Supercapacitors for Micro-Hybrid Automotive Applications

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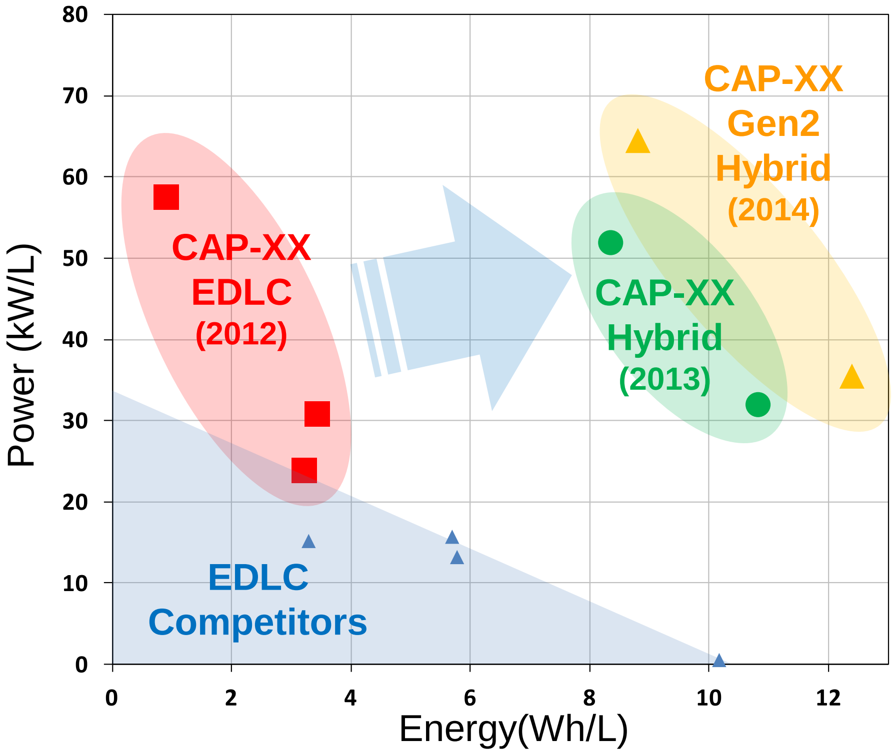
About CAP-XX

- World leader in high power energy storage devices (supercapacitors) for consumer and industrial electronics, cleantech and automotive markets
- More than 8m devices sold globally
- Unique technology, with 19+ patent families
- Technology validated by and licensed to Murata – Murata now in mass production
- Next generation of products - SMD and Large Format Supercapacitors for automotive and other markets - validated by test results and ready for licensing

The CAP-XX Advantage

- World's highest power large supercapacitors for automotive
  - ➢ Low ESR, high voltage, 1400 F
- Next generation: High energy, high power, long life hybrid cells
  - ➢ 3400 F per cell
  - ➢ Low BoM of US$0.002 per Farad
  - ➢ Over 1 million cycles
- Prismatic soft-packaging for easy, low cost cell manufacture
  - ➢ Thin, compact cells
  - ➢ Layered electrodes for modularity and high performance
- Environmentally friendly, simple manufacturing technology
  - ➢ Similar to lithium-ion
- Established development pipeline



What is a Micro-Hybrid?

A Micro-Hybrid vehicle is defined here as having:

- a drivetrain powered by an internal combustion engine (no electric drive)
- a Stop-Start system to reduce fuel consumption and emissions
- a Kinetic Energy Recovery System to capture energy generated during braking and coasting (typically 250A at 14V for 10 sec, ≈ 3.5kW for 10 sec = 35kJ, ≈ 10Wh per event)
- an electrical system optimised to store the recaptured energy and return it to the vehicle's on-board voltage network to reduce the load placed on the engine by the starter-generator

Combining a Supercapacitor and a Battery

- Existing automotive batteries are not able to support all these functions in a Micro-Hybrid vehicle
- High performance batteries may overcome some of these issues, but at a higher cost / risk
- A Supercapacitor / Battery combination will:
  - Accept the charge from regenerative braking
  - Crank the engine for the Stop-Start function
    - More than 50 times/day if necessary, and
    - Keep the on-board 12V network above its minimum threshold voltage so that driver experience and vehicle safety systems are not compromised
  - Support all “hotel” loads while the engine is off
  - Offer a longer operational life than a battery alone

DCA is the rate at which a battery can be recharged

CAP-XX testing has shown:

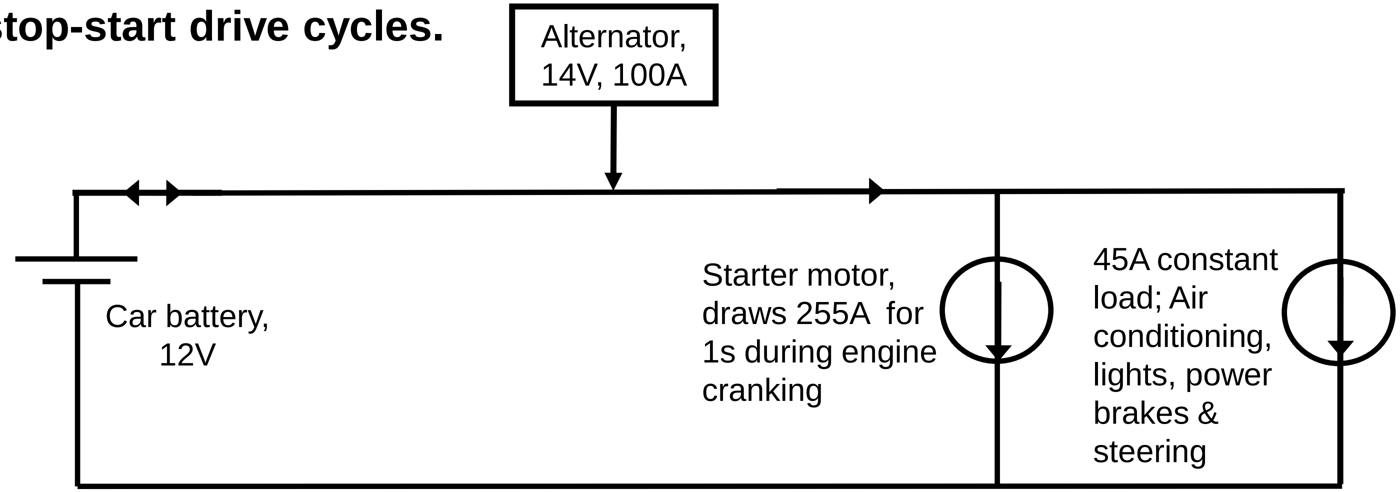
- If supercapacitor supplies all the cranking current, battery life is more than doubled
- But declining Dynamic Charge Acceptance (DCA) means that even if the battery only supplies the accessory (or "hotel") loads it will still will die unexpectedly

