On Charging Equipment and Batteries in Plug-in Vehicles: Present Status

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Introduction

How well do recent plug-in vehicles match Kempton and Tomic's 2005 vision of V2G?

- Battery usage during driving
- Charging equipment/standards
- Fast-charging implications

Kempton and Tomic's proposed use cases:

Spin Reserves (1h)
Regulation Up (1.4h)
Regulation up + down (continuous per 0.33h)
Peak Power (4h)

- **15kW is frequently discussed as a residential line limit and used in several examples…**

Chevrolet Volt

Nissan Leaf

Tesla Roadster

Recent Charger Capabilities and Standards

Type AC	Power Level
AC Level 1 120 VAC	12, 16 amps 1.44, 1.92 kW
AC Level 2 208 - 240 VAC	≤ 80 amps 3.3 to 19.2 kW
▲AC Level 3 TBD Single or three phase?	

AC Level 1 & 2 Chargers are small and on-board the vehicle

Current G2V Charger Capabilities

Volt: 3.3 kW on-board charger

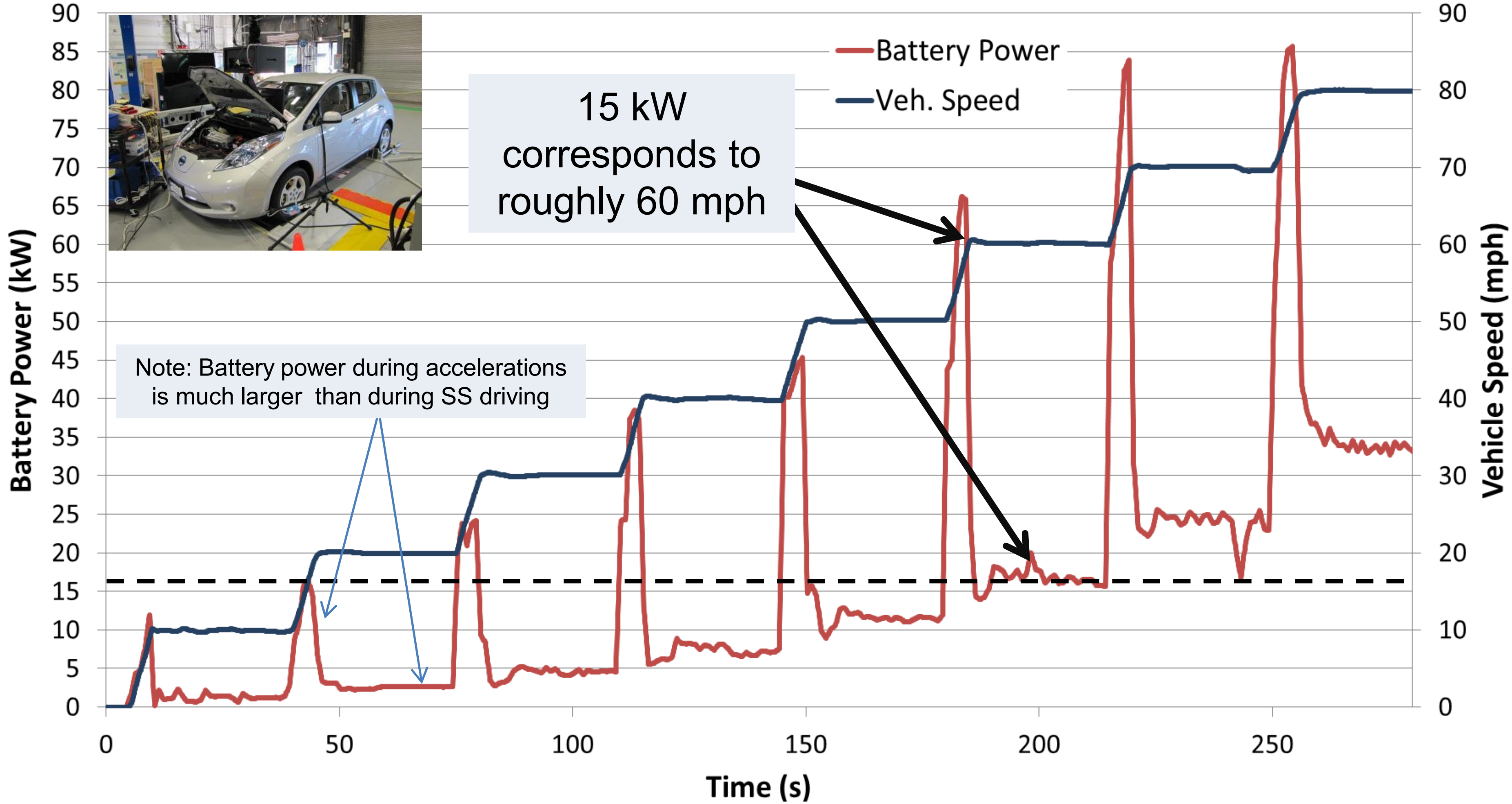
Leaf: 3.3 kW on-board + optional DC fast-charge port

