EPA Battery Sizing and Cost Analysis for Future Plug-in Vehicles

for the Midterm Evaluation of the 2022-2025 Light-Duty GHG Standards

SEPTEMBER 15, 2016

EPA

THE BATTERY SHOW CONFERENCE

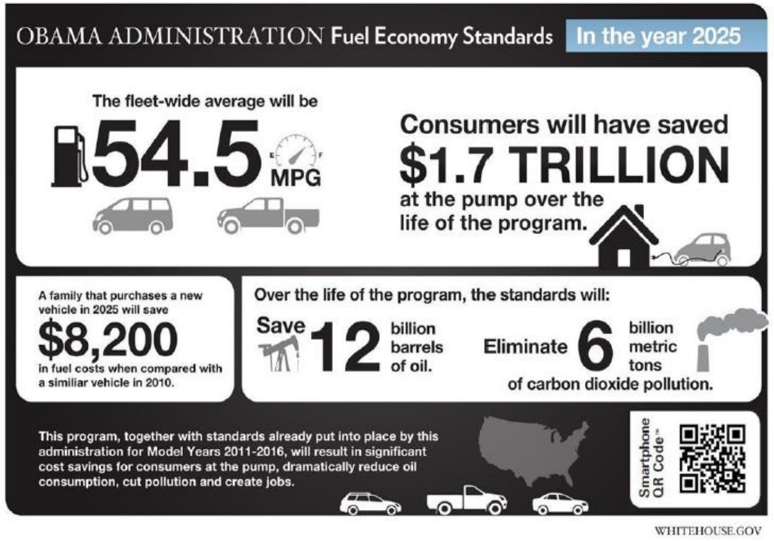
electric & hybrid vehicle technology conference

What we will cover

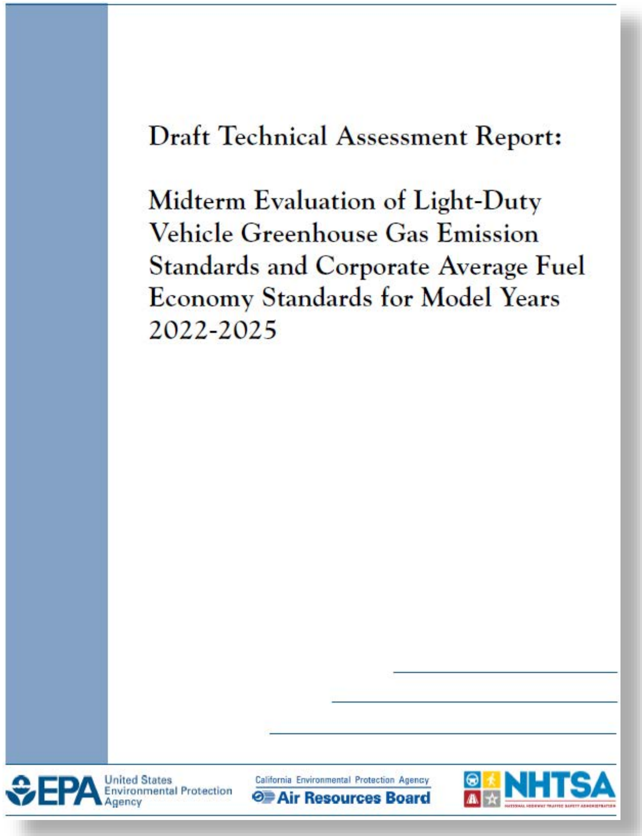
- Why EPA is projecting battery costs for future plug-in vehicles
- How we designed and modeled future batteries for this purpose
- How our 2012 projections fared against MY2012-2016 PEVs
- Battery design trends since 2012 that have been incorporated into the analysis
- How our revised projections compare to the 2012 projections and other sources

Why is EPA projecting battery costs?

- The 2017-2025 Light-Duty GHG/CAFE standards were developed between 2010-2012
- The incremental cost of technologies available for complying with the standards was an important consideration
- Plug-in vehicles are one of these technologies, and battery cost is the largest part of their cost
- A first set of estimates was made in 2011-2012
- They are now being updated for the Midterm Evaluation of the 2022-2025 portion of the rule



Draft Technical Assessment Report (TAR)


Draft Technical Assessment Report:

Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025

EPA United States Environmental Protection Agency | California Environmental Protection Agency Air Resources Board | NHTSA