Ideally the supercapacitor cranks the engine and manages most of the hotel loads

CAP-XX Stop-Start Test System

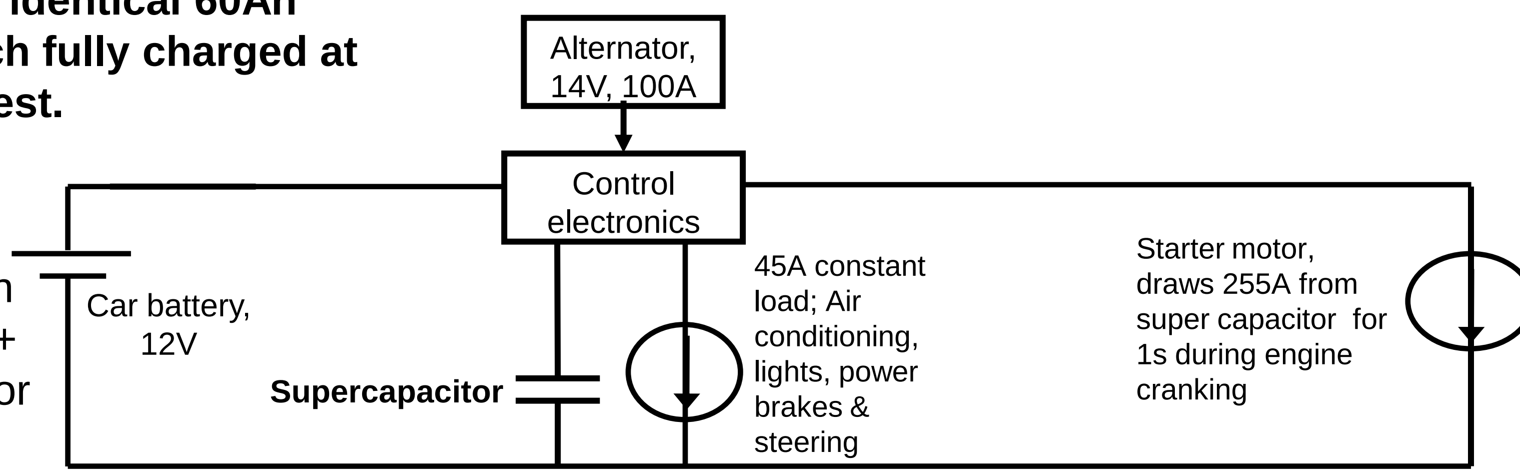
Test systems for stop-start drive cycles.

Configuration with Battery alone



The tests were done with two separate but identical 60Ah batteries each fully charged at the start of test.

Configuration with Battery + Supercapacitor



The Supercapacitor Module

- **Module: 230F, 3mΩ, 15V**

- 6 x 1400F cells, 0.21mΩ each
- L x W x H: 195 x 130 x 9.4mm
- L x W x H: 222 x 147 x 75mm
- 1.7Kg
- Peak current > 1500A (single pulse)
- Active balance circuit inside
- Leakage current < 2mA
  (supercapacitor can maintain charge for a couple of days)

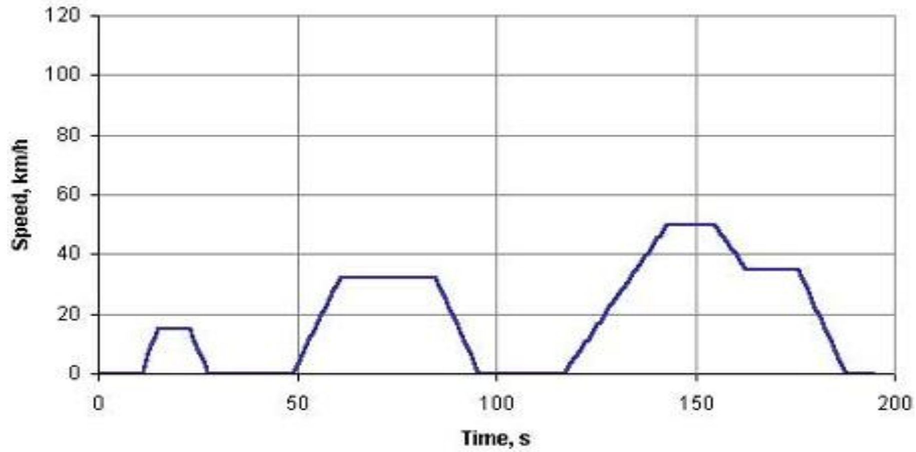
Stop-Start Test Results

- In all tests, end of battery life is defined as system voltage falling below 7.2V during cold cranking or 10V during a Stop-Start cycle

