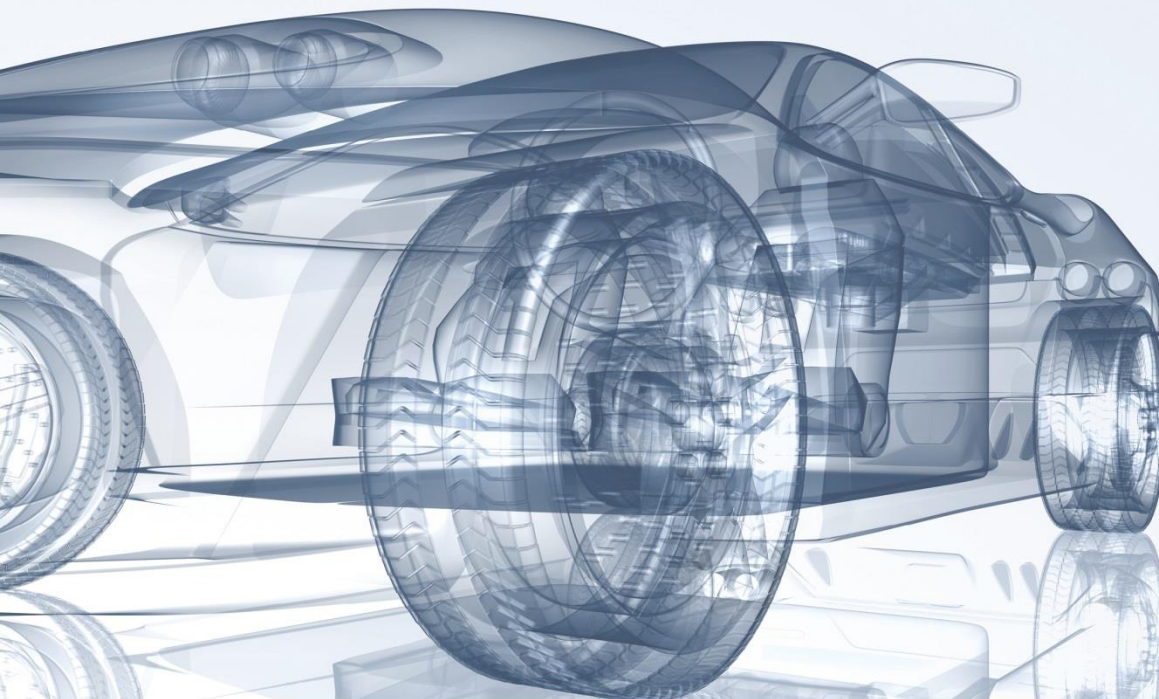


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Vehicle Level Control Analysis for Voltec Powertrain

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The main objective of this study is to understand and model the vehicle level control strategies of 2016 Chevrolet Volt through vehicle dynamometer test data analysis

- Vehicle Thermal Management Systems (VTMS) developed over many years:
 - Conventional Vehicle – Ford Fusion, HMC Sonata
 - Extended Range Electric Vehicles (E-REV) – GM Volt 1st generation, Honda PHEV, **GM Volt 2nd generation**
 - Hybrid Electric Vehicles (HEV) – Toyota Prius Hybrid, Honda Civic Hybrid
 - Battery Electric Vehicles (BEV) – Ford Focus BEV
 - Plug-In HEVs (PHEV) – Toyota Prius Plug-in Hybrid
- Quantify the new Voltec system improvements by comparing its system efficiency with the previous version
- Analyzed control behavior and performance under normal ambient temperature.

Approach

Dynamometer test data



°C

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21

35

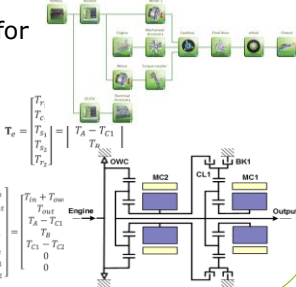
Plant model development

dynamic equations for transmission

$$\begin{bmatrix} 1 & C_1^T \\ C_0 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ \lambda \end{bmatrix} = \begin{bmatrix} T_r \\ 0 \end{bmatrix}$$

or for a Linear Time Invariant (LTI) system

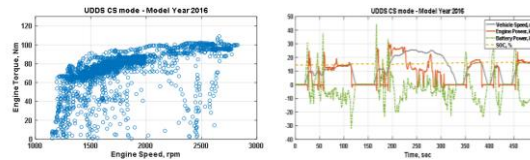
$$\begin{bmatrix} I_m & 0 & 0 & 0 & 0 & -R_2 & 0 \\ 0 & I_{out} & 0 & 0 & 0 & 1 + R_1 & 1 + R_2 \\ 0 & 0 & I_p & 0 & 0 & -1 & -1 \\ 0 & 0 & 0 & I_b & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & I_{c2} & 0 & 0 \\ -R_1 & 1 + R_1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 + R_2 & 0 & -1 & -R_2 & 0 & 0 \end{bmatrix} \begin{bmatrix} \theta_m \\ \theta_{out} \\ \theta_p \\ \theta_b \\ \theta_{c2} \\ \lambda_{11} \\ \lambda_{12} \end{bmatrix} = \begin{bmatrix} T_m + T_{in} \\ T_m - T_{c1} \\ T_m - T_{c2} \\ T_m - T_{c2} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$



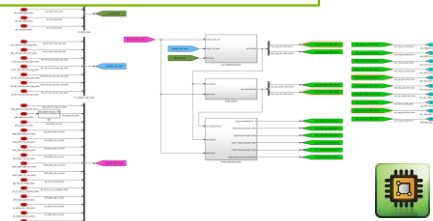
Test data

Control analysis

engine operation, mode selection, power management, thermal impact, ..