Tesla: 16.8 kW max available power

EEtrex 4 kW V2G Inverger

Prototype test setup at ANL

Leaf Battery Power During 0.8 hrs. of Testing for 0.01 hr. Steady-State Intervals

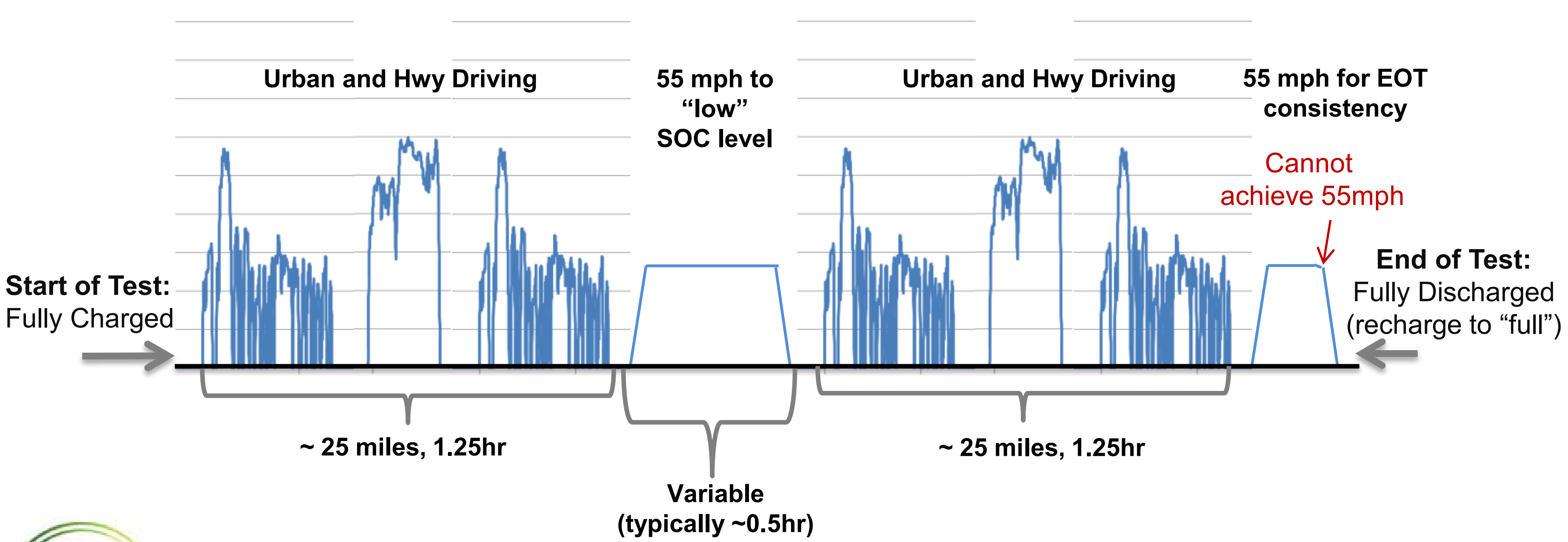


15 kW output @ 16 kW from battery and ~93% inverter efficiency

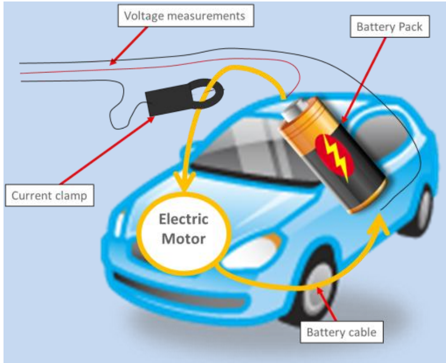
PEV batteries are predominantly designed around driving scenarios:

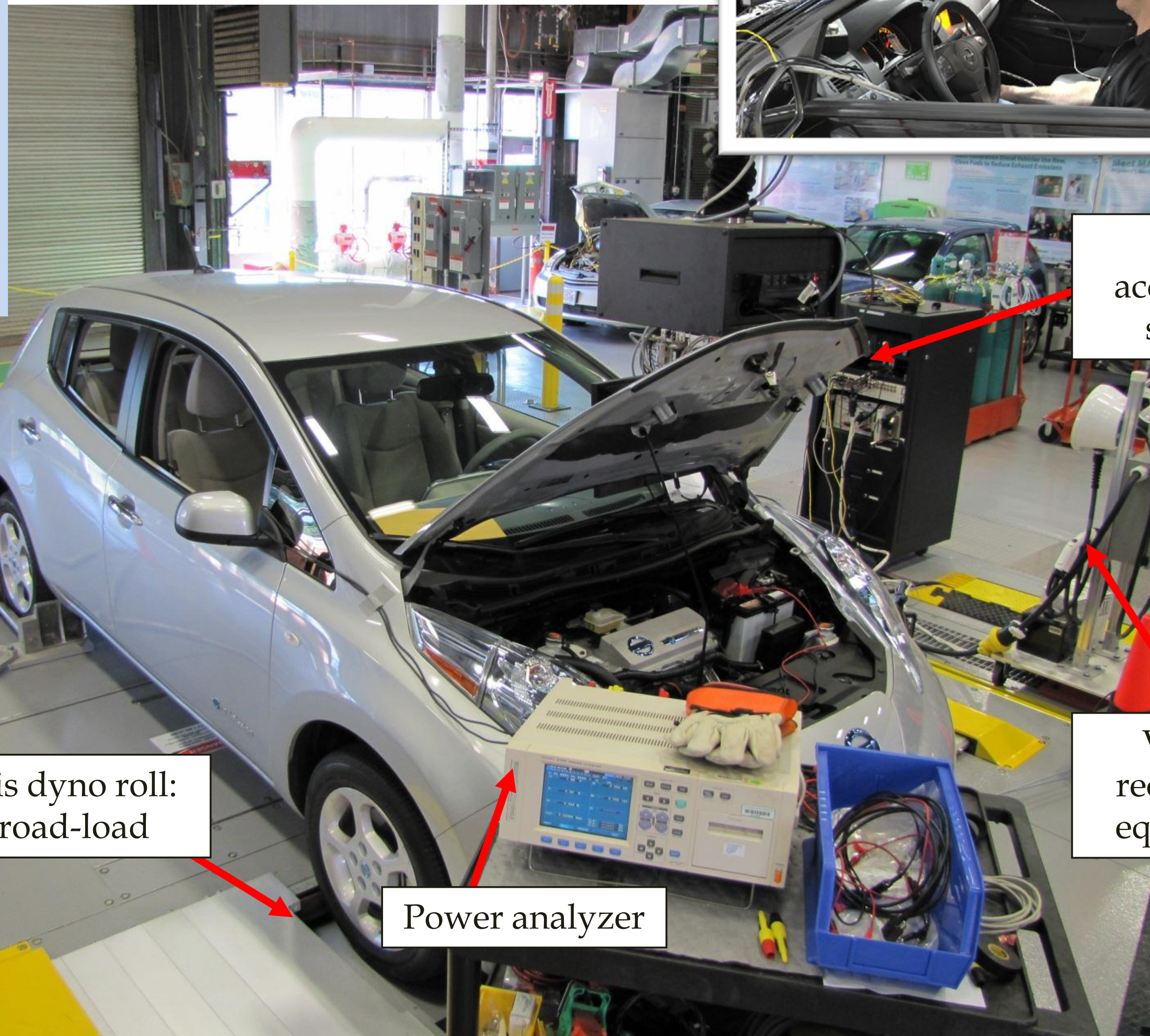
- 0-60 time and aggressive accelerations (peak power…usually 2-10 second range)
- Operation over "thermal" drive cycles and soak scenarios (cooling requirements)
- Desired range over specified drive/duty cycles (usable energy, typical cooling)
  - This testing is typically done on a chassis dynamometer using EPA defined cycles