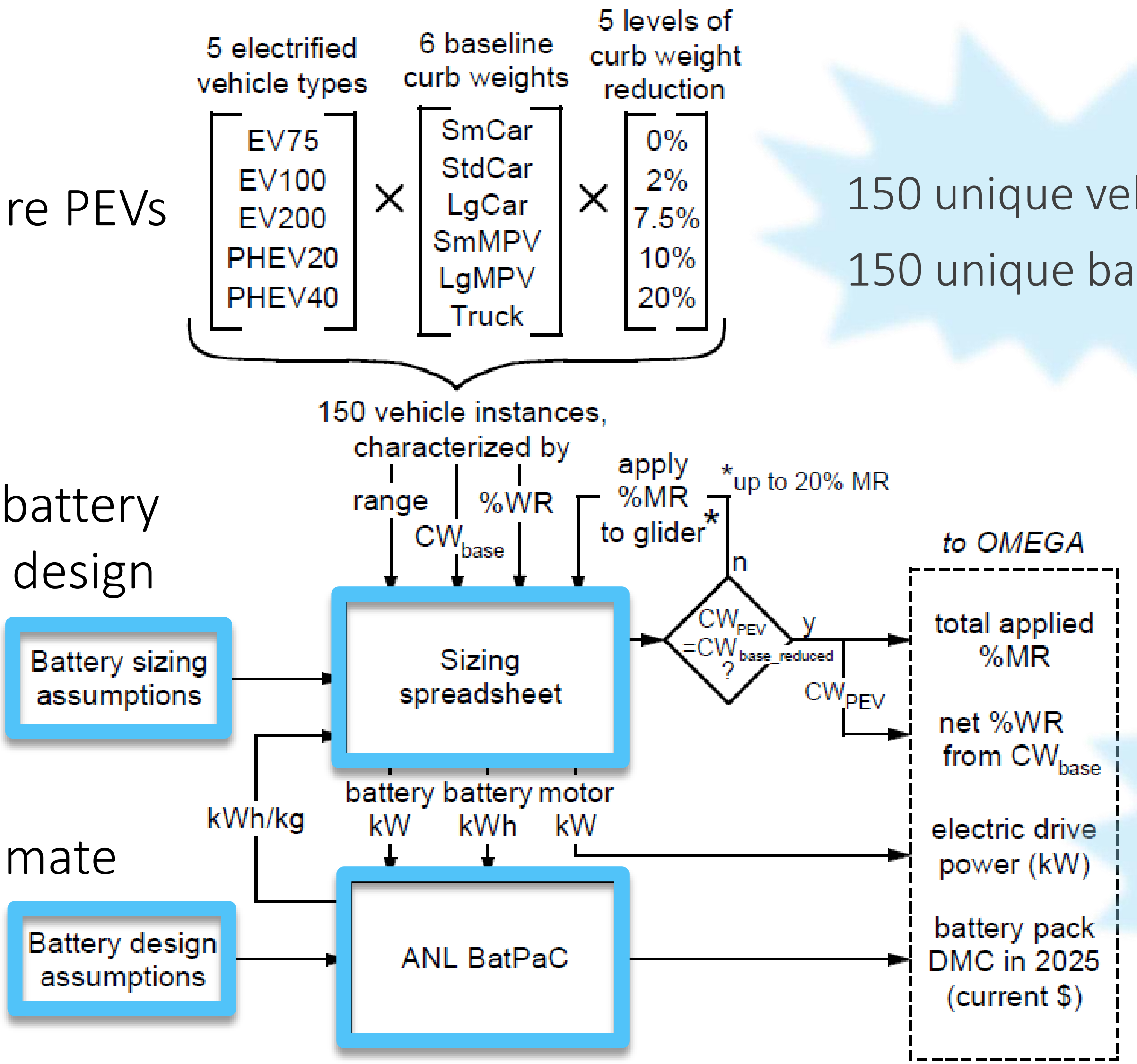
- Released July 18, 2016
- http://www.epa.gov/otaq/climate/mte.htm
- Open for public comment until September 26, 2016
- Sections 5.2.4 and 5.3.4.3.7 cover the material of this presentation
- To comment, visit www.regulations.gov and search for Docket ID No. EPA-HQ-OAR-2015-0827
- Follow the online instructions for submitting comments

Battery cost modeling approach

1 Define an array of future PEVs

2 Determine required battery capacity, power, and design attributes for each

3 Use ANL BatPaC to estimate direct manufacturing cost in 2025



150 unique vehicles

150 unique batteries

Results fed to adjoining analyses

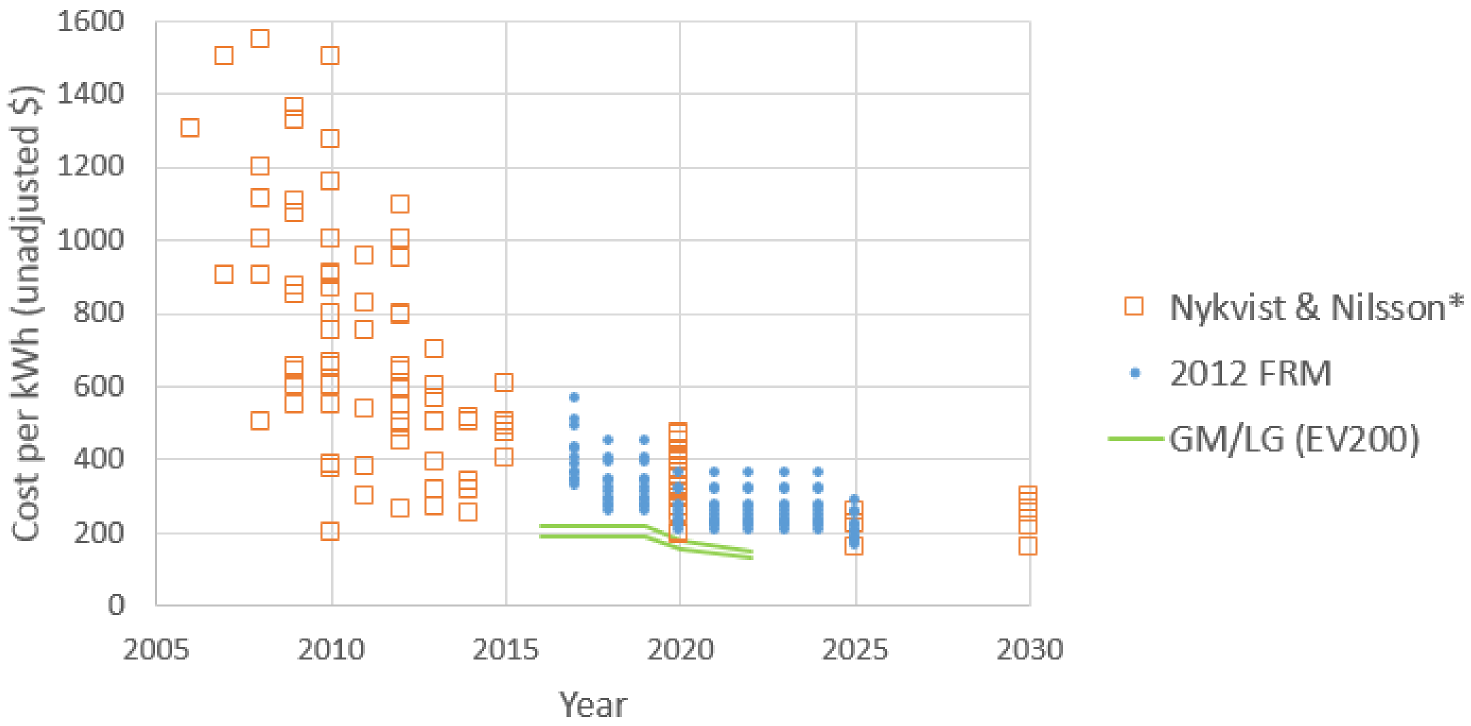
Many design variables affect battery size and cost

- Driving range and acceleration performance
- Assumed powertrain efficiencies
- Usable SOC window
- Chemistry (NMC622, NMC441, LMO, etc)
- Topology (cell capacity, cells per module, parallel strings, etc)
- Thermal medium (liquid or air)
- Electrode dimensions (thickness, aspect ratio)
- and many others

How well did our 2012 estimates perform vs. the emerging market?