1. **New European Drive Cycle (ADR79) at 23ºC:**
   - **Battery alone - Failed after 44,000 starts**
   - **Battery + Supercapacitor – Ran for 120,000 starts**
2. **Japanese Battery Charge Acceptance Test at 23ºC:**
   - **Battery alone - Failed after 981 starts**
   - **Battery + Supercapacitor - Ran for 9,553 starts**
3. **Modified New European Drive Cycle (ADR79) at -18ºC:**
   - **Battery alone - Failed after 1 Stop-Start cycle at 10V/ failed after 4th cold start**
   - **Battery + Supercapacitor – Failed after 4500 Stop-Start cycle at 10V/ failed after 17th cold start**
4. **NEDC (ADR79) Light Commercail Diesel Vehicle at 23^{0}C:**
   - **3.4% fuel saving; 21% faster starting; battery voltage > 12V**

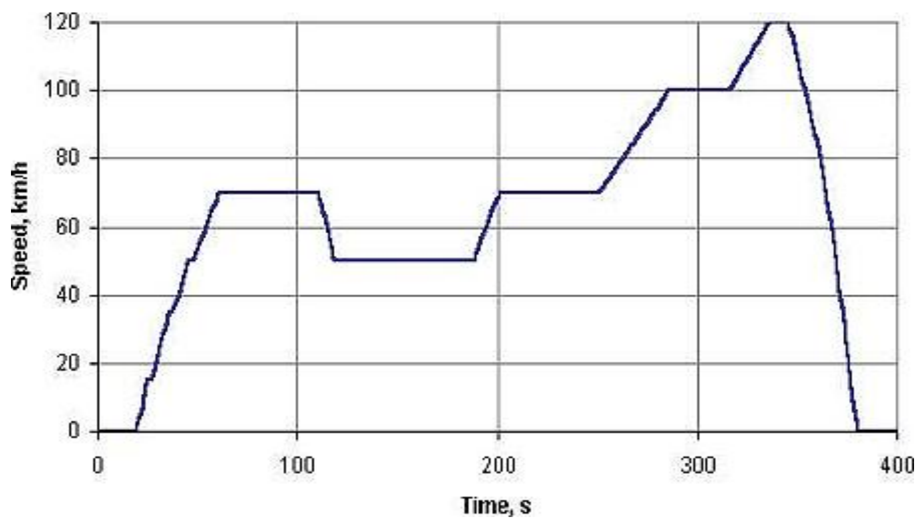
New European Drive Cycle: ADR 79 - A Standard Automotive Test

Repeat this urban cycle 4 times ...

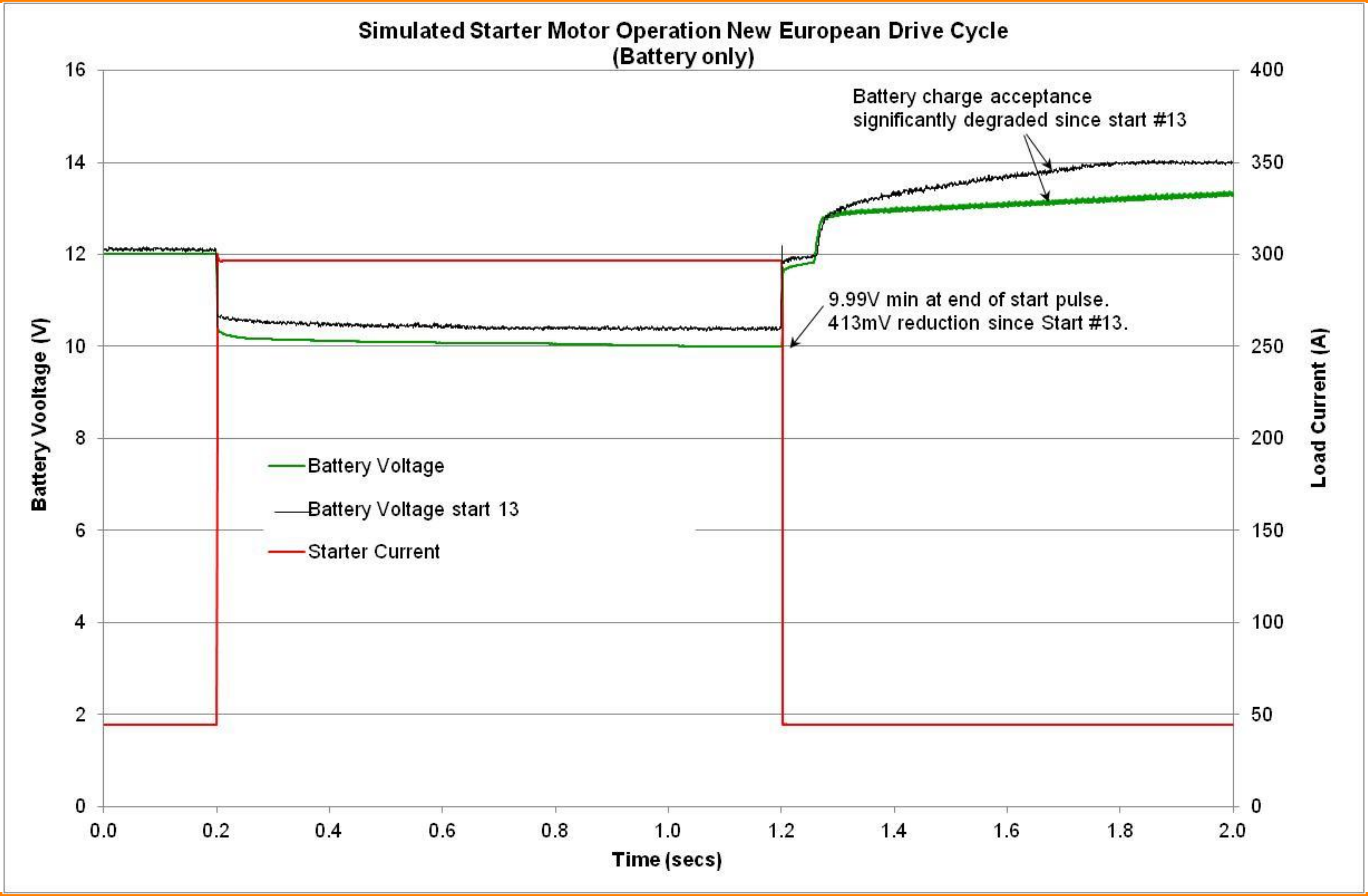


... then do this highway cycle once.