Draft SAE J1634 "Shortcut" EV Range Test Overview
For Urban and Highway Evaluation



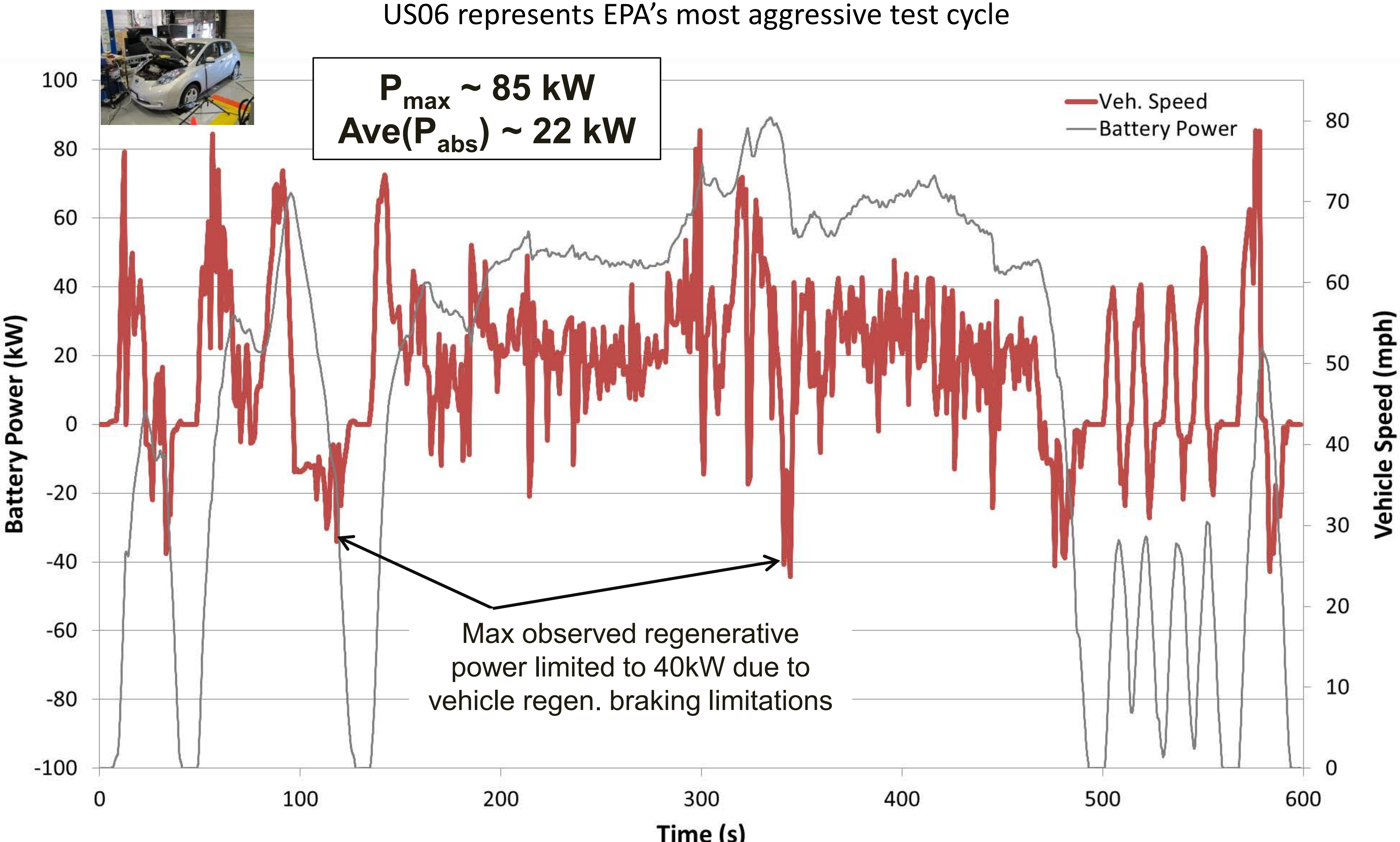
Example Dynamometer Setup for BEV





Leaf Battery Usage During US06 Aggressive Driving

US06 represents EPA's most aggressive test cycle



Recent Vehicles Energy Consumption and Capacity

	Average Tested Energy Output (kWh)	EPA Combined Adjusted Energy Consumption (kWh/mi)*	Approximate Depth of Discharge (%)
Chevy Volt	9.5	0.30	59%
Nissan Leaf	21	0.29	88%
Tesla Roadster	43	0.25	77%
RAV 4 EV (Kempton 2005)	21.9	0.40	80%

Chevrolet Volt

Nissan Leaf

Tesla Roadster