Controller development

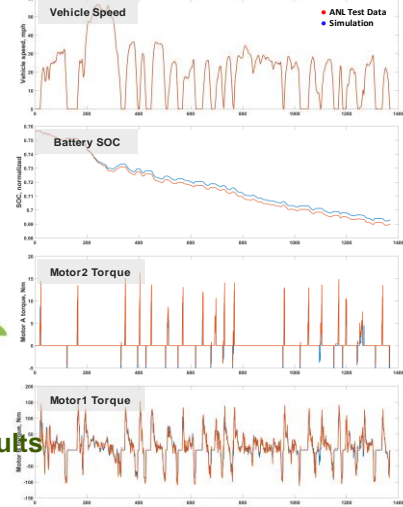


Simulation results

Model validation

compare test data with simulation results

Normal Temp. (UDDS CD)



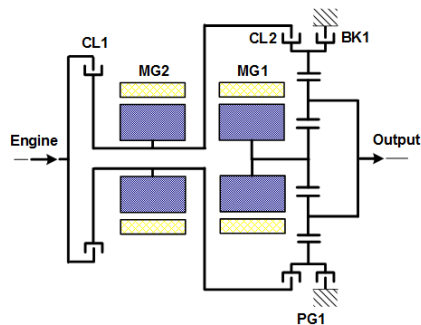
Vehicle System Configuration - vs. VOLT Generation1

Voltec Gen2 Propulsion System

- Differences between Gen1 (2011 Volt) and Gen2 (2016 Volt)



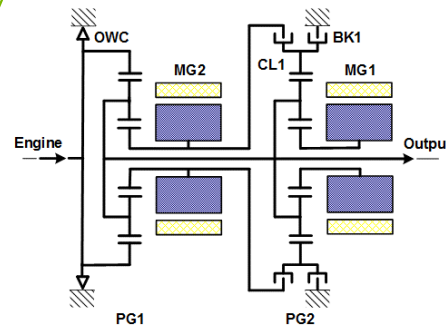
Voltec Gen1



| Mode | BK1 | CL1 | CL2 |
|--------------------|--------|--------|--------|
| EV1 | closed | open | open |
| EV2 | open | open | closed |
| Series | closed | closed | open |
| Output power split | open | closed | closed |

| Components | Spec. |
|---------------|-------------------------|
| Engine | 1.4L, 63kW |
| Battery | Li-Ion, 16.5kWhr, 110kW |
| Motor 1 (MG1) | 111kW |
| Motor 2 (MG2) | 55kW |
| PG ratio | 3.24 |
| Final drive | 2.16 |

Voltec Gen2



| Mode | BK1 | CL1 | OWC |
|---------------------|--------|--------|--------|
| EV1 | closed | open | open |
| EV2 | closed | open | closed |
| Low extended range | closed | open | open |
| Fixed ratio | closed | closed | open |
| High extended range | open | closed | open |

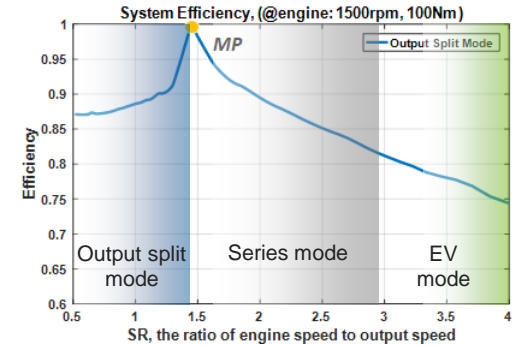
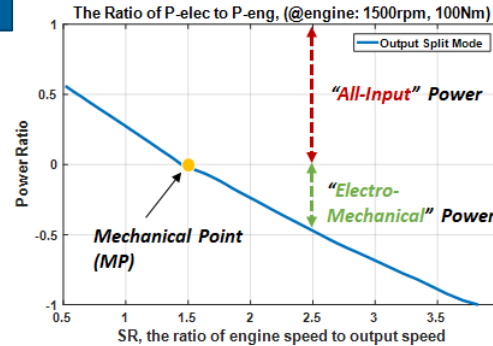
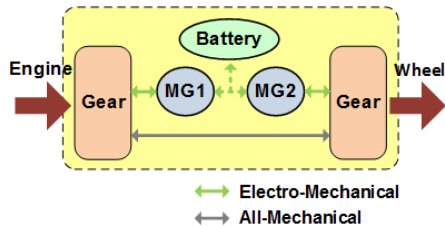
| Components | Spec. |
|---------------|-------------------------|
| Engine | 1.5L, 75kW |
| Battery | Li-Ion, 18.4kWhr, 120kW |
| Motor 1 (MG1) | 87kW |
| Motor 2 (MG2) | 48kW |
| PGs ratio | 2.87, 3.08 |
| Final drive | 2.64 |

Voltec Gen2 Propulsion System

- System efficiency (CS mode) for Gen1 and Gen2

Voltec Gen1

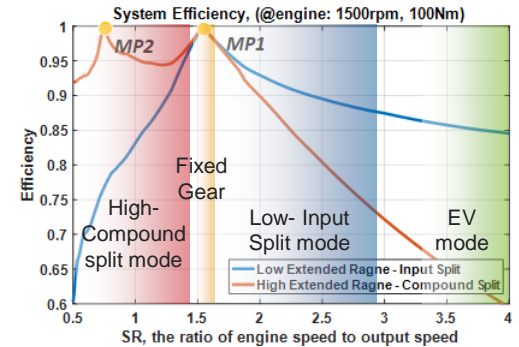
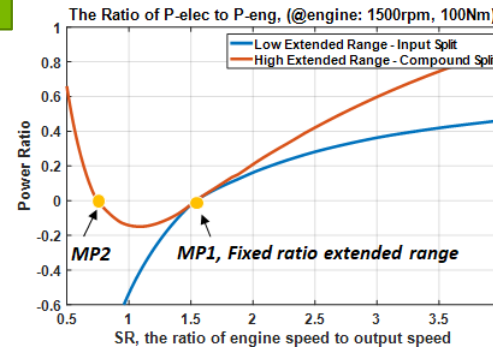
An power-split system uses differential gearing to split power into two paths:



Voltec Gen2

Note :
Power ratio = electro-mechanical power / all-input power

Small absolute values mean little power-conversion, higher efficiencies.
So, the objective is to minimize the power ratio, to minimize recirculation

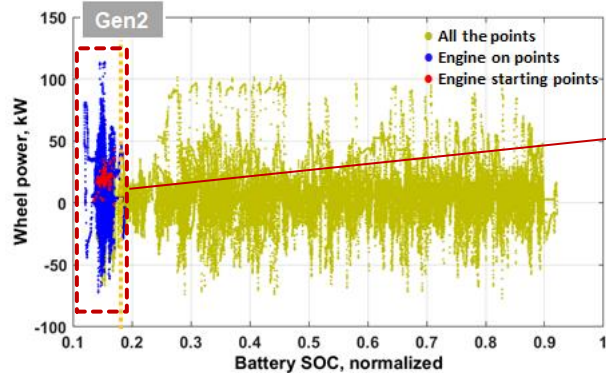
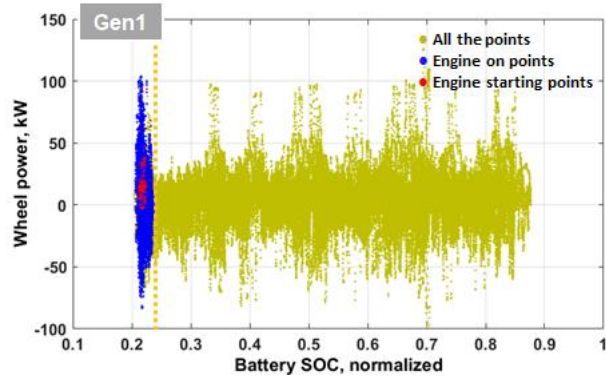


Vehicle Testing Analysis (under normal temp.)

- **Engine On/Off control**
- **Driving mode control**
- **Power management control**

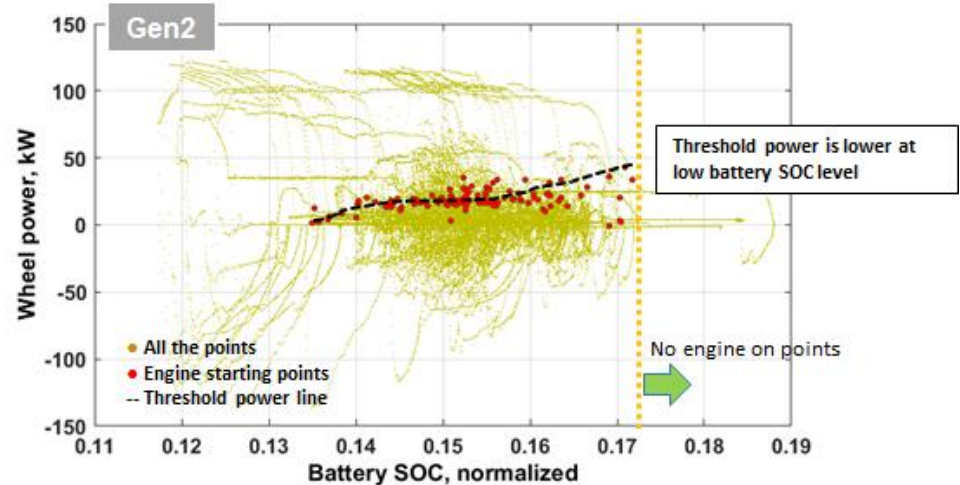
Engine Turning On Control

- Engine starts when wheel power > threshold power



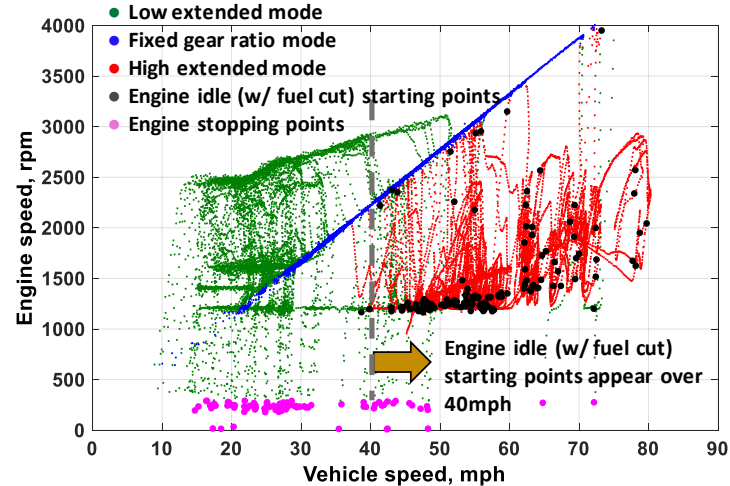
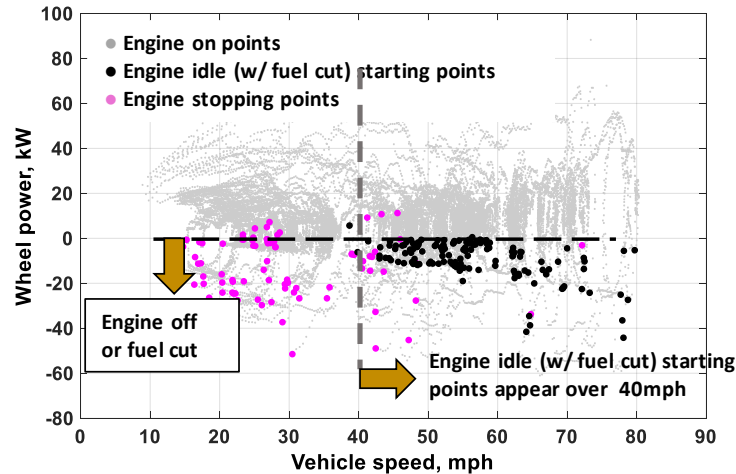
No engine on points over threshold battery SOC for both Gen1 & 2
Not only has the battery pack energy in the second generation pack increased by 12%, but the operating range of battery SOC also has been expanded.