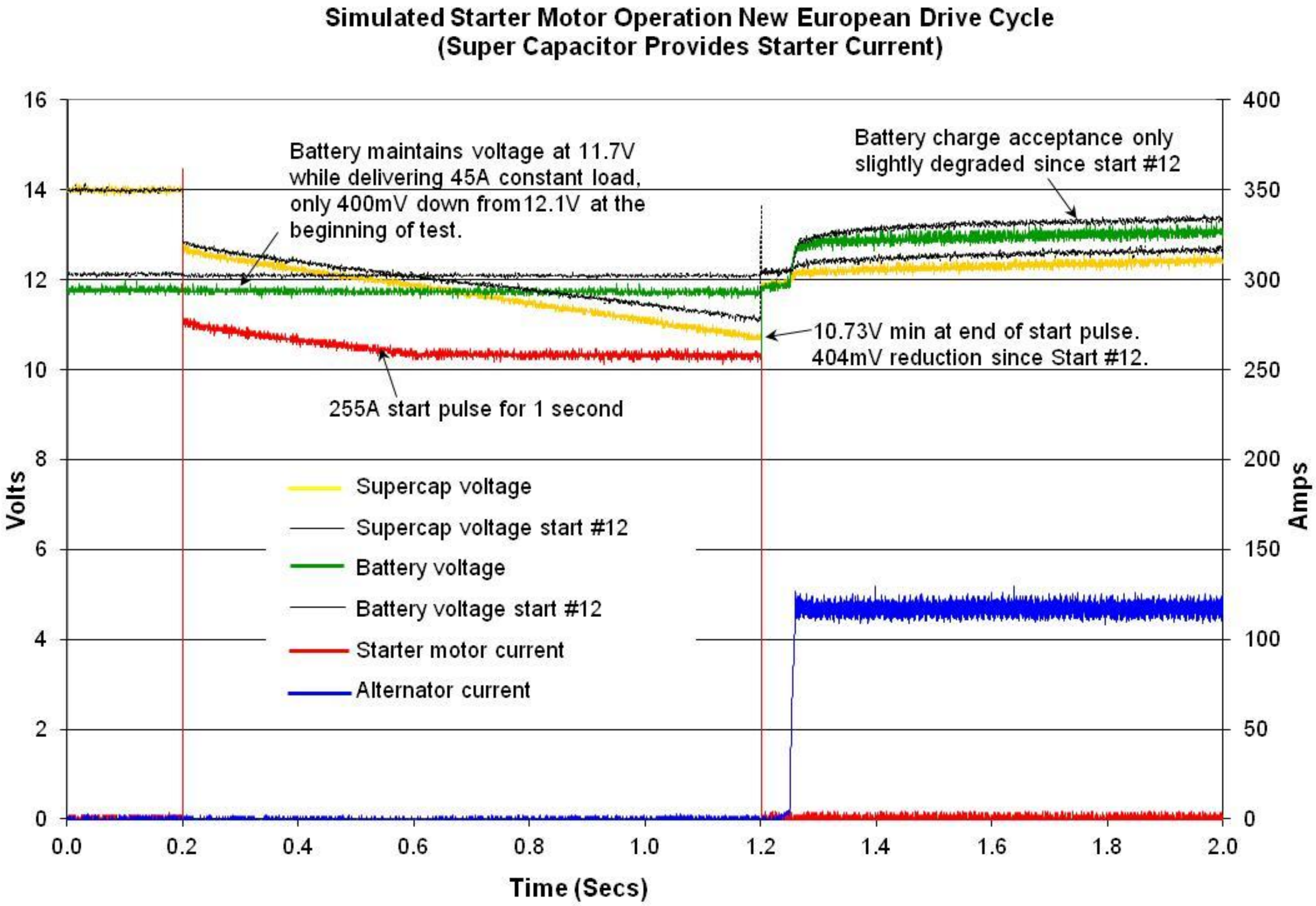
Repeat until battery voltage <7.2V (total failure) or <10V (functional failure)