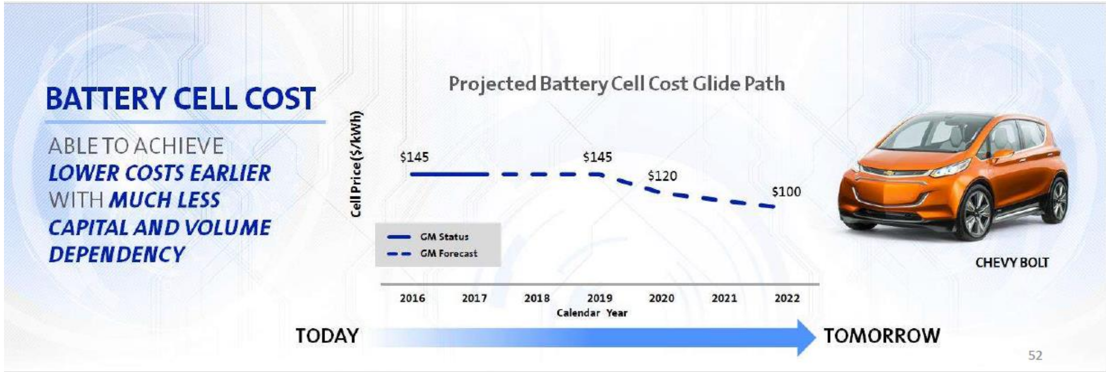
Are the choices we made in 2012 matching up with industry practice?

Projected cost per kWh (all BEV+PHEV40)



*Nykvist, B. and Nilsson, M.; "Rapidly Falling Costs of Battery Packs for Electric Vehicles," Nature Climate Change, March 2015; doi: 10.1038/NCLIMATE2564

Comparison to GM Chevy Bolt announcement



Mark Reuss, GM: "When we launch the Bolt, we will have a cost per kWh of $145, and eventually we will get our cost down to about $100."

GM Global Business Conference, October 2015

- Chevy Bolt = ~ EV200
- These are cell-level costs, not pack-level costs
- We aren't sure if they represent direct manufacturing costs or something different
- If we can convert them to pack-level costs, we can make a qualified comparison

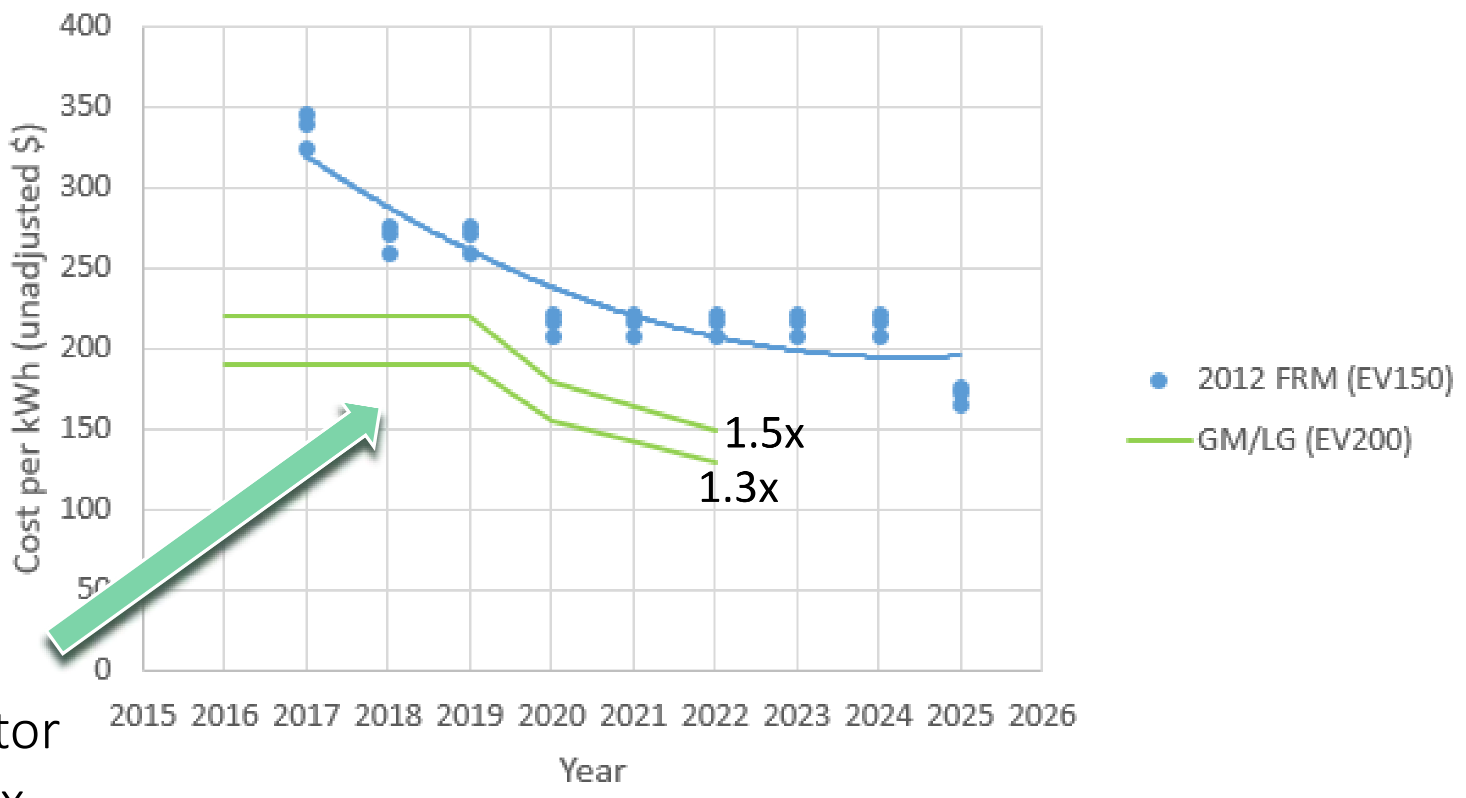
Converting cell-level costs to pack-level costs

- Several sources suggest a conversion factor for $/kWh of about 1.2 to 1.4
- BatPaC modeling of BEV batteries suggests a factor of 1.3 for a 32 kWh pack
- The factor diminishes further as capacity increases

Source	Low	High
Kalhammer et al.[340]	1.24	1.4
Element Energy[269]	1.6	1.85
Konekamp[248]	1.29	
USABC[341]	1.25	
Tataria/Lopez[342]	1.26	
Keller[343]	1.2	
BatPaC, 16 kWh	1.5	
BatPaC, 32 kWh	1.3	

