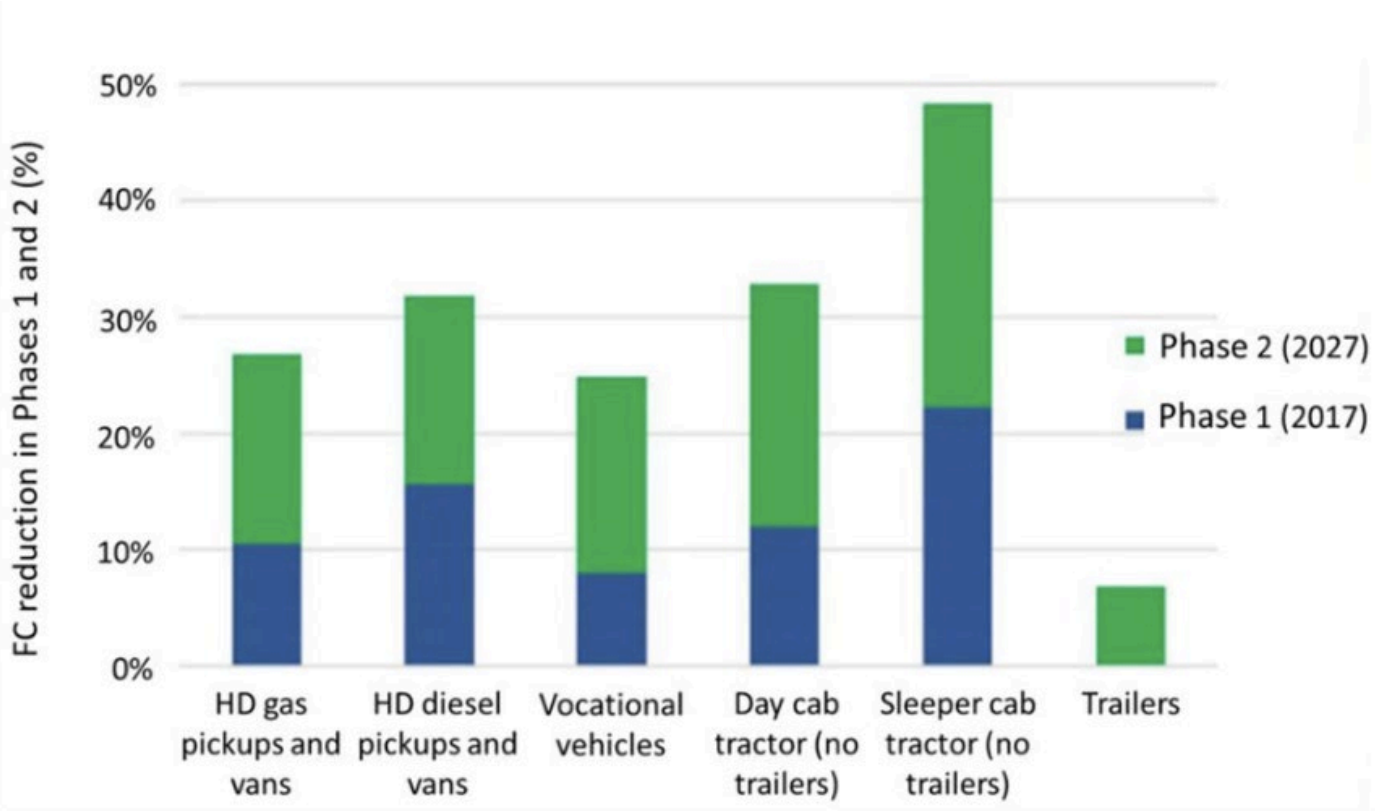
What's new in the world of ICEs?

ICE efficiency continues to increase

(because regulations are requiring them to)



HD Fuel Consumption Reductions Mandated by the US HD Greenhouse Gas Rules



Source: Cummins, SAE 2019-01-0247

Why are we focused so much on the engine?