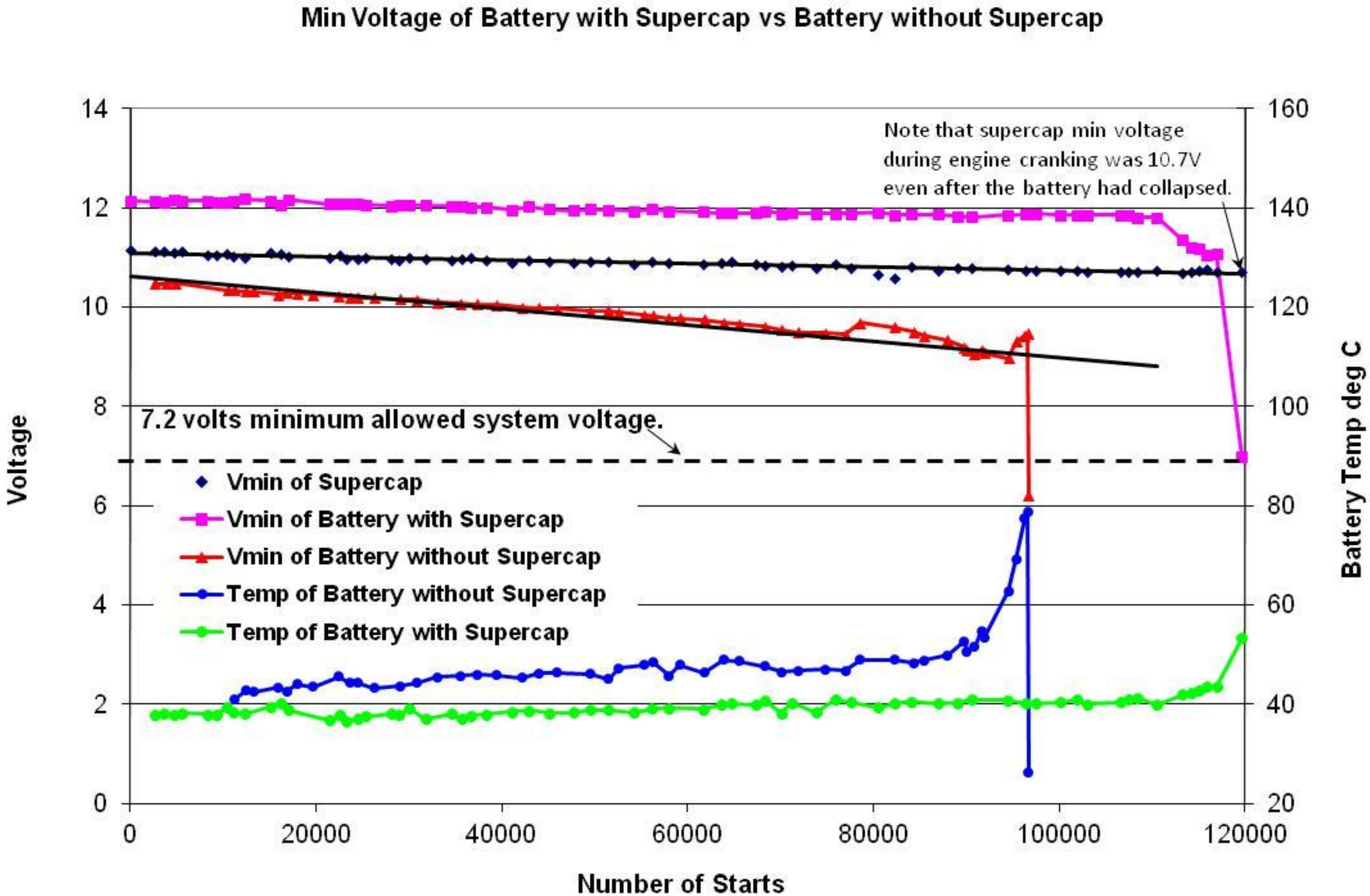
New European Drive Cycle: Battery alone; 44,000 starts



New European Drive Cycle: Battery + Supercapacitor; 110,000 starts



NEDC: Battery Voltage & Battery Temperature



Key Learnings

- Batteries fail suddenly and without warning
- If a Supercapacitor is used for cranking then battery life is more than doubled
- ... but the battery still fails suddenly due to declining Dynamic Charge Acceptance (DCA), even though a 100A, 14V supply is available to re-charge the battery
- The solution is a Supercapacitor combined with a much smaller battery

Combining a Supercapacitor and a Battery: Strengths & Weaknesses

Lead Acid battery	Supercapacitor	Lithium ion Battery
Limited cycle life	"Unlimited" cycle life	Good cycle life
Good low temp discharge performance	Excellent low temp discharge performance	Very limited low temp performance
Limited charge acceptance	Excellent charge acceptance	Very good charge acceptance
Medium energy density at low $/kWh	Low energy density at high $/kWh	High energy density at high $/kWh
Low power density at medium $/kW	Excellent power density at low $/kW	Medium power density at high $/kW

Combining a Supercapacitor and a Battery: Strengths & Weaknesses

Lead Acid battery	Supercapacitor	Lithium ion Battery
The requirements can be met by combining a supercapacitor and a small battery (~5-10Ah) which could be either Li-Ion or Pb Acid, the choice depending on the desired size, weight & cost of the battery	"Unlimited" cycle life	
	Excellent low temp discharge performance	
	Excellent charge acceptance	
Medium energy density at low $/kWh	Low energy density at high $/kWh	High energy density at high $/kWh
	Excellent power density at low $/kW	

Sizing the Supercapacitor + Battery

- Run supercapacitor at a partial state of charge:
  - Enough head room to accept regenerative energy recovery
  - High enough voltage to be above minimum cranking voltage during engine start
  - Supplies engine off accessory loads for most short stops during stop-start cycles
  - High enough C to capture energy from regenerative braking
  - Low enough ESR to accept power from regenerative braking and deliver power to crank engine
- Battery to provide energy for accessory loads during longer stops
- Battery keeps supercapacitor at voltage (replenish leakage current) if car parked for 1 month or more