Draft TAR p. 5-124, Table 5.6
Conversion Factors for Cell Costs to Pack Costs
(See Draft TAR for references)

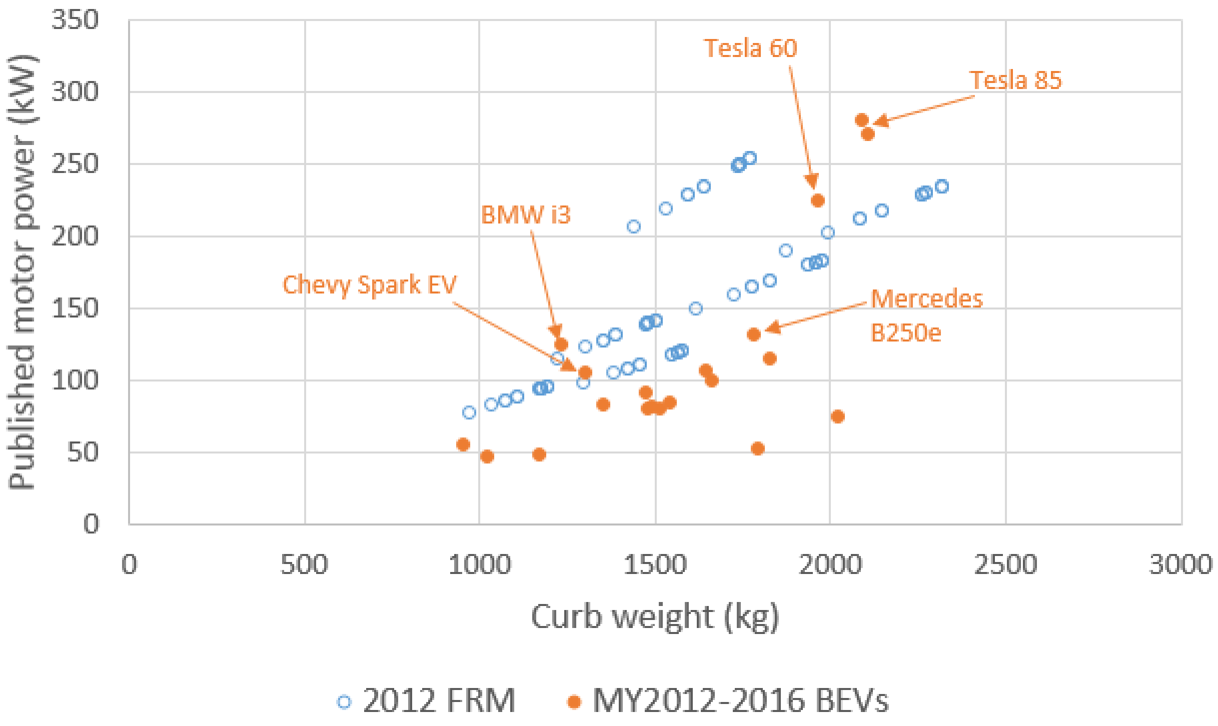
2012 projections for EV150 vs GM/LG estimated pack level cost for EV200



Assuming cell-to-pack conversion factor of 1.3x to 1.5x

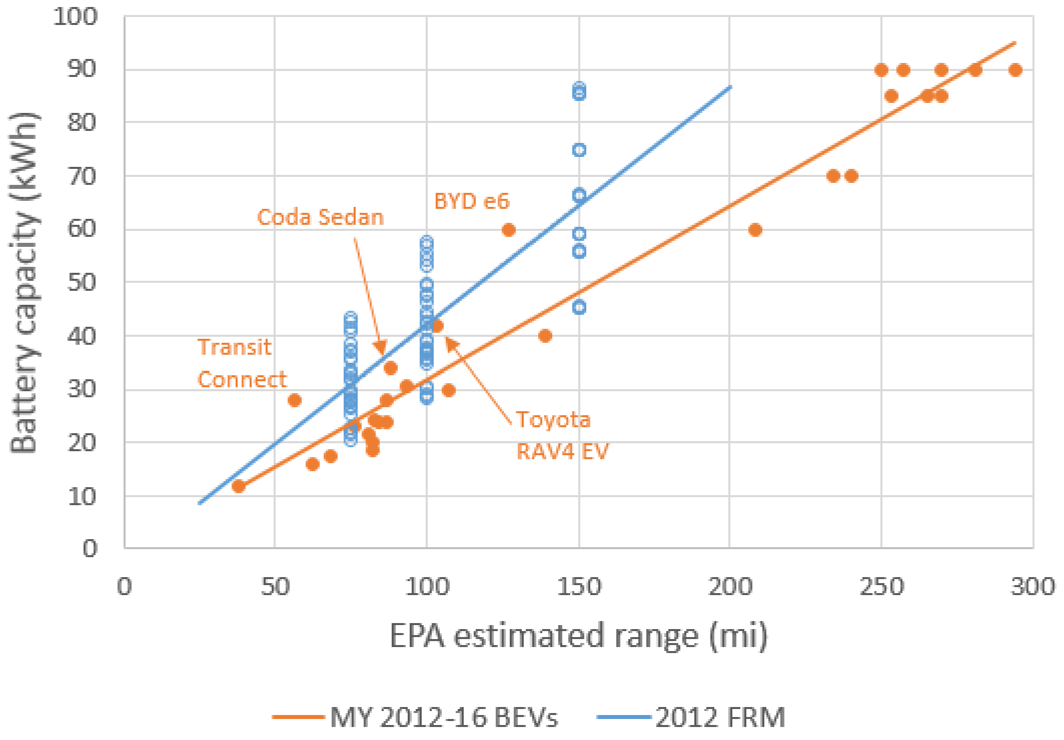
Projected peak motor kW

- Originally, we sized the motor to provide the power-to-ETW ratio of a baseline conventional vehicle
- Manufacturers are providing less nominal power than that, while maintaining or exceeding baseline performance
- High low-end torque of electric motors is probably a factor
- Right-sizing the motor is important for performance neutrality, motor costing, and battery P/E ratio