Auxiliary Losses: 1-4%

Engine Losses: 56-59%

Drivetrain Losses: 2-6%

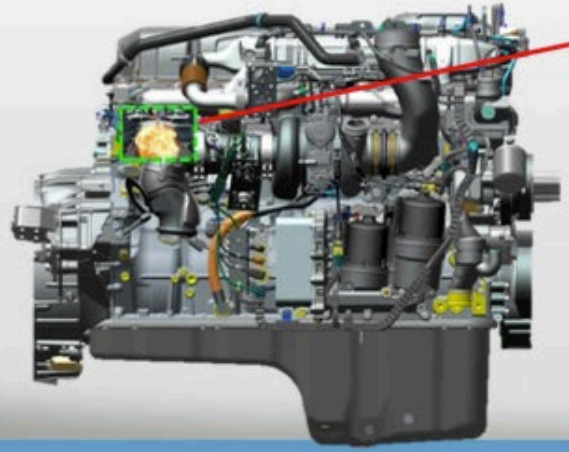
Aerodynamic Losses: 16-25%

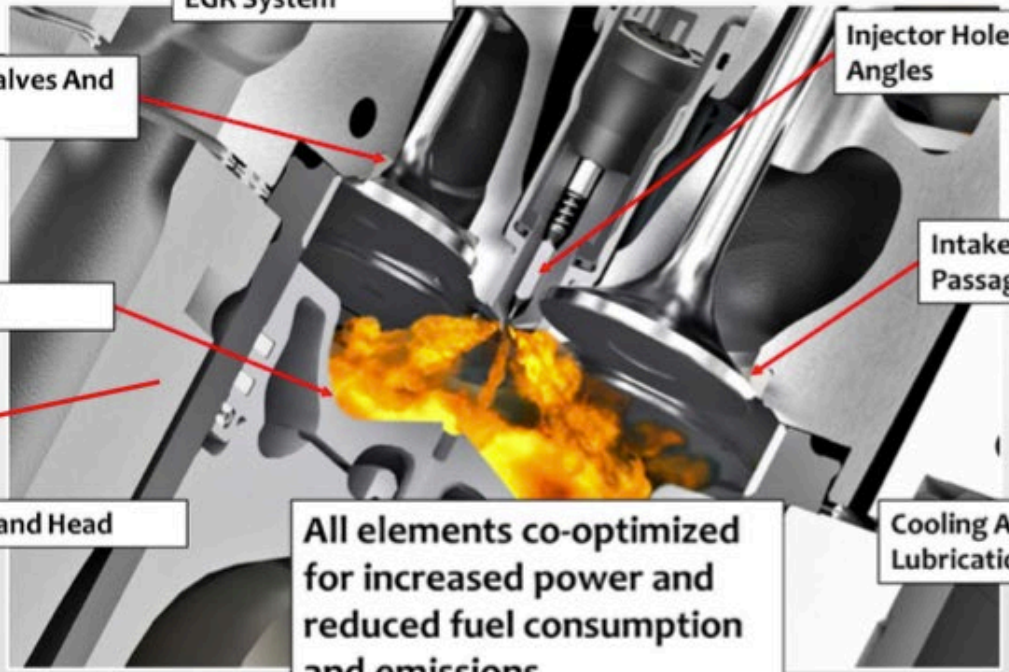
Rolling Resistance: 12-17%

The Engine Represents Biggest Source of Energy Loss and Provides an Opportunity to Improve Vehicle Fuel Consumption

Source: Steve Ciatti, PACCAR, SAE HEICE Symposium 2019

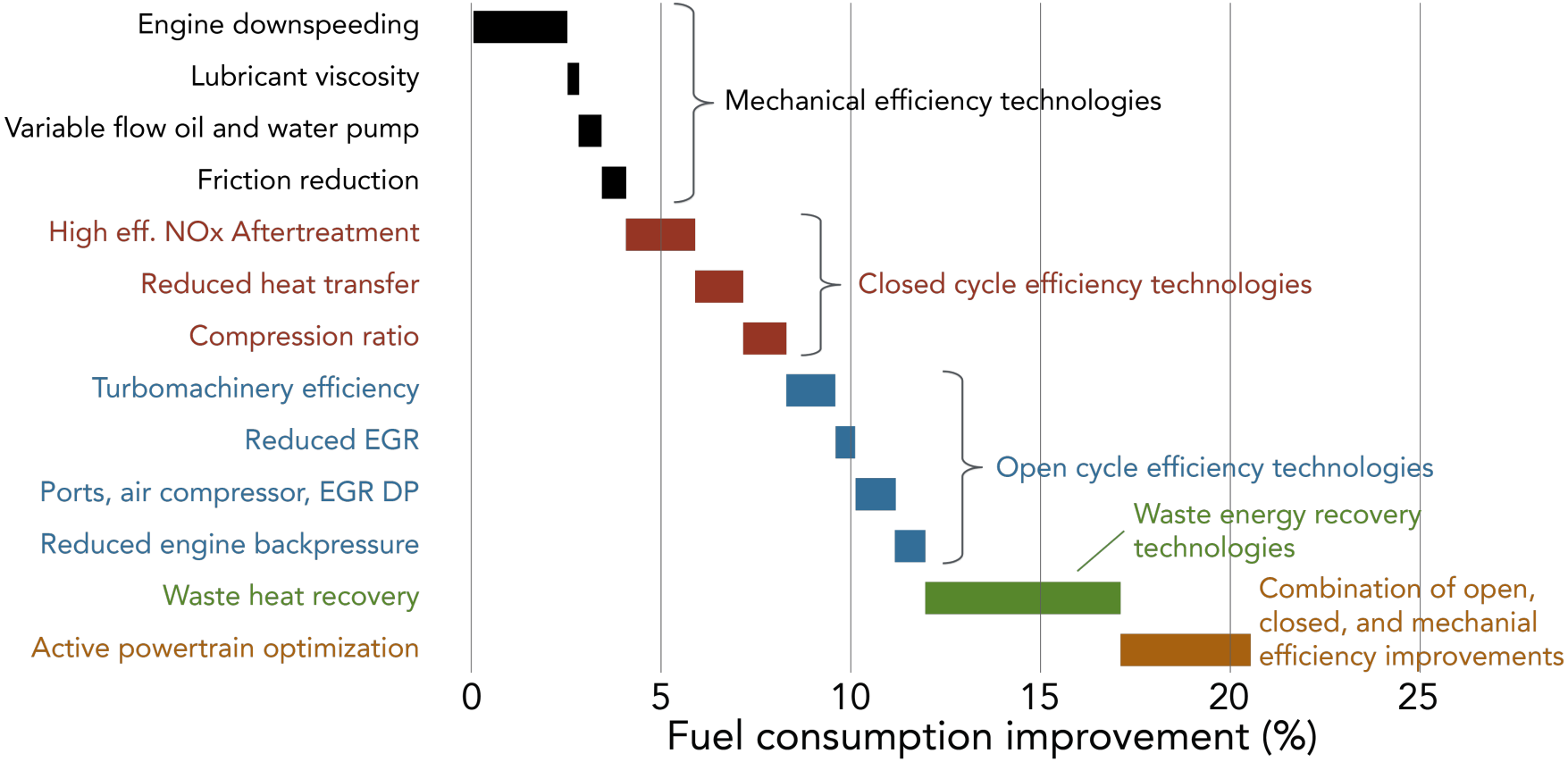
Engine optimization opportunities ("silver buckshot")