* EPA numbers adjusted to account for charger efficiency

Calculating Kempton & Tomic's Theoretically Available Battery Pack Power for Recent Vehicles

- Per vehicle useable battery pack power using Kempton's 2005 assumptions and calculations

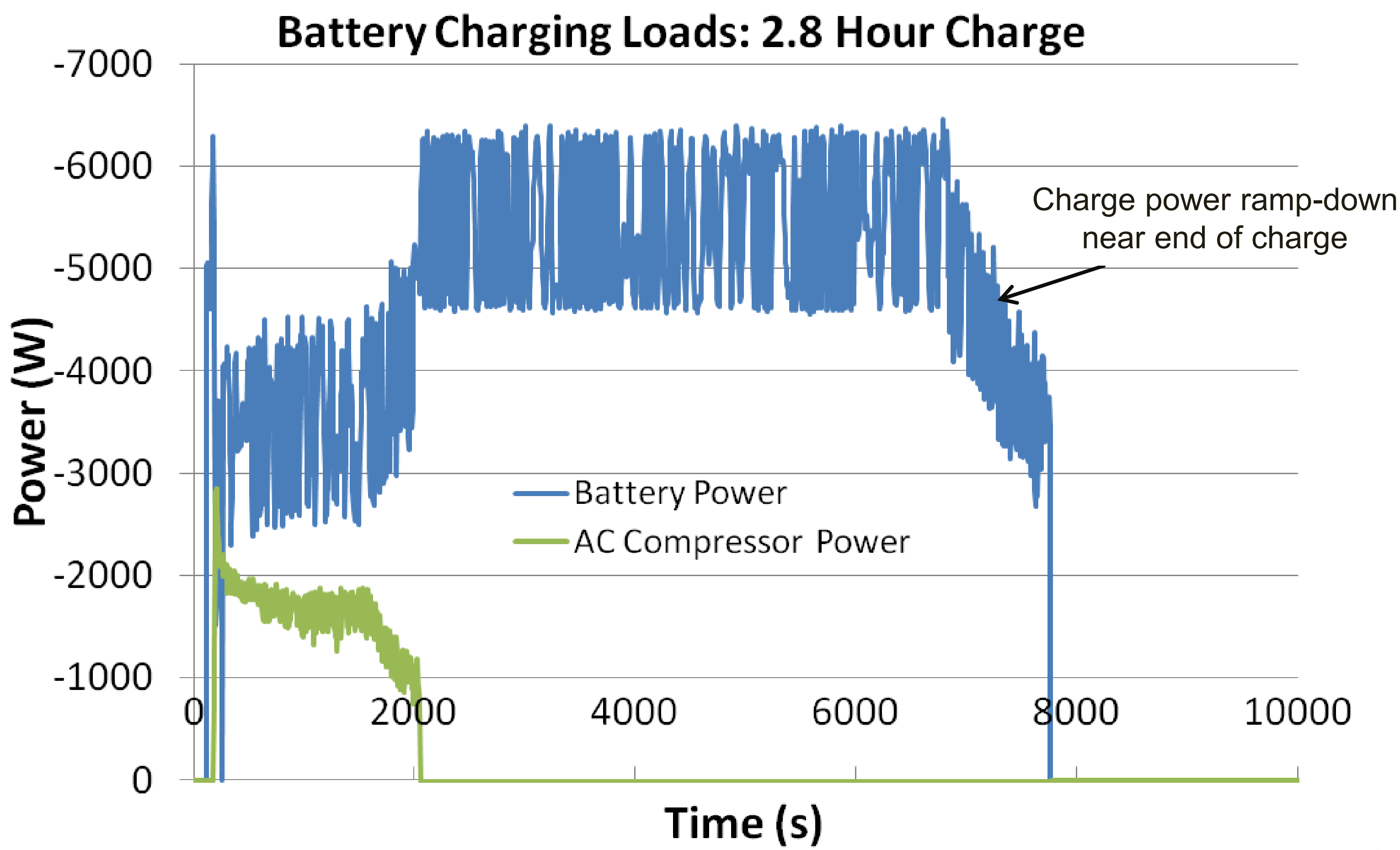
	Per Vehicle Available Power (kW)			
	Spin Res. (1h)	Reg. Up (1.4h)	Reg. up+down (continuous per 0.33h)	Peak Power (4h)
Chevy Volt - No range buffer	4.3	3.1	13.1 + 16.3	1.1
Chevy Volt - 20mi range buffer	0.0	0.0	0.0 + 16.3	0.0
Nissan Leaf	10.0	7.1	30.2 + 15.4	2.5
Tesla Roadster	31.5	22.5	95.6 + 13.6	7.9
RAV 4 EV (Kempton 2005)	7.0	5.0	21.1 + 21.5	1.7