Sizing the Supercapacitor + Battery

Charge Voltage	14	V	C required to absorb regenerative braking energy ②	667	F	=Icharge x duration/(Vcharge - Vmin - ESR x Icharge)
Min Voltage to support off engine accessory loads	10.5	V	Module ESR ①	2.5	mΩ	
Min Voltage during engine cranking	7.2	V	Module C ③	680	F	5 x 3400F cells in series
Charge current from starter-gen during regenerative braking	200	A				
Charge current duration during regenerative braking	10	s	Check time supercap supports regen energy capture ④	10.2	s	=(Vcharge - Vmin - ESR x Icharge) x C/Icharge
Peak Cranking Current	500	A				
Peak Cranking Current duration	0.1	s	Min V during peak cranking current ⑤	9.18	V	=Vmin - Ipeak_crank x (ESR + duration/C)
Cranking current	200	A				
Cranking current duration	0.9	s	Min V at end of cranking ⑥	9.66	V	=Vmin - Ipeak_crank x duration_peak_crank/C - Icrank x (ESR +duration_crank/C)
Engine off accessory (or hotel) load during Stop-Start cycle	60	A				
Stop duration during Stop-Start cycle	120	s	Duration of supercapacitor support of accessory loads before battery takes over ⑦	41.4	s	= (Vcharge - Vmin + iaccessoryxESR) x C/Iaccessory. **Longest stop time in NEDC = 25s**
Battery energy for stop cycle ⑧	1.31	Ah				=Iaccessory x (Stop duration - duration of supercapacitor support)/3600
Battery energy for 1 month support of supercapacitor ⑨	3.6	Ah	Supercapacitor leakage current (incl balancing circuit)	5	mA	
Nominal Battery Energy ⑩	10	Ah				> max(1.28Ah, 3.6Ah)
Max time to support full accessory load (battery + supercapacitor) ⑪	641.4	s				Assuming 10Ah battery. EMS can turn engine on for extended stops > 10mins.

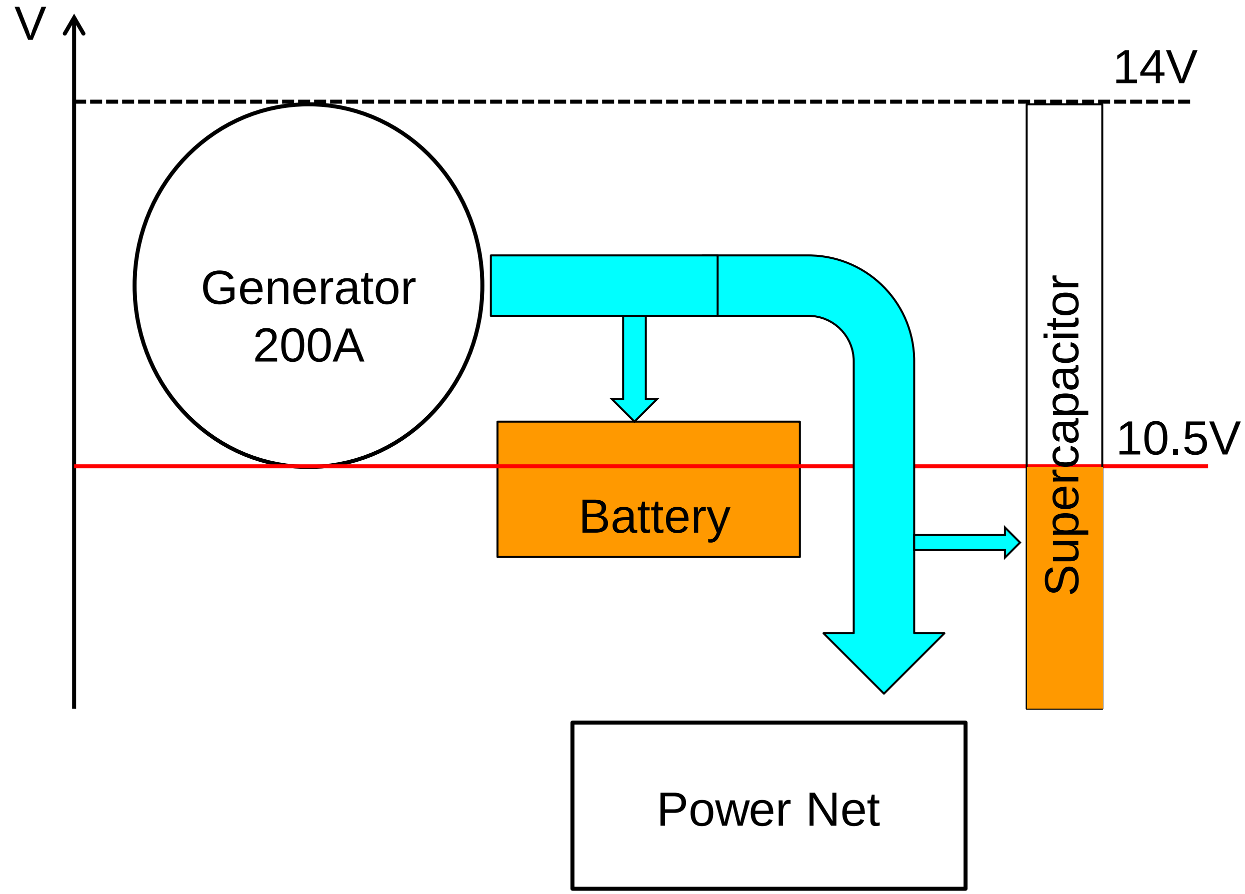
Specifications & Requirements

The Supercapacitor / Battery combination:

- Must have excellent charge acceptance (200A for 10 secs ~2.8KW for up to ~ 40K/p.a. Stop-Start cycles)
- Must have excellent discharge performance (to start the vehicle ~40K times/p.a. In Stop-Start mode)
- Must be able to start the car in northern winters
- Must offer 43Wh of energy storage. At nominal 12V this is only 3.6Ah – much smaller than today's typical car battery
- Selected 10Ah battery (120Wh) to allow extended stops
- Supercapacitor alone can support 60A hotel loads for up to 43s, >> 25s longest stop in NEDC. **For most stops in the Stop-Start cycle, the battery does nothing.**
- **This greatly reduces the charge acceptance problem.**