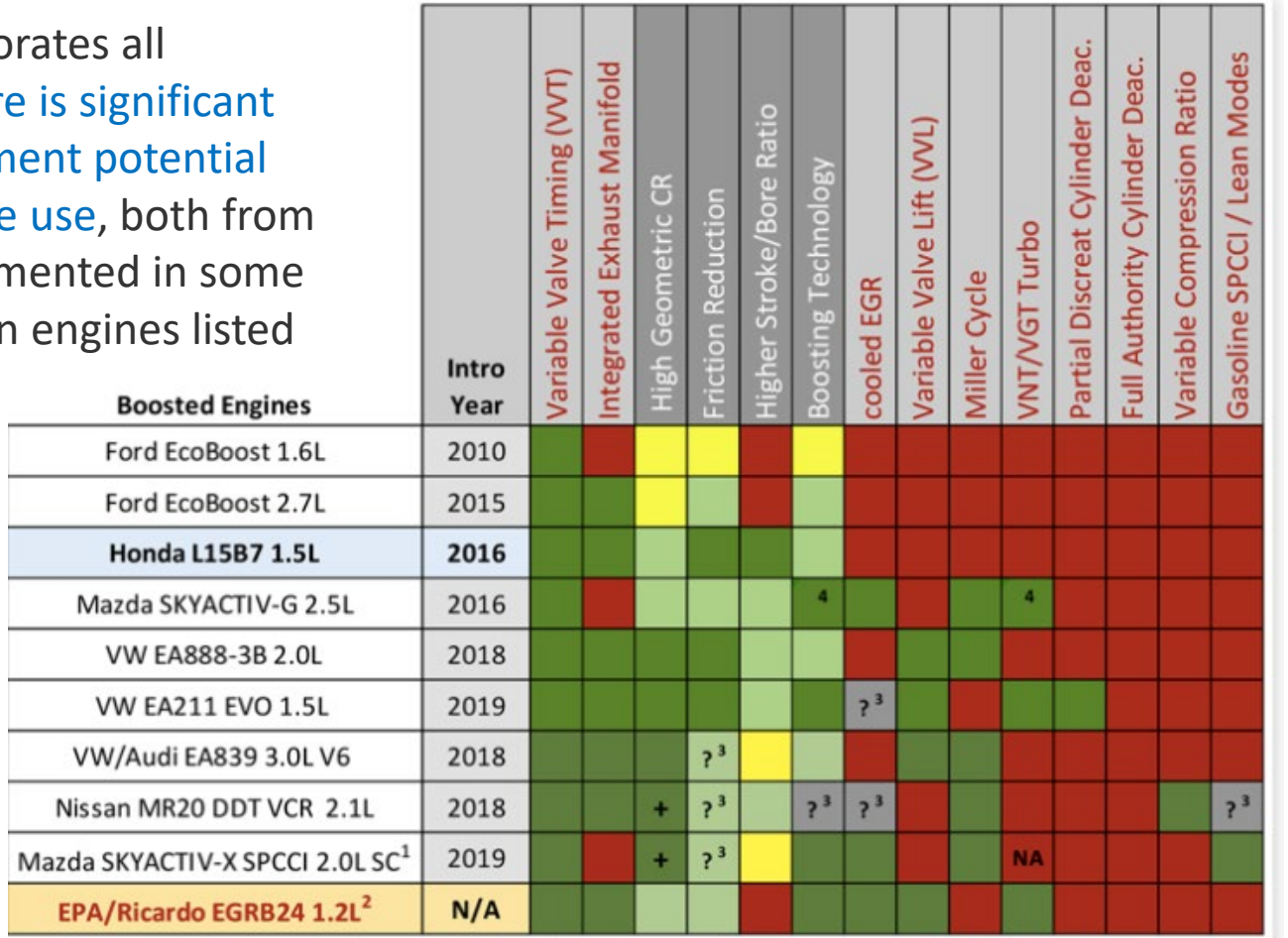
Source: Steve Ciatti, PACCAR, SAE HEICE Symposium 2019

Integration with other vehicle components



Source: Cummins SAE paper 2013-01-2421

"However… no engine incorporates all potential improvements. There is significant untapped efficiency improvement potential still available for future vehicle use, both from the technology already implemented in some form in the current production engines listed and from technology that has not been applied in combination with the other advanced technologies."



Boosted Engines	Intro Year	Variable Valve Timing (VVT)	Integrated Exhaust Manifold	High Geometric CR	Friction Reduction	Higher Stroke/Bore Ratio	Boosting Technology	cooled EGR	Variable Valve Lift (VVL)	Miller Cycle	VNT/VGT Turbo	Partial Discreat Cylinder Deac.	Full Authority Cylinder Deac.	Variable Compression Ratio	Gasoline SPCCI / Lean Modes
Ford EcoBoost 1.6L	2010														
Ford EcoBoost 2.7L	2015														
Honda L15B7 1.5L	**2016**														
Mazda SKYACTIV-G 2.5L	2016						4				4				
VW EA888-3B 2.0L	2018														
VW EA211 EVO 1.5L	2019							?[3]							
VW/Audi EA839 3.0L V6	2018				?[3]										
Nissan MR20 DDT VCR 2.1L	2018			+	?[3]		?[3]	?[3]							?[3]
Mazda SKYACTIV-X SPCCI 2.0L SC[1]	2019			+	?[3]						NA				
EPA/Ricardo EGRB24 1.2L[2]	N/A														

yellow = early implementation *light & dark green* = nearing maturity *red* = technology not present