$$P_{\text{vehicle}} = \frac{\left(E_s - \frac{d_d + d_{rb}}{\eta_{\text{veh}}}\right)\eta_{\text{inv}}}{t_{\text{disp}}}$$

d_d = 16mi
d_{rb} = 20 mi
n_{inv} = 0.93

Kempton & Tomic assumptions for available power did not address battery temperature and/or low/high SOC power limiting issues

- Cabin HVAC loads may significantly increase required “range buffer”
- Battery de-rating and thermal conditioning (following usage or hot/cold soak conditions)



ANL Perspective: Standards are the common thread that enables interoperability of new technologies

Detroit was the first American city to use electric taxi cabs, in 1914.

Outdoor Curb-Side Charging Port

Are Indoor/Outdoor Charge Ports New?

Indoor charging stations

Detroit's first electric taxi accumulated >46,000 miles first two years.

SAE J1772™ Task Force Charge System Names vs. Readiness and Power (kW)

Type AC	Power Level
AC Level 1 120 VAC	12, 16 amps 1.44, 1.92 kW
AC Level 2 208 - 240 VAC	≤ 80 amps 3.3 to 19.2 kW
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AC Level 1 & 2 Chargers are small and on-board the vehicle

Type DC	Power Level
None at this voltage	None at this power
▲DC Level 1 200 – 450 VDC	≤ 80 amps ≤ 19.2 kW
▲DC Level 2 200 - 450 VDC	≤ 200 amps ≤ 90 kW
▲DC Level 3 TBD 200 – 600 VDC?	≤ 400 amps? ≤ 240 kW?

DC Chargers are large and off-board the vehicle

Only AC Level 1 and 2 are finalized by SAE, but the Leaf has an optional Japanese 50 kW DC quick charge *port* (yellow box, "DC-JARI ChAdEMO", generally 50 kW).