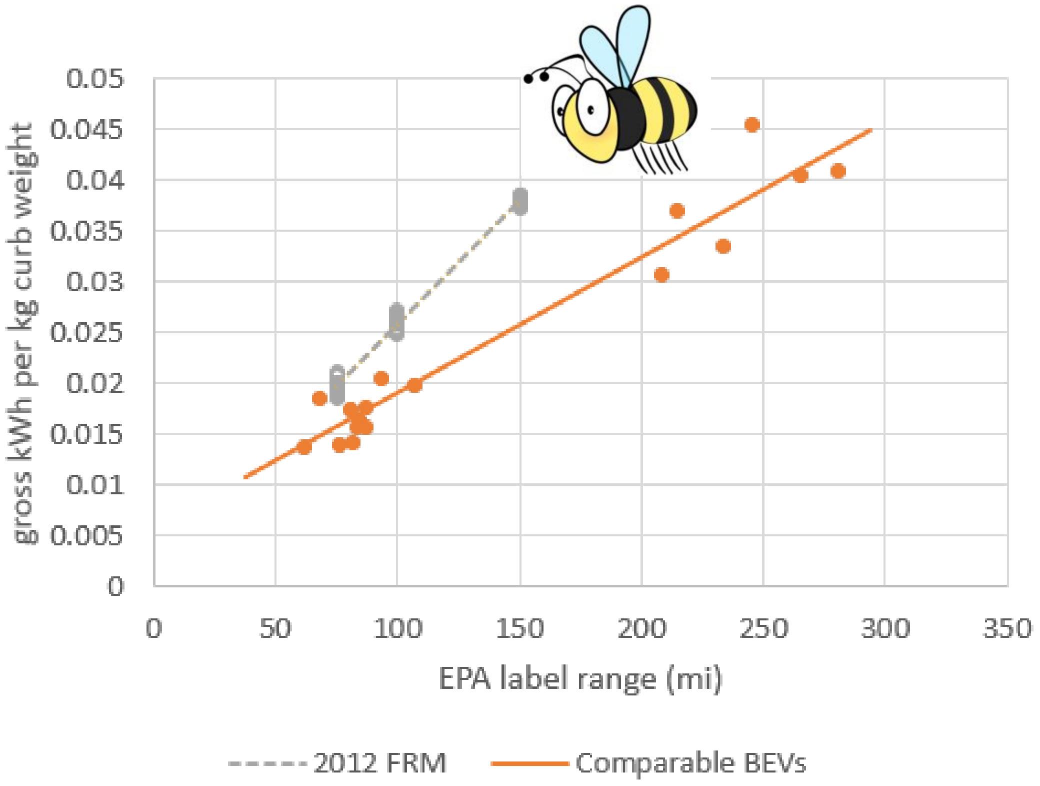
Projected capacity per unit range

- BEV manufacturers appear to be getting more range per kWh than we projected
- The sizing model seems to be particularly challenged by longer-range vehicles
- Could weight differences or other factors be responsible?



Projected capacity, normalized to weight

- The disparity is not explained by differences in vehicle weight
- The existing model would fail to explain the Tesla Model S 85, or even a BEV200
- *Can bumblebees fly?*
- The sizing model and/or its assumptions needed significant updating to keep up with the industry

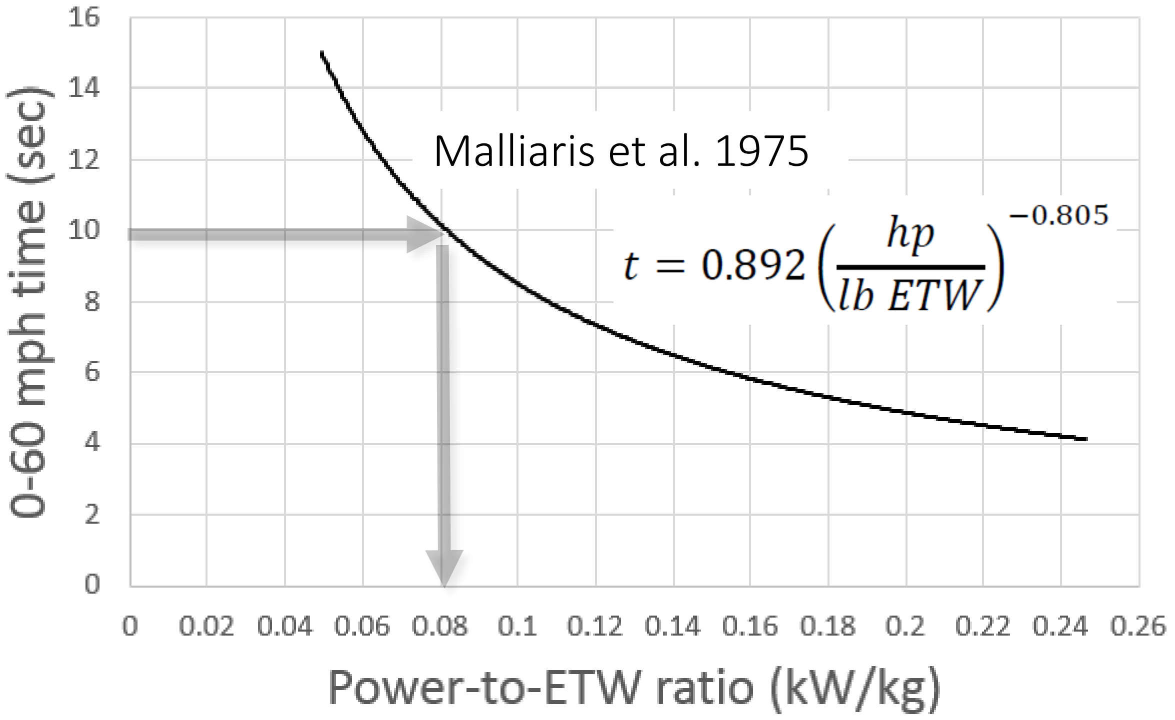


What we changed

- Driving range target: EV150 changed to EV200
- Motor power sizing basis
- 0-60 acceleration targets updated to MY2014
- SOC windows
- Pack topology (cell size targets, aspect ratio, modules)
- Updated version of ANL BatPaC
- Others (see Draft TAR)

Revised motor sizing basis

- Originally, we sized the motor to provide the power-to-ETW ratio of a baseline conventional vehicle
- ***Engine*** power can be related to a 0-60 time by Malliaris equation
- To target a 10-sec 0-60 time, size the ***engine*** to provide a power-to-ETW ratio of about 0.08
- We've already suggested that this may not be valid for electric motors