1- Supercharged **2**- EPA Draft TAR **3**- Not known at time of writing

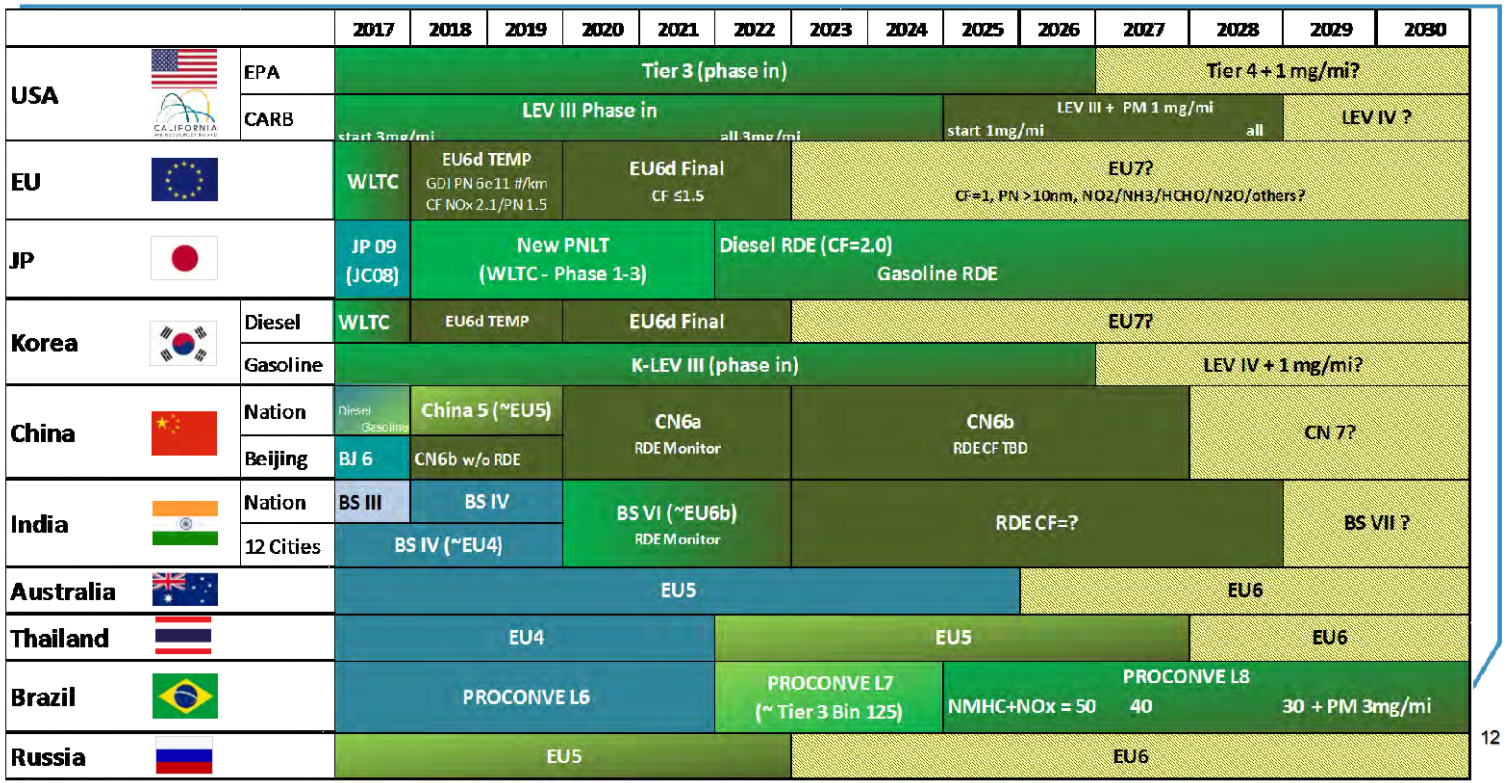
4- Mazda accomplishes equivalent of VNT/VGT using novel valving system

Source: Stuhldreher et al., EPA, SAE 2018-01-0319

Emissions regulations are also becoming more stringent

WCX APRIL 9-11 2019 DETROIT

Global Light Duty Regulations
US Regs Drive Advanced Substrates, EU & CN Enforce Filters