The engine on threshold power is a function of battery SOC.



Engine Turning Off Control

- Engine idles (w/ fuel cutoff) when vehicle speed > 40mph



The engine is always turned off when the wheel power is negative

Staying on idle speed with no fuel if the vehicle speed is higher than about 40 mph

The engine idling (w/ fuel cutoff) occurs mostly in the fixed gear ratio and high extended modes

This control helps the engine become ready to be turned on rapidly during highway driving

Driving Mode Control

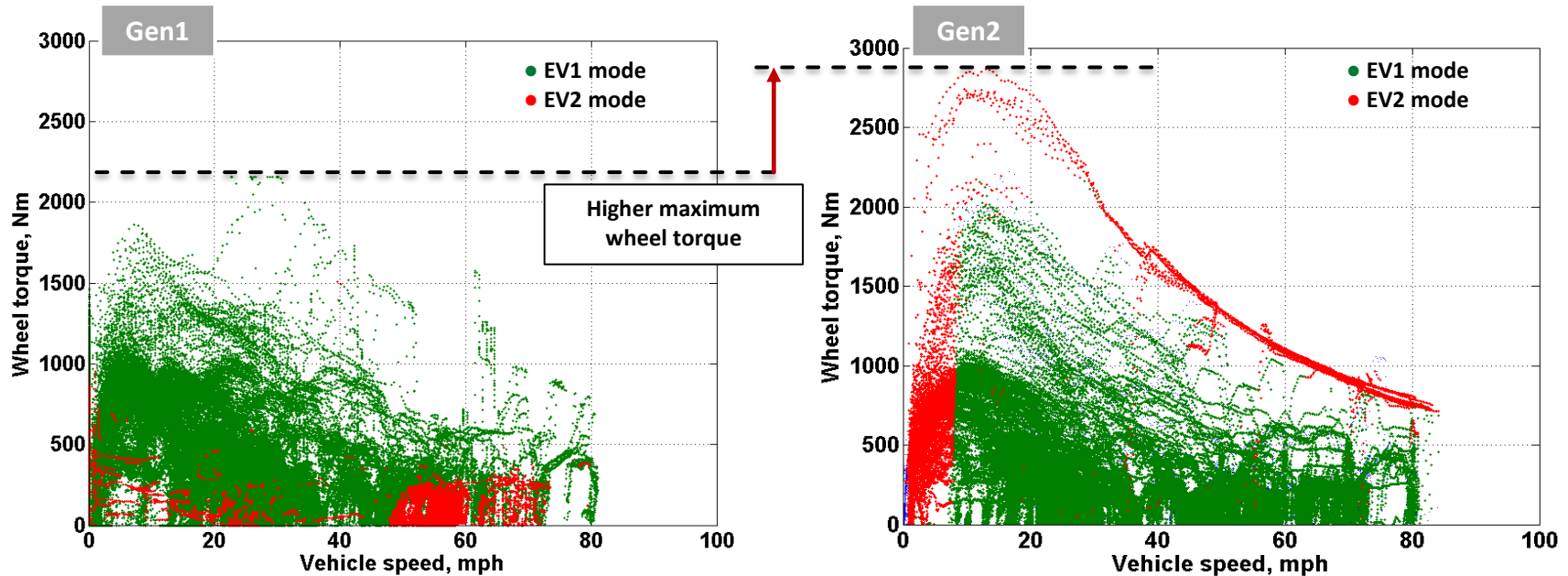
- EV driving mode control comparison: EV1 or EV2 mode

Different roll of EV2 mode

Gen1 starts with EV1 mode whereas Gen2 starts with EV2 mode

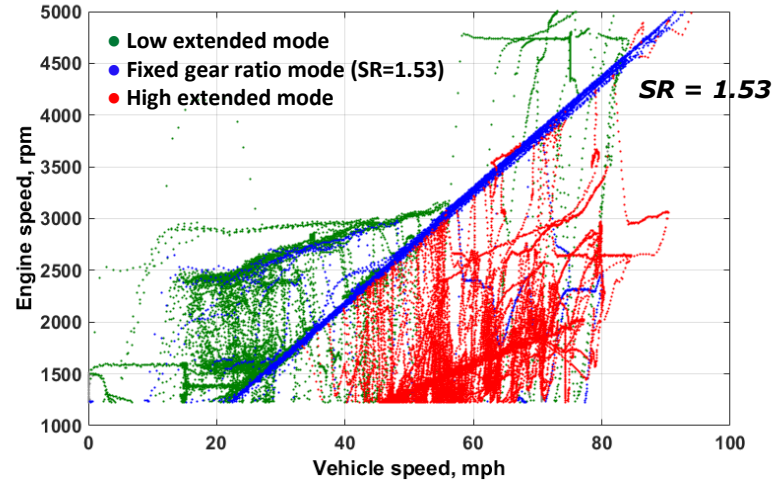
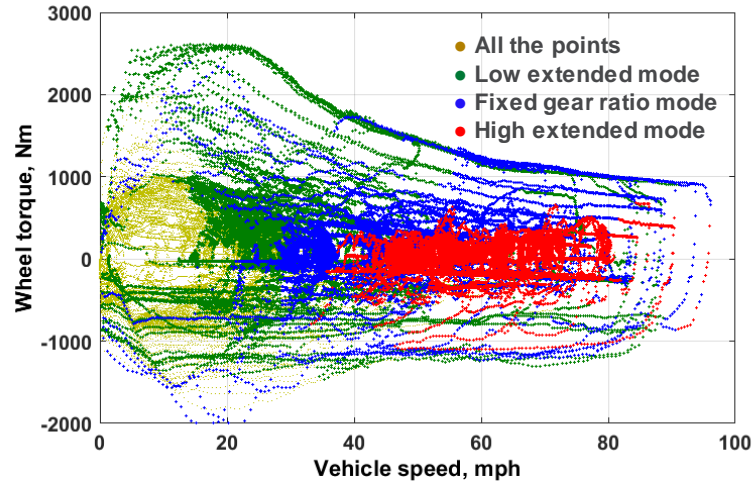
Mode transitions much easier in Gen2