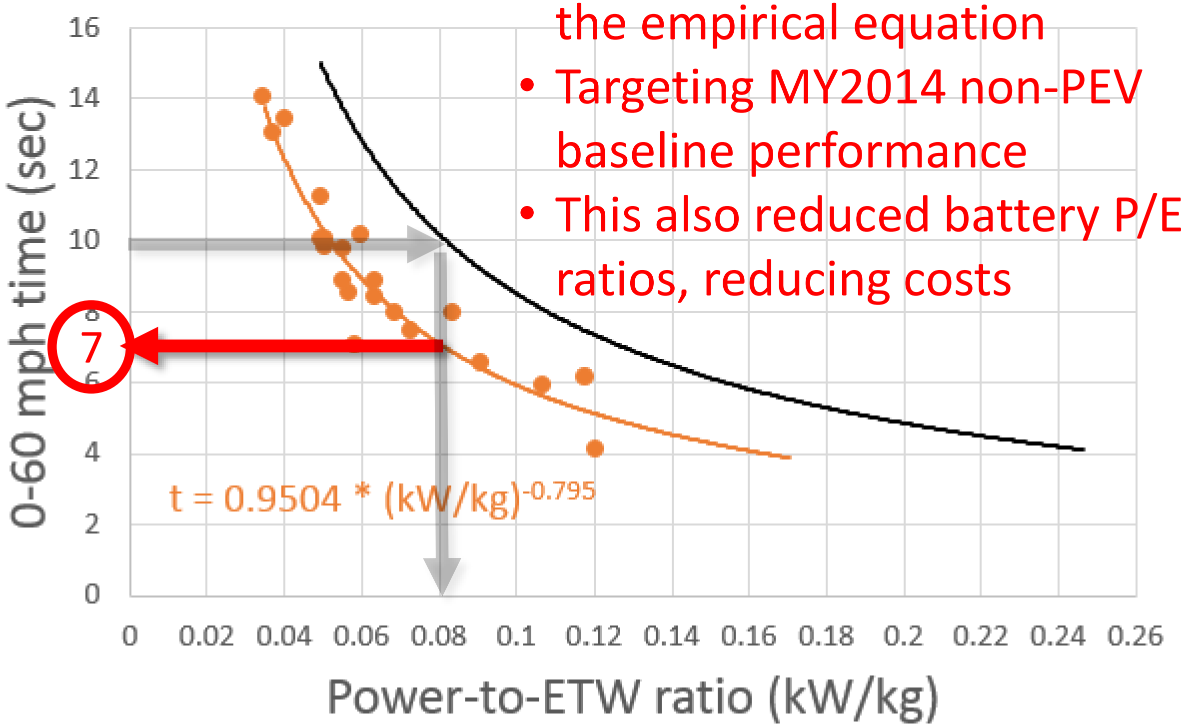


Revised motor sizing basis

- So we surveyed MY2012-2016 PEVs for their rated peak power and all-electric 0-60 mph time (from manufacturer and press information)
- We then related 0-60 time (t) to power-to-ETW* ratio:

$$t = 0.9504\left(\frac{kW}{kg\ ETW}\right)^{-0.795}$$

* Equivalent test weight = curb weight + 136 kg



- Motors were resized using the empirical equation
- Targeting MY2014 non-PEV baseline performance
- This also reduced battery P/E ratios, reducing costs

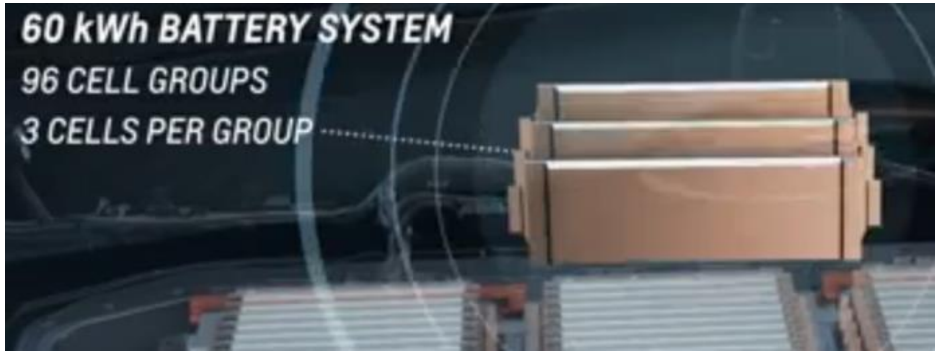
Revised SOC design windows

- Test results and manufacturer information suggest that MY2012-2016 EVs and PHEVs are beginning to use more SOC than anticipated
- PHEV40 widened to 75%
- EV75, EV100 widened to 85%
- EV200 widened to 90%
  - Larger battery capacity may be associated with fewer cycles in a given lifetime
  - Cycles potentially shallower on average

	SOC design window	
	FRM	draft TAR
HEV	40%	40%
PHEV20	70%	70%
PHEV40	70%	75%
EV75	80%	85%
EV100	80%	85%
EV150/200	80%	90%

Revised pack topologies

- Cells per module now varies
  - 24 to 32 instead of 32
  - Better targets pack voltage and preferred cell capacities
- Cell capacities better targeted
  - BEV targets 60 A-hr (max 75)
  - PHEV targets 45 A-hr (max 50)
- Electrode aspect ratio 3:1
  - Supports trend toward flat floor mounted packs
  - BatPaC places tabs on short dimension
- Module arrangement optimized
  - Again, trend toward flat packs