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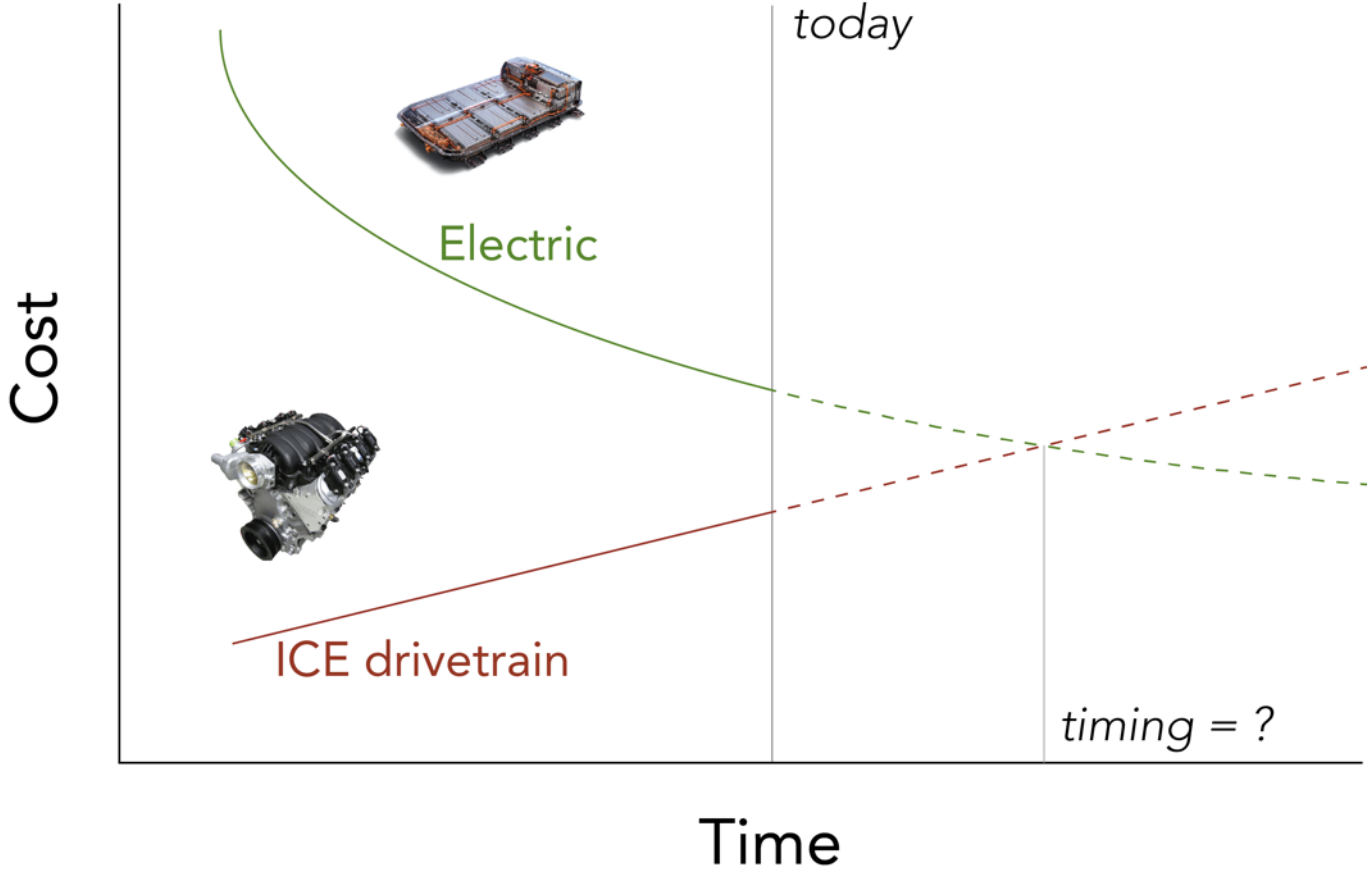
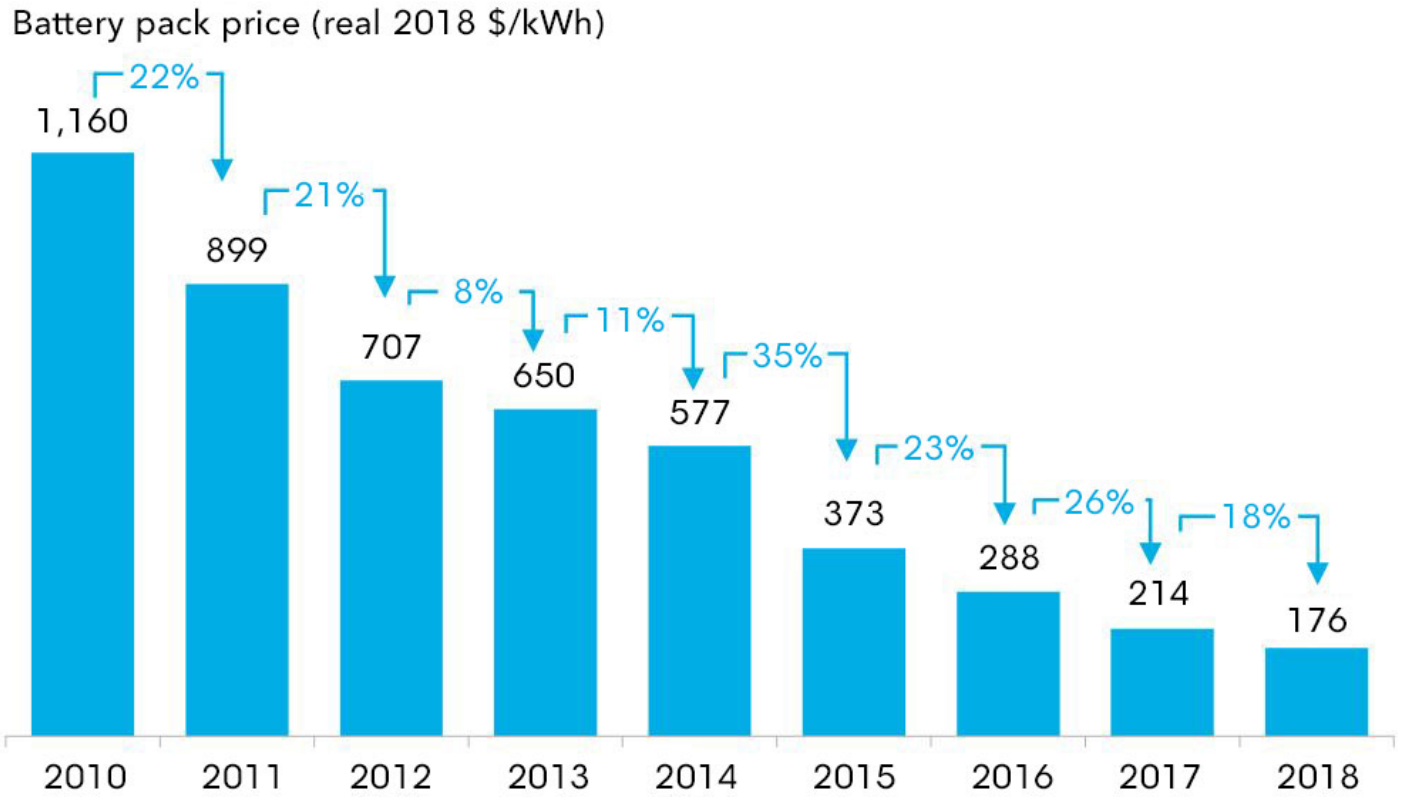
Source: Corning SAE presentation 2019

Cost curves



EV Battery Cost Reductions

Lithium-ion battery price survey results: volume-weighted average



Source: BloombergNEF

General Motors starting 4,300 white-collar layoffs this week

A mural is seen on a wall Nov. 27, 2018, at the General Motors plant in Lordstown, Ohio. GM plans to close five North American factories in the coming months and thousands of jobs are at stake. (Tony Dejak/AP)

By The Associated Press Chicago Tribune, Feb 4, 2019

Many of the layoffs will happen at GM's technical center near Detroit. Most work on components for internal combustion engines and discontinued car models.