Gen2 only need to generate torque of the motor 2, but Gen1 need to engage a clutch to change to EV2



Driving Mode Control

- Extended mode: vehicle speed & wheel torque determine modes

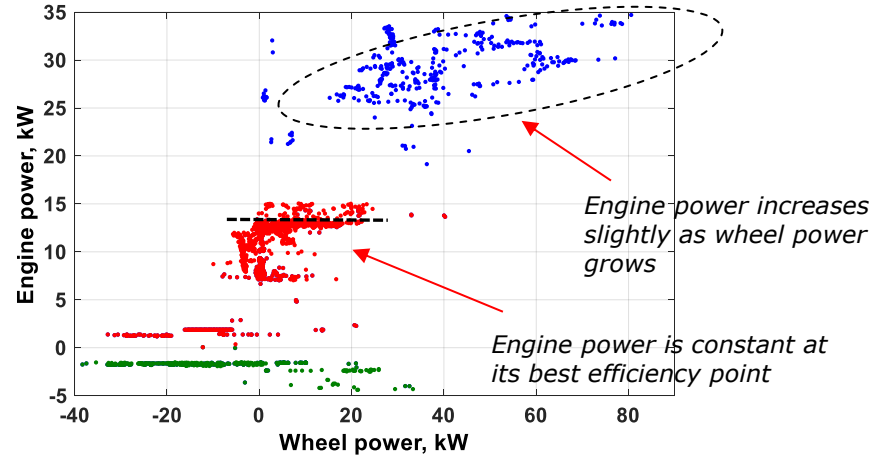
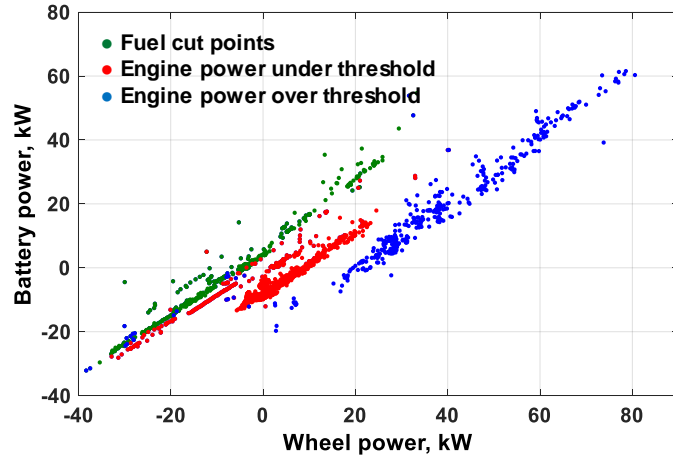


The fixed gear ratio mode supplements the low extended mode when the vehicle speed is over 30 mph
Fixed gear ratio mode appears in the transition area between the low and high extended modes

The fixed gear ratio mode (blue line) is used if the speed ratio is around 1.53,
which means that the system is changing from low extended mode to fixed gear ratio mode to avoid low system efficiency.

Power Management Control (low extended)

- Engine operating points are controlled in an appropriate range



Fuel cut: battery power covers all wheel power,

When the required driving power is lower than about 15 kW,

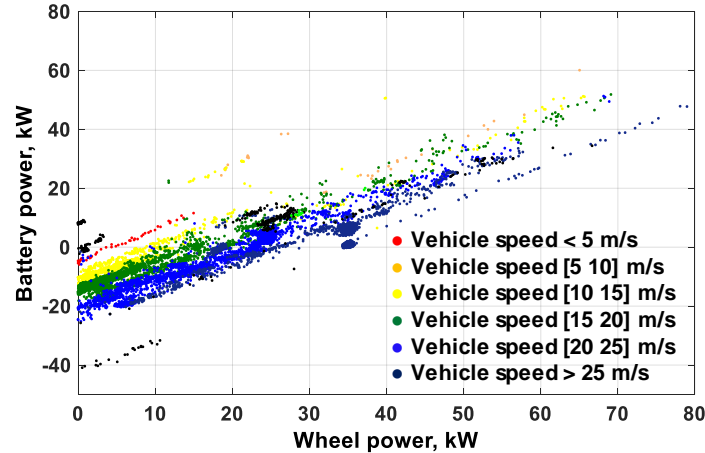
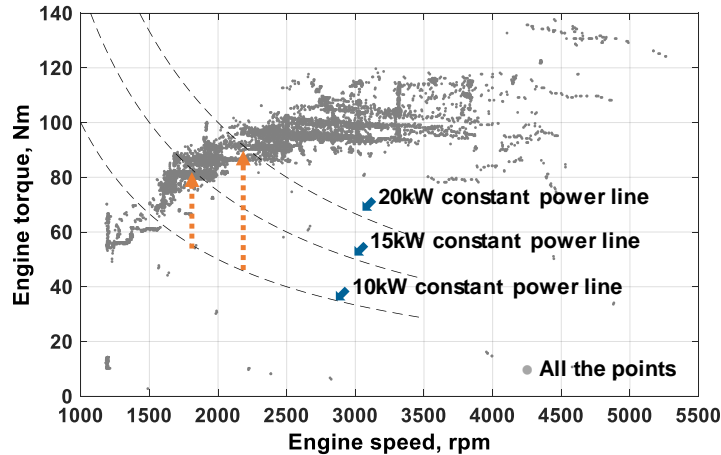
The engine operates on its best efficient area and keeps the power level steady.