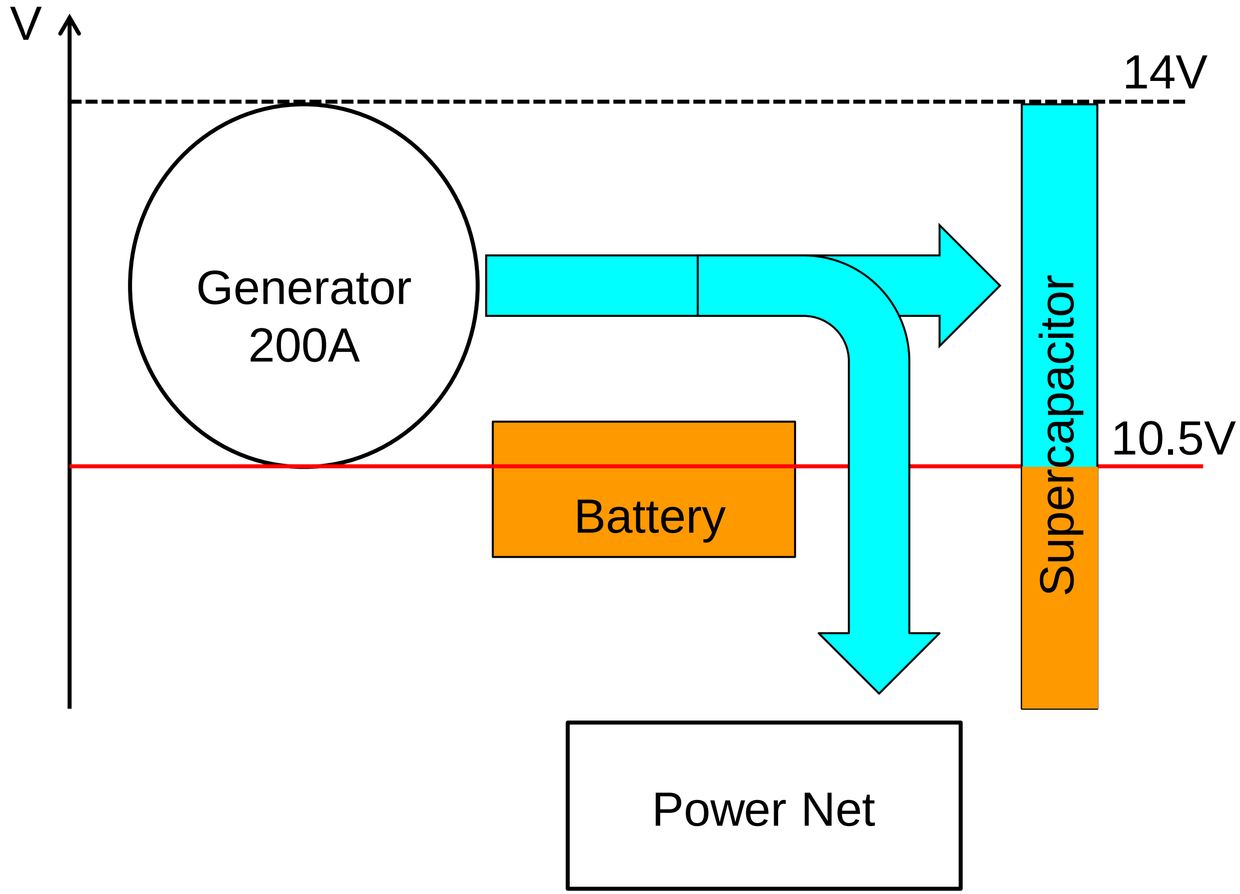
Engine running

The Supercapacitor module is kept at a partial state of charge (10.5V) during normal running



Regenerative braking

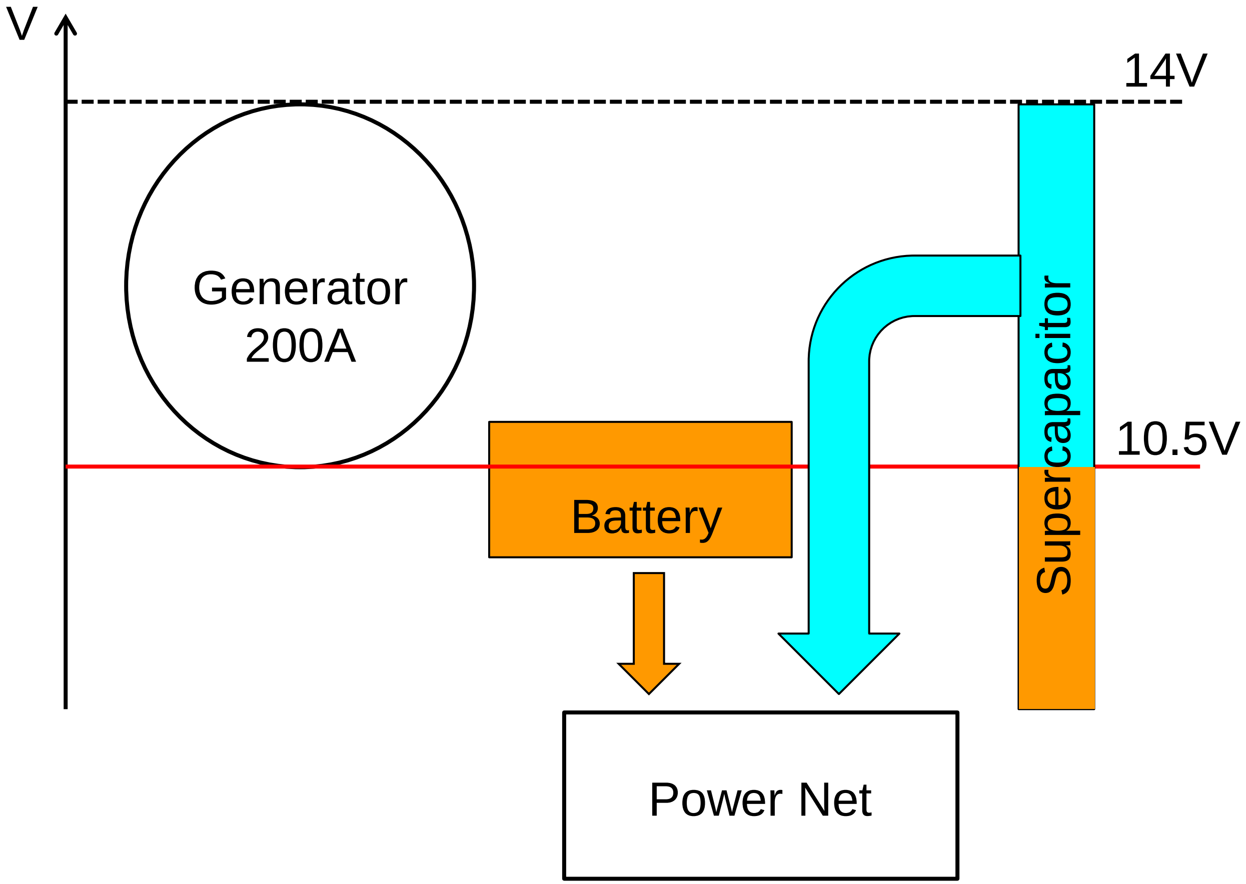
During regenerative braking, the Supercapacitor module accepts the 200A KERS current for 10 sec, and is charged up to its maximum voltage of 14V