2019 ACT Expo: Allison Transmission Embraces Electrification

April 25, 2019 by Susan Carpenter, @CarpenterWheels

Allison Transmission announced a partnership with Peterbilt, which has integrated the company's transmissions into its trucks. (Photo: Peterbilt)

2019 ACT Expo: Meritor, TransPower Electrify Terminal Tractors

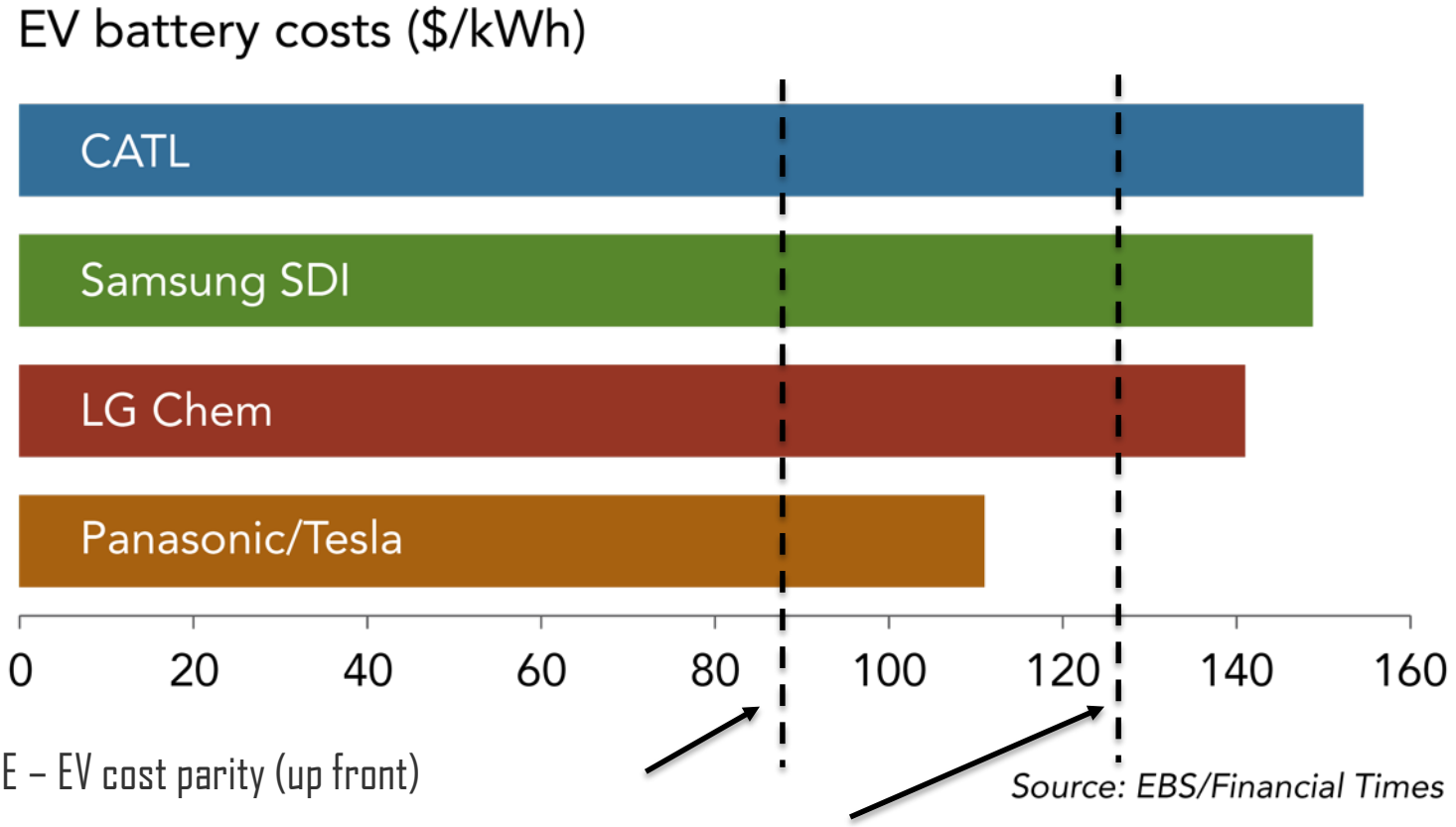
April 24, 2019 by Alan Adler, @AlanAdler

Michael Simon, chief executive of TransPower, left, and Chris Villavarayan, president of global trucks for Meritor Inc., stand with one of the port terminal trucks the companies will build for the ports of Long Beach and Oakland, Calif. (Photo: Alan Adler/Trucks.com)

Erik Neandross, CEO of Gladstein, Neandross & Associates, joked that the event had morphed from a natural gas vehicle conference a few years ago into a "commercial electric vehicles summit."

Why all the hysteria about electrification?

Battery cost reductions are now believable…



And then there's California

California adopts ZEV mandates for state heavy-duty vehicle fleets

Posted on 11 October 2017

California Governor Jerry Brown signed Assembly Bill (AB) 739, which requires at least 15% of vehicles with a GVWR of over 19,000 lbs that are newly purchased by the California Department of General Services and other state agencies to be Zero Emission Vehicles (ZEV) beginning in 2025, and at least 30% of those vehicles to be ZEV beginning in 2030.

"With the Federal Government rolling back environmental protections and clean air regulations, it is more important than ever for California to step-up and take a leading role in the fight against climate change," said Assemblymember Ed Chau (D-Monterey Park) who authored AB 739.

The ZEV requirements do not apply to vehicles that have "special performance requirements necessary for the protection of public safety".

And then there's California

L.A. City Approves Full LADOT Transit Electrification by 2030

By Joe Linton | Nov 9, 2017 | 5

This week, the L.A. approved LADOT bus electrification by 2030. Photo of LADOT's first electric DASH bus earlier this year - by Joe Linton/Streetsblog L.A.