When the required driving power is more than about 15 kW,

The engine power increases slightly as the wheel power increases within a narrow range

Power Management Control (fixed gear ratio)

- Engine load is adjusted by charging or discharging the battery to operate the engine efficiently



In fixed gear ratio mode, the engine speed depends on the vehicle speed linearly:

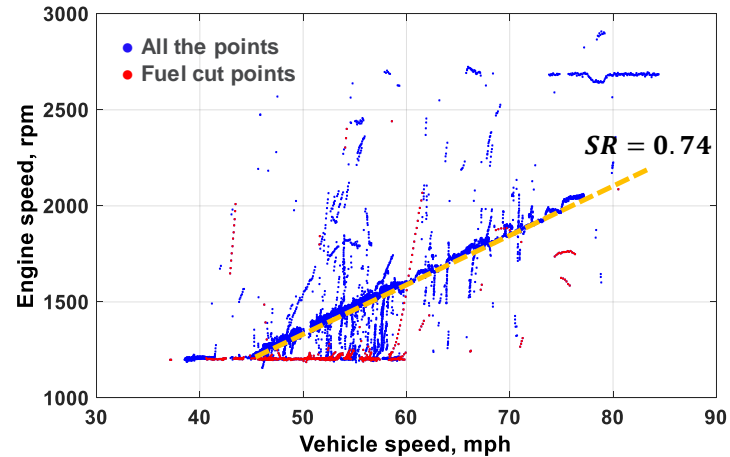
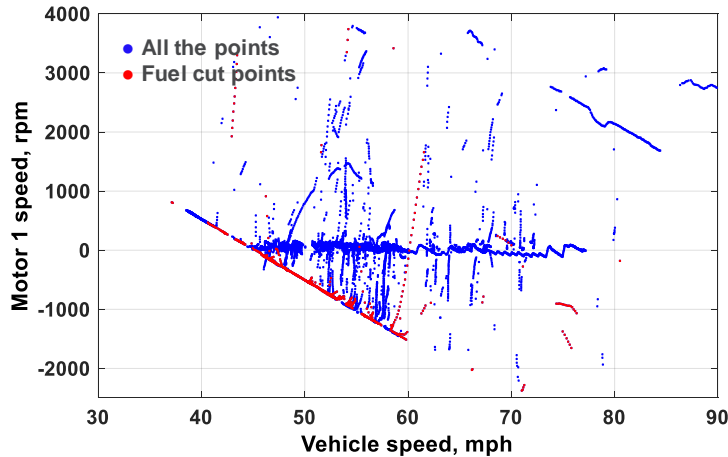
Engine torque is controlled at its best efficiency range by charging or discharging the high-voltage battery.

Battery power is proportional to the wheel power but has different gains according to vehicle speed,

The higher the vehicle or engine speed, the greater the amount of battery charging at light loads to trace the optimal target speed of the engine.

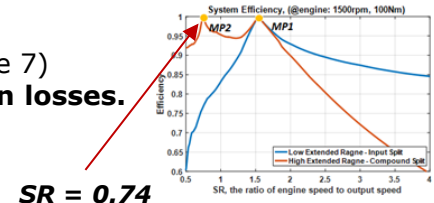
Power Management Control (high extended)

- Electric motor1 operates around zero speed to keep system on mechanical point



In high extended mode, engine speed can be determined arbitrarily without any relationship with vehicle speed:
However the electric machine1 operates around zero speed to keep the system on the second mechanical points (at speed ratio = 0.74).

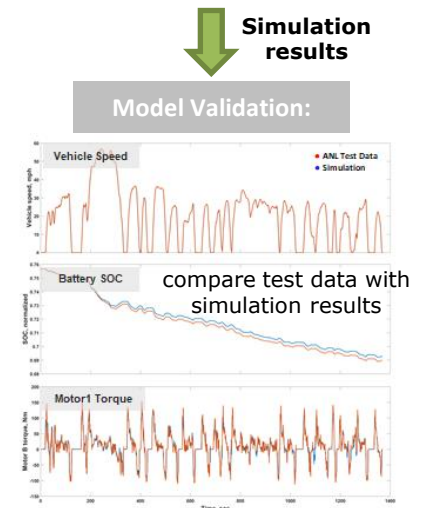
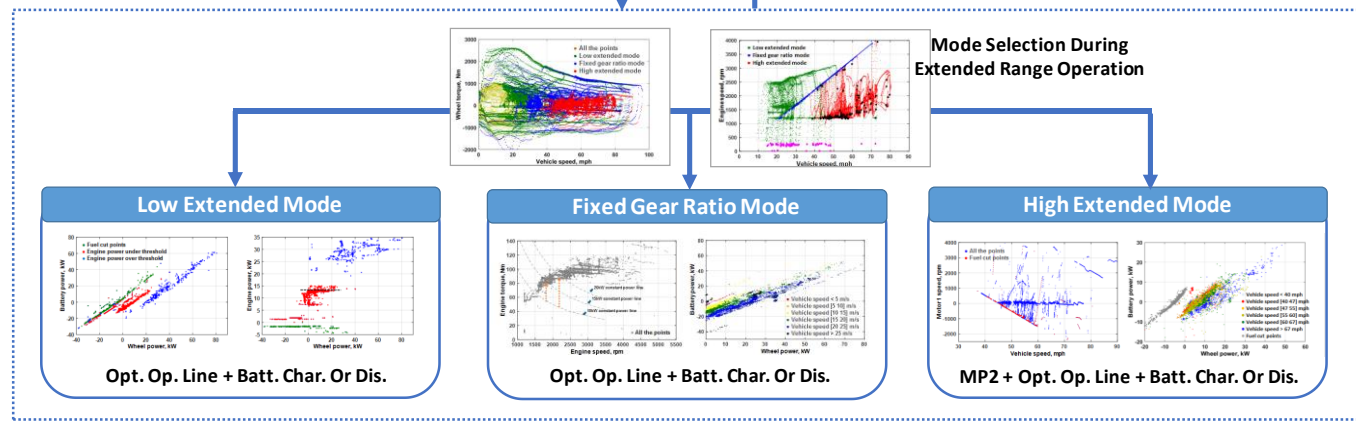
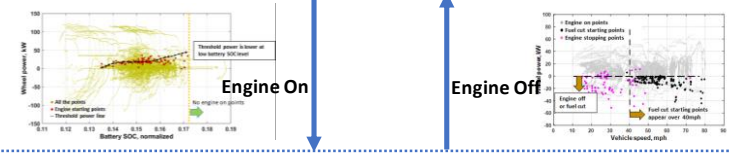
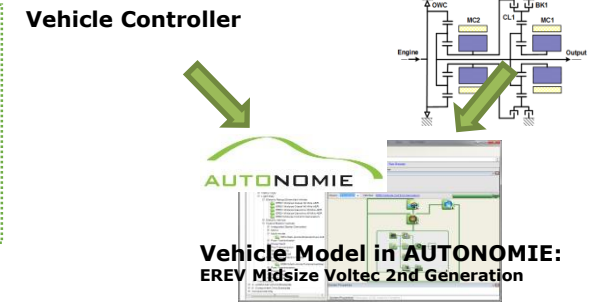
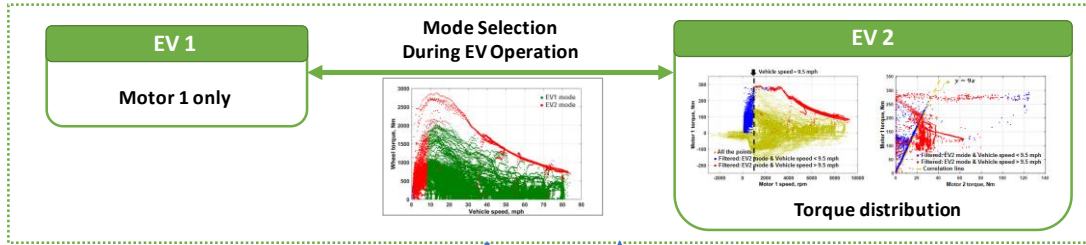
When the speed ratio is 0.74, the electro-mechanical power ratio becomes zero, (as shown in slide 7)
All the power can be transmitted through the mechanical part to avoid energy conversion losses.