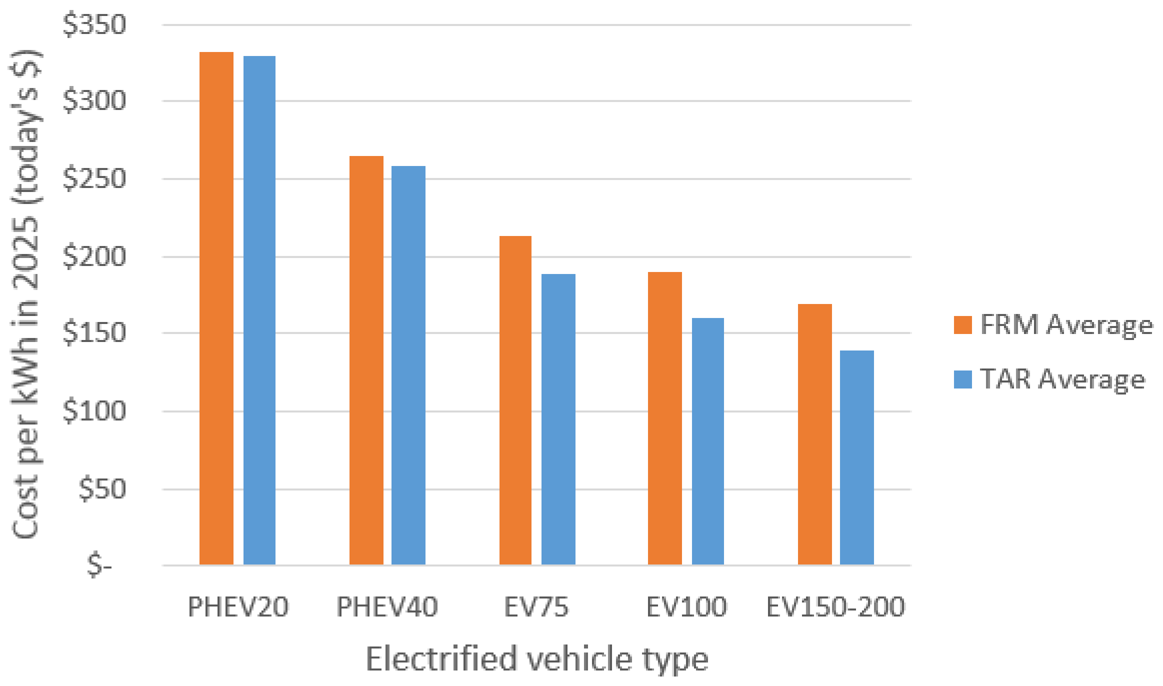
Trend toward flat, floor mounted packs using large, low-profile cells

Other changes

- EV200 range derating factor (2-cycle to 5-cycle) increased to 80% (from 70%) based on Tesla practice
- Small adjustments to energy consumption calculations
- Aero, tire 20% improved from 2008 baseline (was 10%)
- Small changes in power oversizing factors
- Chemistry updates
  - NMC441 → NMC622
  - LMO → blended LMO (75% LMO, 25% NMC)
- See the Draft TAR for others

Effects on projected battery cost

- On a cost per kWh basis:
  - BEV battery costs fell by about 15%
  - PHEVs were relatively unchanged (due to changes in battery power levels that offset some cost reductions)
- Changes in pack topology, battery power, and material and component costs within ANL BatPaC were significant factors



Effects on projected battery cost

- On a pack cost basis:
  - BEV pack costs declined by ~ 25%
  - PHEV pack costs declined by ~ 8-12%
- Smaller pack sizes and reduction in cost per kWh drove these reductions

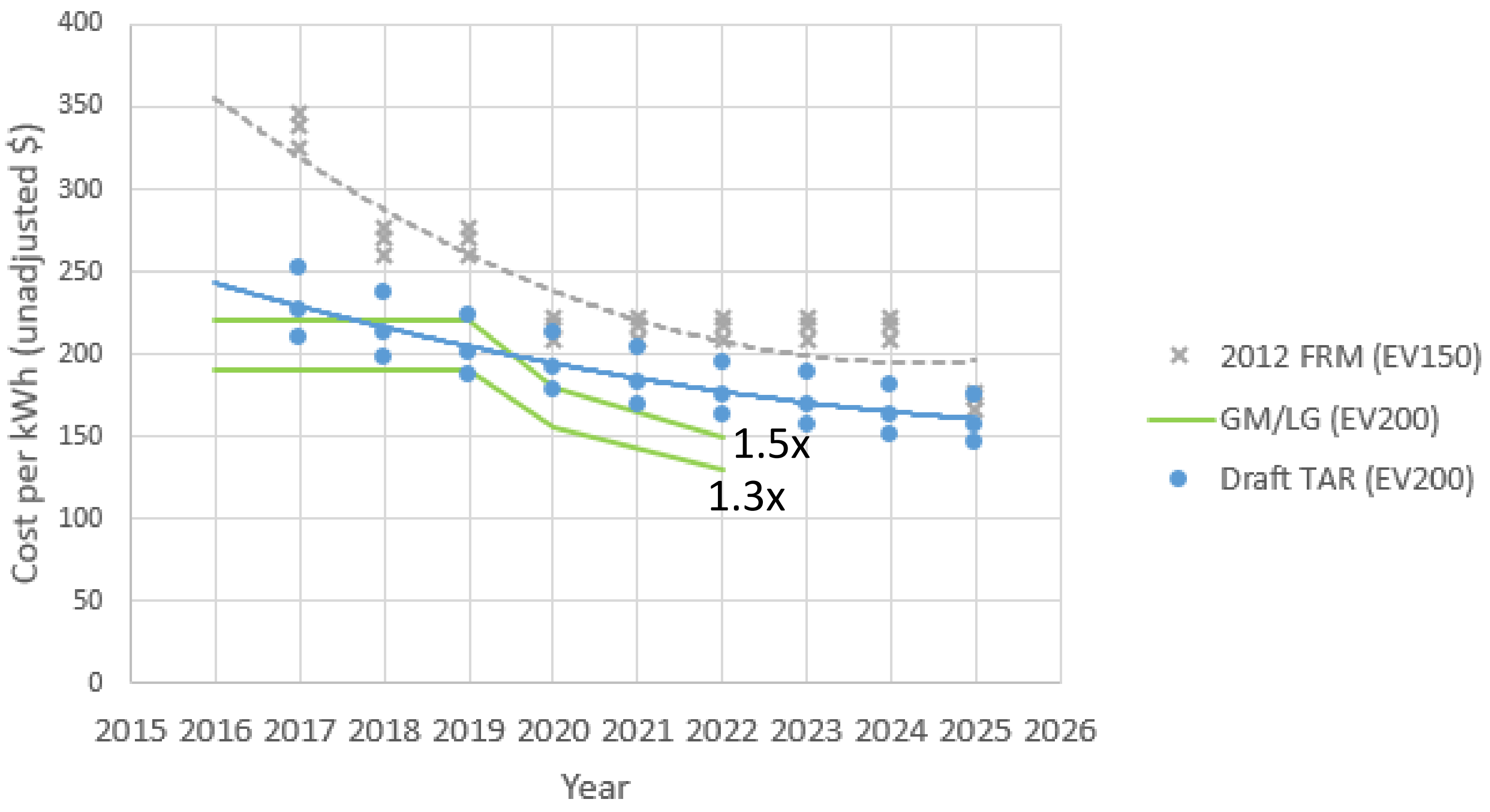
Average change from 2012 FRM	
	Change in projected pack cost
EV75	-24.9%
EV100	-27.1%
EV200†	-24.0%
PHEV20	-8.7%
PHEV40	-12.2%