Engine Stopped (Stop-Start)

At engine stop, the supercapacitor is fully charged from energy recaptured during braking

The module supports all hotel loads (~60A) for 30-40 sec while the engine is off, discharging to 10.5V (The battery takes over if the engine is off for longer periods)



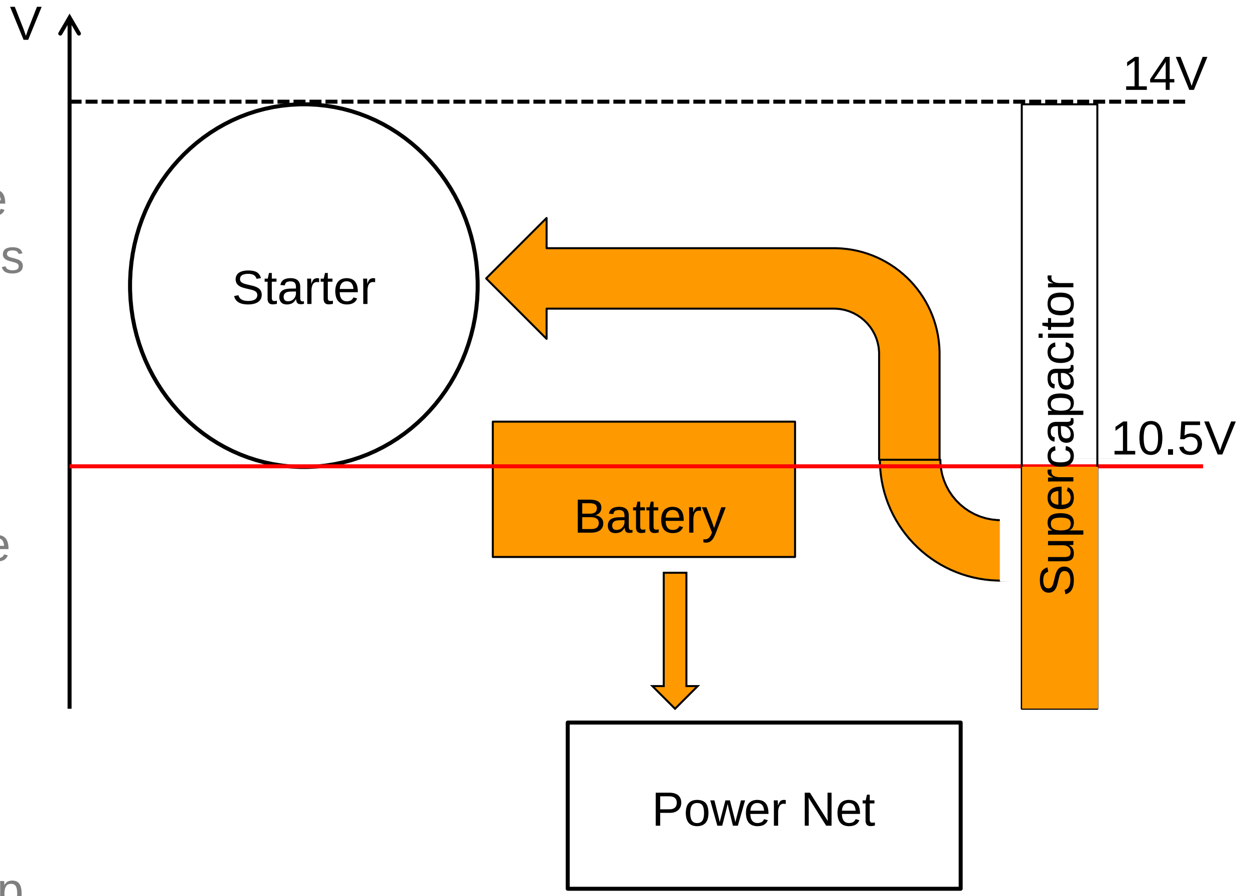
For many short stops, the battery will not have to provide any current, greatly reducing the charge acceptance required

Engine cranking (Stop-Start)

When the engine re-starts, the supercapacitor module is still at 10.5V, which is sufficient to crank the engine

The supercapacitor module supplies all the cranking current

The battery supports the on-board network during cranking, so there is no voltage drop and no loss of function



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