$SR = 0.74$

Summary and Next Step

- Main control flow summarized
- Next: Validation under different ambient temperatures



Vehicle Level Control Analysis for Voltec Powertrain

Acknowledgements

Sponsored by David Anderson from the U.S. Department of Energy



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<http://www.autonomie.net/>

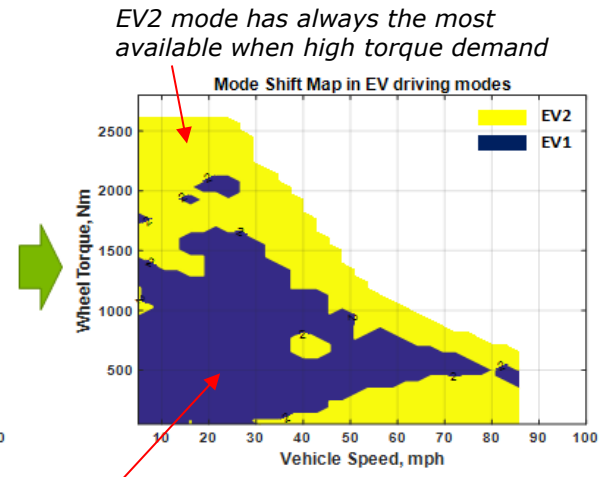
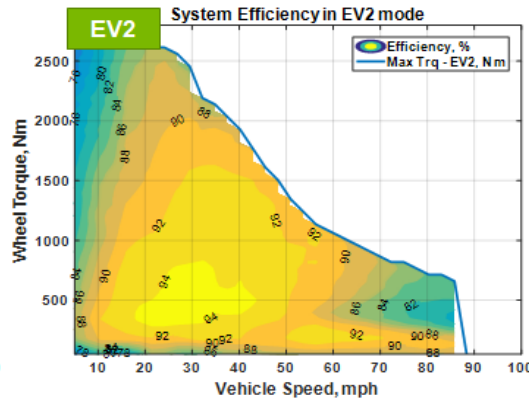
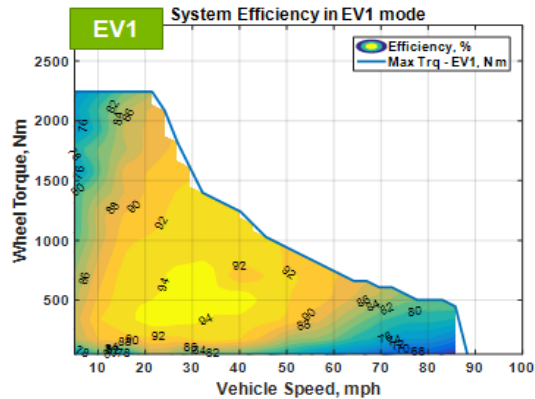
Argonne National Laboratory, 9700 South Cass, Argonne IL 60439, USA

Voltec Gen2 Propulsion System

- Mode shift strategy: for EV drive mode



- The simplified system efficiency for EV drive mode was calculated by using efficiency values of electric machines. The algorithm generates an optimal input speed and torque for each mode, indexed by gearbox output speed, battery power, and gearbox output torque.