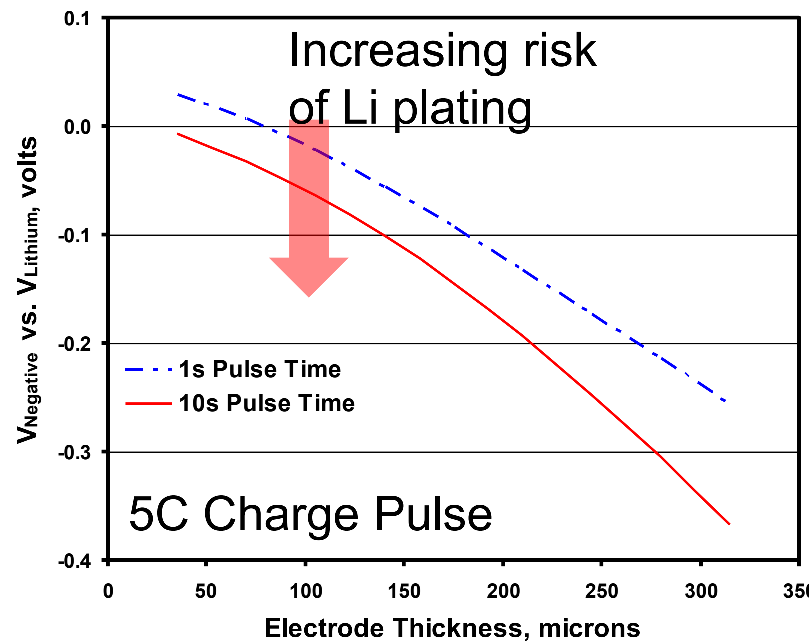
▲ Not finalized by SAE

Greater Fast Charge Ability May Require Battery Redesign

- Conservative battery designs are needed to enable Fast Charge & V2G
- High power charge rates may lead to side reactions, *ie* Lithium plating
  - At best, capacity fade will shorten battery life
  - At worst, a "thermal event" may occur from dendrite formation

- Battery design changes to mitigate lithium deposition/plating
  - Replace graphite with hard carbon
  - Reduce electrode loadings/thicknesses to minimize polarization
  - Use lithium titanate (LTO) anode

- Lithium plating more likely during
  - High rates of charging
  - High states of charge
  - Longer charge duration
  - Low temperatures



Condensed Battery Life Extension Instructions From Nissan Leaf Owners Manual

- Avoid 24 hr. exposure @ 120° F or more (EV-21)
- After use, allow vehicle & battery to cool down before charging (EV-21)
- Park and store in cool locations avoiding sunlight & heat sources (EV-21)
- Minimize use of public Fast Charge or Quick Charge (EV-21)
- Avoid exceeding 70-80% charge if using fast charge or quick charge > 1 time/week (EV-21)
- Deplete to at least 80% before recharge (EV-21) (i.e. do not top off)
- Use long-life charge mode except for long trips (i.e. limit total SOC, do not top off)
- Do not store for >14 days when the battery is empty (EV-21)
- To extend the life of the battery use long life mode by selecting 80% charge (EV-21 and CH-20).
- If the battery temperature gage indicates too hot or too cold, charging is not possible (CH-31).
- Drive moderately & use ECO driving mode (EV-21) (i.e. limit max. kW used)

Battery Charging Advice From Nissan Leaf Owners Manual

- Quick charge (up to 50 kW) should be minimized to prolong life (CH-7)
- 30 minute Quick charge is limited to 80% of capacity (CH-8)
- Routine charge should be “normal charge” (i.e. 220-240 V AC, 3.3 kW)
- It is important to avoid complete discharge (p. CH-7)
- Time to charge varies with ambient temperature (p. CH-7)
- Power limitation mode protects the battery in heat, cold, and low SOC. Charging may be automatically terminated, especially with repeated quick charging in extremely hot weather (CH-8).

BatPac $ For Faster Charge Capability for EV100

Charging rate, battery cost and size

Increasing fast charge & V2G capability increases battery size (+60 %) and cost (+30 %)

$LiMn_2O_4$-Graphite
2.2 mAh/cm^2 loading
60 micron negative

$5680 Cost to OEM
185 kg
95 L

$LiMn_2O_4$-Graphite
1.1 mAh/cm^2 loading
30 micron negative

$7160 Cost to OEM
220 kg
110 L

$LiMn_2O_4$-$Li_4Ti_5O_{12}$
2.4 mAh/cm^2 loading
100 micron negative

$7440 Cost to OEM
300 kg
150 L

Increasing fast charge capability increases battery size and cost
Calculations for an 80 kW, 24 kWh using BatPaC v1.0 www.cse.anl.gov/BatPaC

Conclusions / Discussion

- Current vehicle **batteries** appear to be capable of supplying **some** scenarios of V2G power.
- Battery thermal management & high/low SOC lithium plating longevity effects will significantly reduce the “real-world” capability of V2G enabled PEVs.
- Numerous communication standards are being developed to facilitate the effective communication and integration of grid connected vehicles.
- Increasing the power transfer capacity of vehicles for V2G will escalate infrastructure and per vehicle cost.
- V2G does not appear to be a plug-in vehicle market pull factor and requires long term RD+D.
- Though not always directly related, ANL is performing research in many areas associated with V2G, ranging from vehicle assessment to standards development.

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