All configurations target 20% curb weight reduction

†Compares EV200 (Draft TAR) to EV150 (FRM)

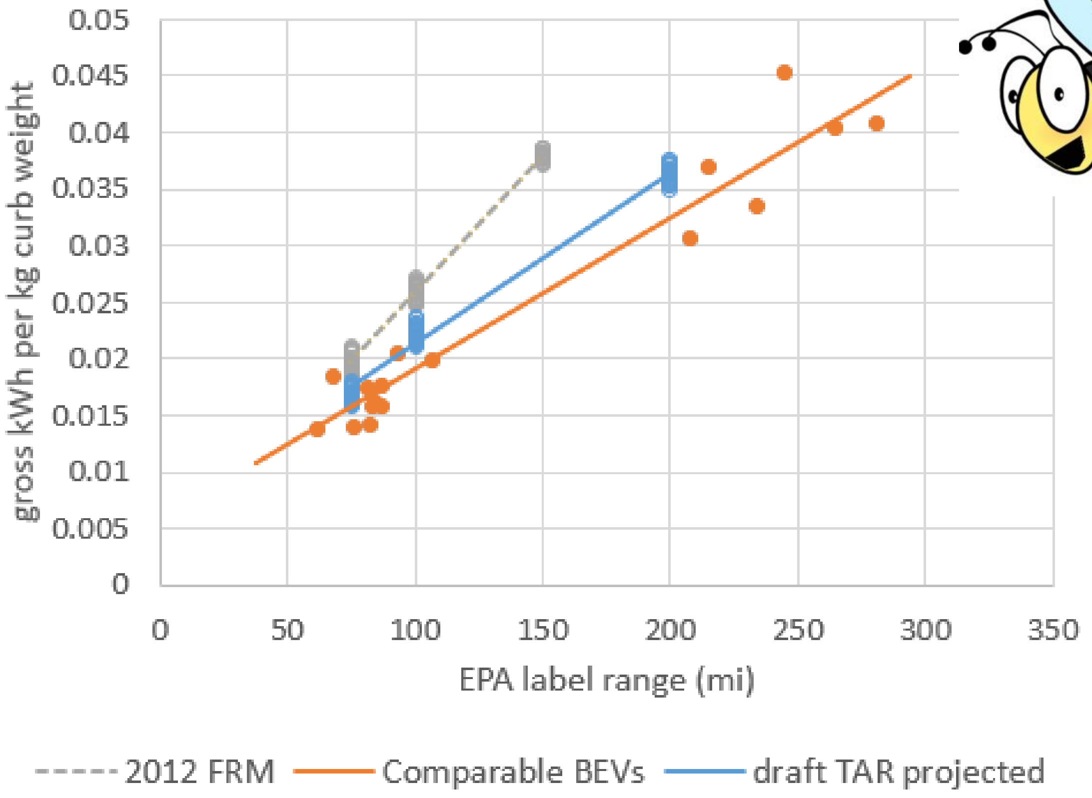
New projections for EV200 vs GM/LG estimated pack level cost

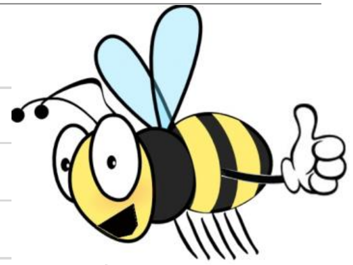
- Projected cost per kWh closer to GM/LG pack level estimates
- Refinements to learning curve also played a role
- Still above the 1.3x trend line



New projections: capacity per kg CW

- Greatly improved – we can do EV200 and Tesla
- Still conservative – can/should we close the gap?
- Best candidate: Improve the method of estimating energy consumption (kWh/mi)
- Unfortunately, structural requirements of the adjoining analyses make this difficult
- Future uncertainties favor a conservative estimate (range trends, regulations, volumes, etc)

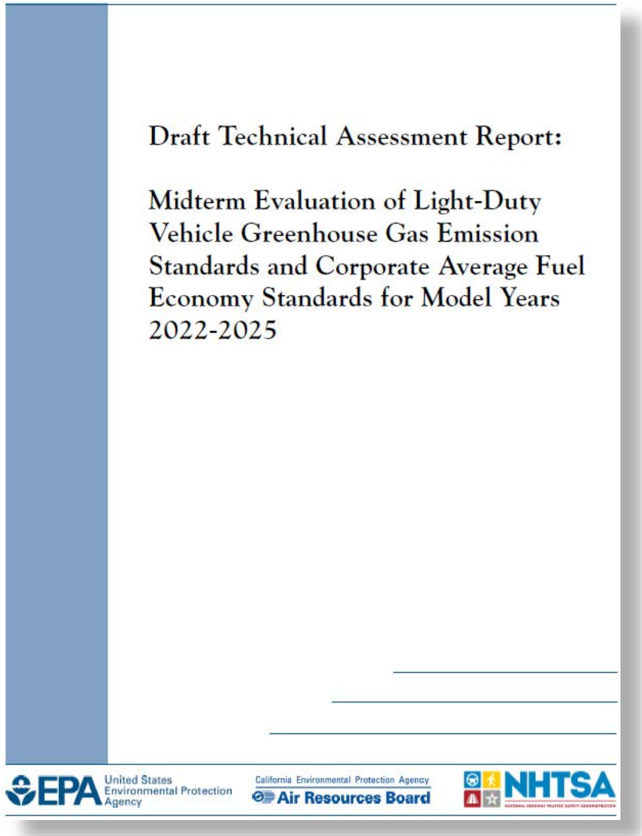




Conclusions

- MY2012-2016 PEVs outperformed our 2012 predictions:
  - 200+ miles range can be expected in mainstream vehicles (vs. 150 miles)
  - Less battery capacity needed for a given range
  - Less nominal motor power needed for equivalent 0-60 acceleration
- Trends in battery design have continued to converge
  - Increased cell capacities and more cells per module
  - Flat, low-profile pack and module configurations becoming more popular
  - Advanced chemistries and learning are widening SOC design windows
- Revised cost and capacity projections are lower, while maintaining a buffer for future uncertainties

Thank you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- http://www.epa.gov/otaq/climate/mte.htm

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