And then there's China

Shenzhen's silent revolution: world's first fully electric bus fleet quiets Chinese megacity

"All 16,000 buses in the fast-growing Chinese megacity are now electric...
... and soon all 22,000 taxis will be too"

A perspective on battery costs

- The majority of battery cost reductions over the past decade have been realized due to **engineering** improvements
- Achieve the next round of dramatic cost reductions requires **chemistry** changes
- These chemistry changes are going to be **hard to realize and commercialize**
- **Recycling** will also likely need to be adopted at the same scale as lead-acid batteries

e-fuels

CO_2-based fuels

Syn fuels

electro-fuels

e-ethanol

e-diesel

e-gasoline

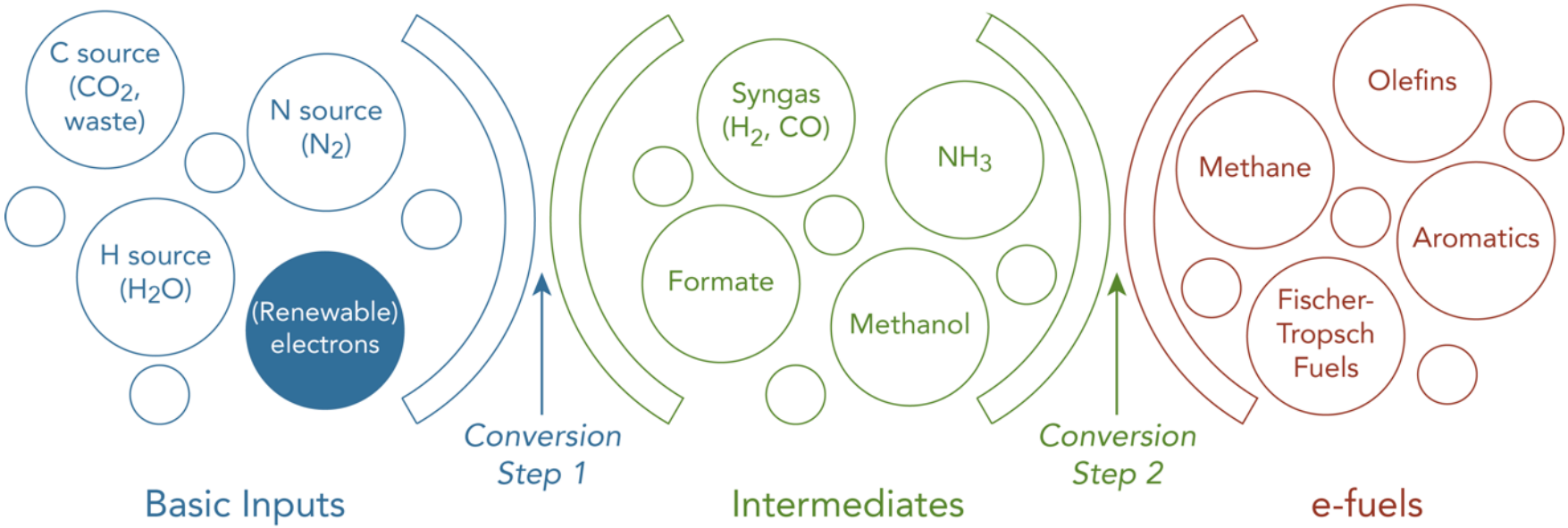
Fischer-Tropsch fuels

FT fuels

Power to fuel

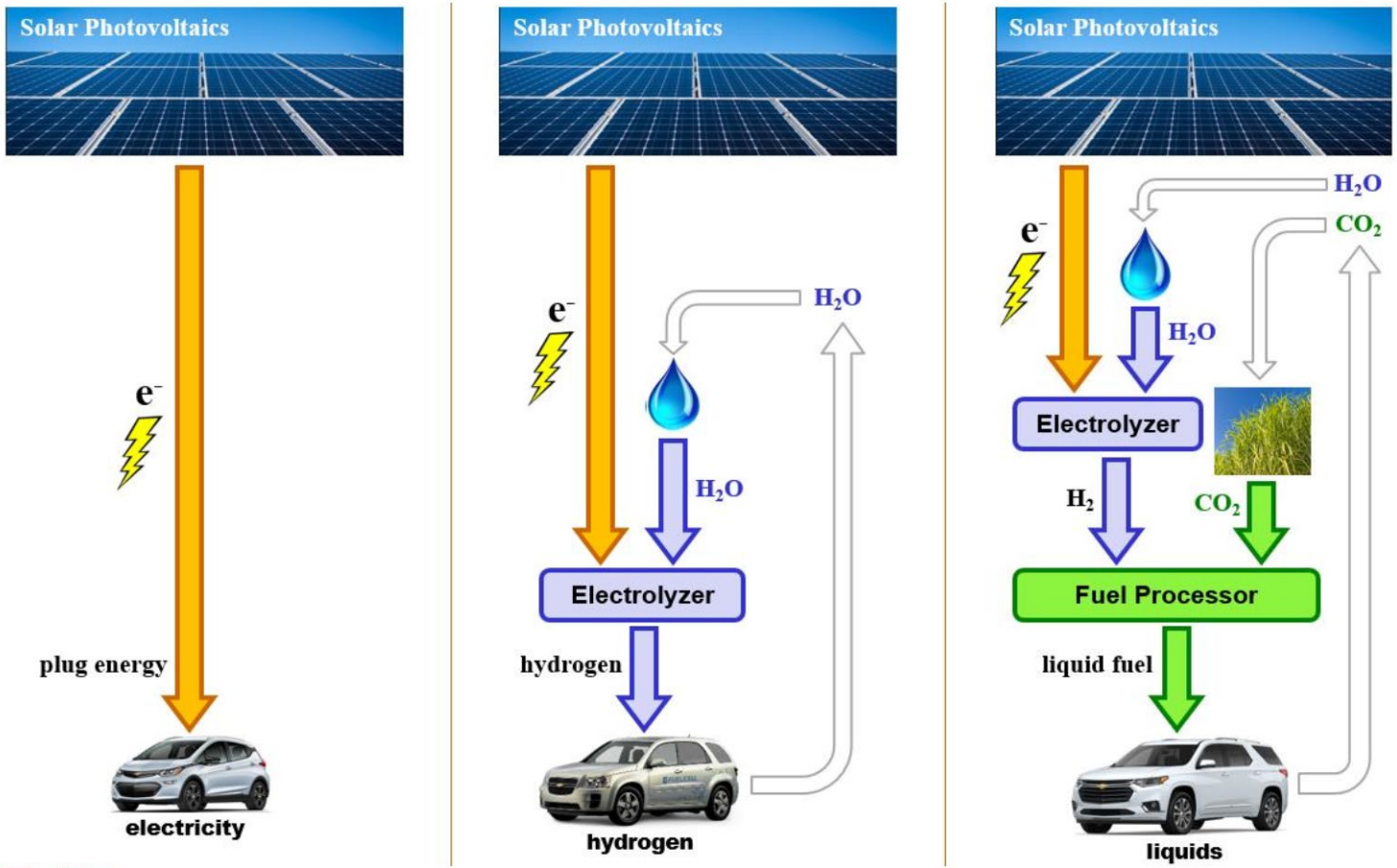
What are e-fuels?