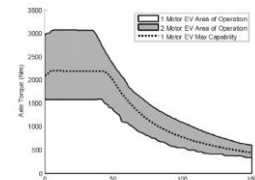


Efficiency/ Max Torque in EV modes

Motor1 (or + Motor2)

Battery only

Inserting the efficiency values of electric machines [S. Jurkovic, SAE 2015-01-1208]



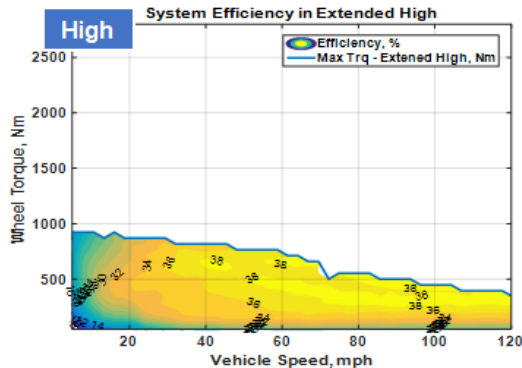
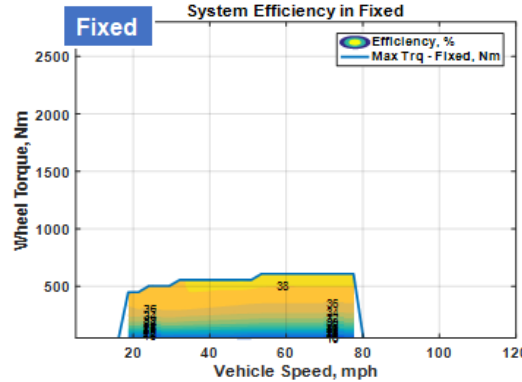
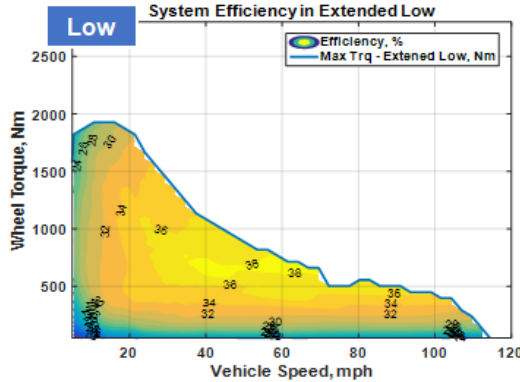
[B. Conlon, SAE 2015-01-1152]

Voltec Gen2 Propulsion System

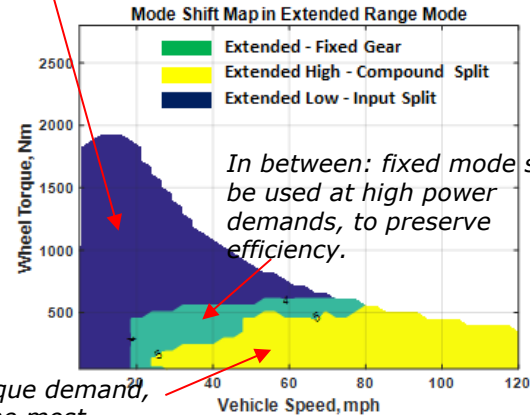
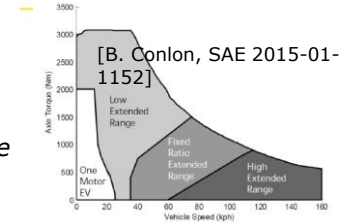
- Mode shift strategy: for extended drive mode



- Charge sustaining mode:



At low speed or high torque demand, low mode has always the most efficient.



In between: fixed mode shall be used at high power demands, to preserve efficiency.

At high speed or low torque demand, high mode has always the most efficient.

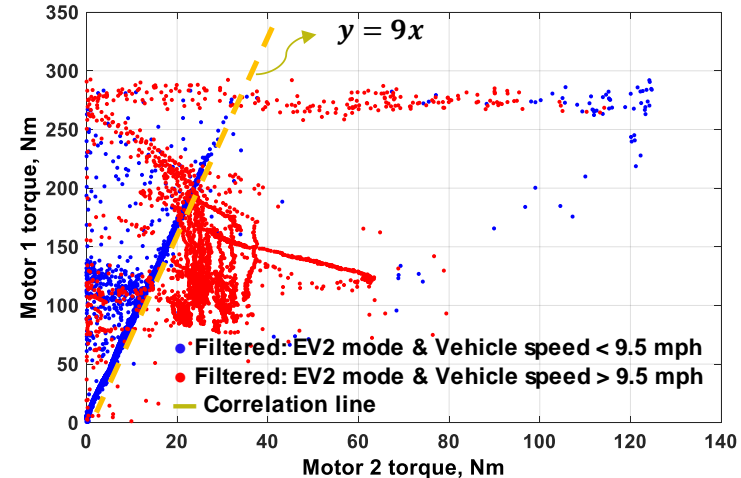
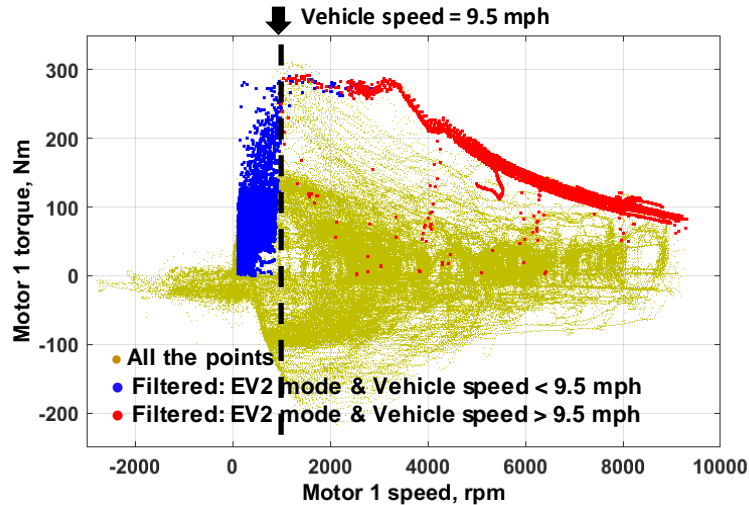
Efficiency/ Max Torque in extended modes (CS mode)

Engine only (but, Motor1 + Motor2 for electric variable transmission modes)

Assumes no battery

Power Management Control (EV2 mode)

- There is a boundary of vehicle speed at around 9.5 mph for torque distribution in EV2 mode



When the vehicle speed is lower than 9.5 mph, electric machine 2 provides only about 10% of demand torque, and electric machine 1 produces the rest of demand torque

When the vehicle speed is higher than 9.5 mph, electric machine 1 provides an almost maximum torque that can be generated at that speed, and electric machine 2 covers the short demand torque to propel the vehicle.