Electrofuels ("**e-fuels**") are **hydrocarbon or oxygenate fuels** synthesized primarily using a **carbon source** and **electricity**



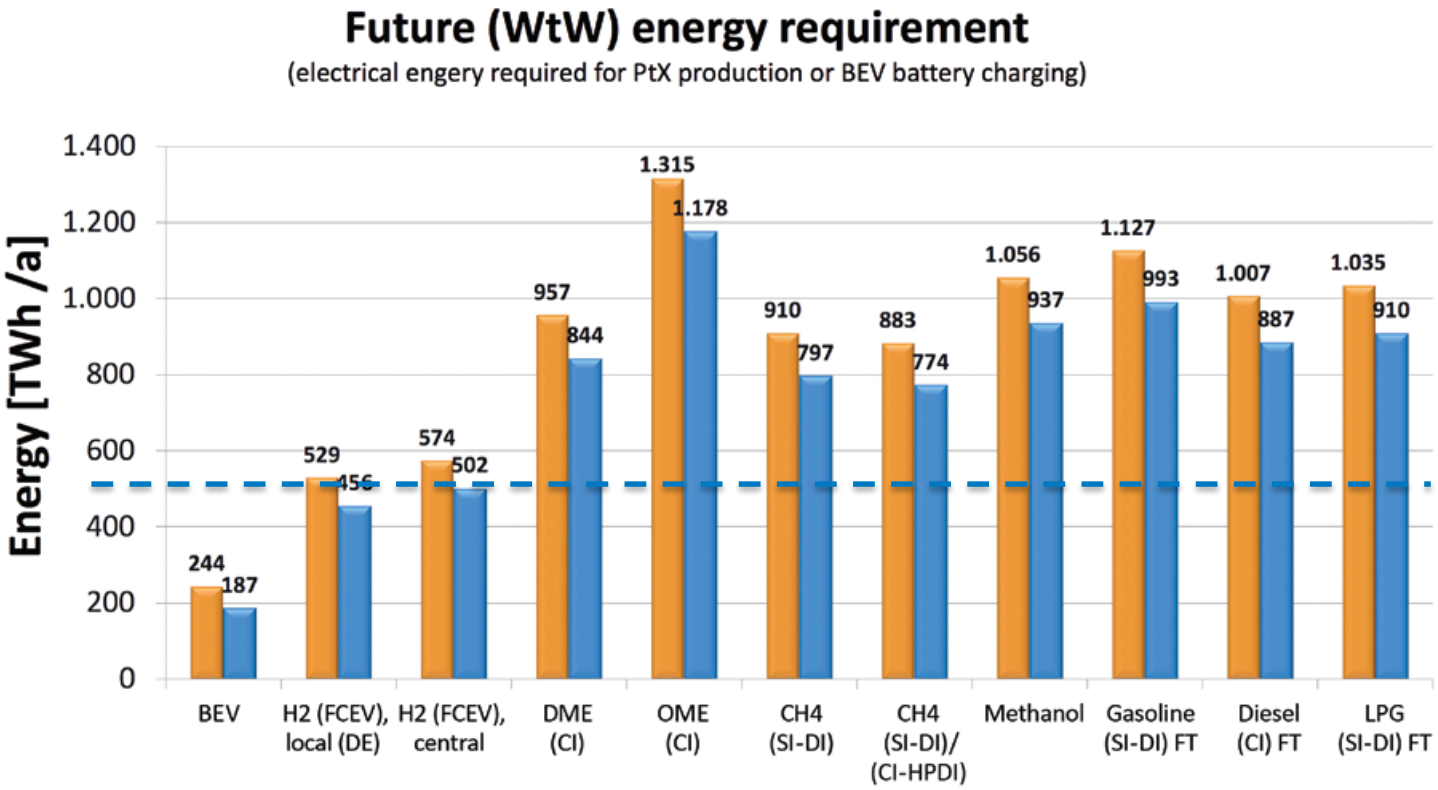
e-fuels attributes

- e-fuels are not new
  - But some technical approaches are new and have significant potential benefits
- e-fuels can be made with pretty much any desired structure/property
  - The same is true with biomass- and petroleum-derived fuels
- Much of the current interest in e-fuels results from their potential to be a low-GHG alternative to petroleum-derived fuels
  - Maximum benefit assumes abundance of cheap clean electrons



Source: Paul Najt, USCAR

How much electricity is required?



Germany's current annual electricity production

Energy required to convert 100% of Germany's LD and HD fleet

http://www.fvv-net.de/fileadmin/user_upload/medien/materialien/FVV_Future_Fuels_Study_report_Defossilizing_the_transportation_sector_R586_final_2018-09-01_EN.pdf

e-fuels: are they feasible at scale?

- In a world with constraints on low-cost, carbon-free electrons…
  - Is it cheaper and easier just to electrify the on-road fleet?
- Do e-fuels make most sense for jet and marine applications, where incumbent technologies are harder to substitute?

Summary/Conclusions

- Significant ICE efficiency gains are still possible
  - Technologies exist to meet future fuel economy and emissions targets but are increasingly expensive
  - Who is willing to pay for the needed R&D?
- Electrification promises to transform the entire on-road fleet
  - Cost (including TCO) and performance are driving the transformation
  - The pace will be slow; squeezing costs out will be hard
- e-fuels could be a low-GHG technology that helps extend the life of ICEs (in theory)
  - We need to use our renewable electrons wisely

TCO = Total cost of ownership

Thank You

john.farrell@nrel.gov

www.nrel.gov/transportation

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