# *Tradeoff Between Powertrain Complexity and Fuel Efficiency*

**2009 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review**

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Sponsored by Lee Slezak


**Project ID #VSS010**

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

# Project Overview

## Timeline

- Start – September 2009
- End – September 2010
- 70% Complete

## Budget

- FY09 - $150K (2Mode Development and Validation)
- FY10 - $400K

## Barriers

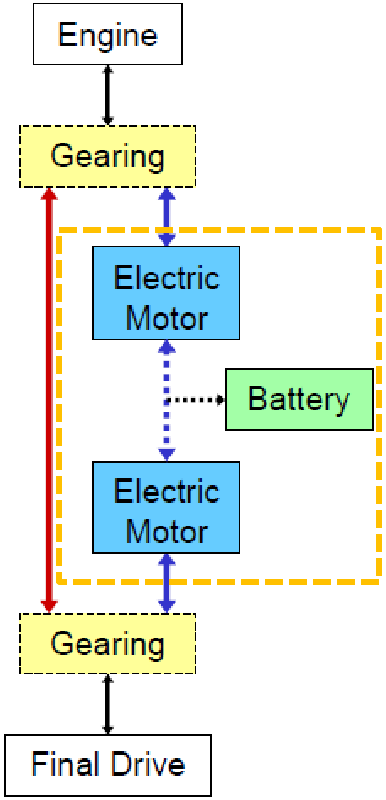
- Evaluate fuel consumption potential and cost benefit of powertrains
- Assess impact on component requirements

# Objectives

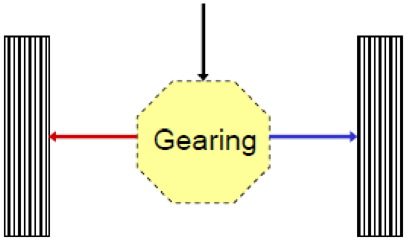
***The objective is to evaluate the benefits of several multi-mode powertrain configurations from a fuel consumption and cost point of view.***

- EVT efficiency of electro-mechanical power path increases with powertrain (PT) configuration complexity
- EVT mechanical losses also increase with PT complexity
- Evaluate the trade-offs between EVT system efficiency and EVT mechanical loss based on multi-mode powertrain complexity
- Select the most promising configuration to support future DOE fuel consumption studies

# EVT Hybrid

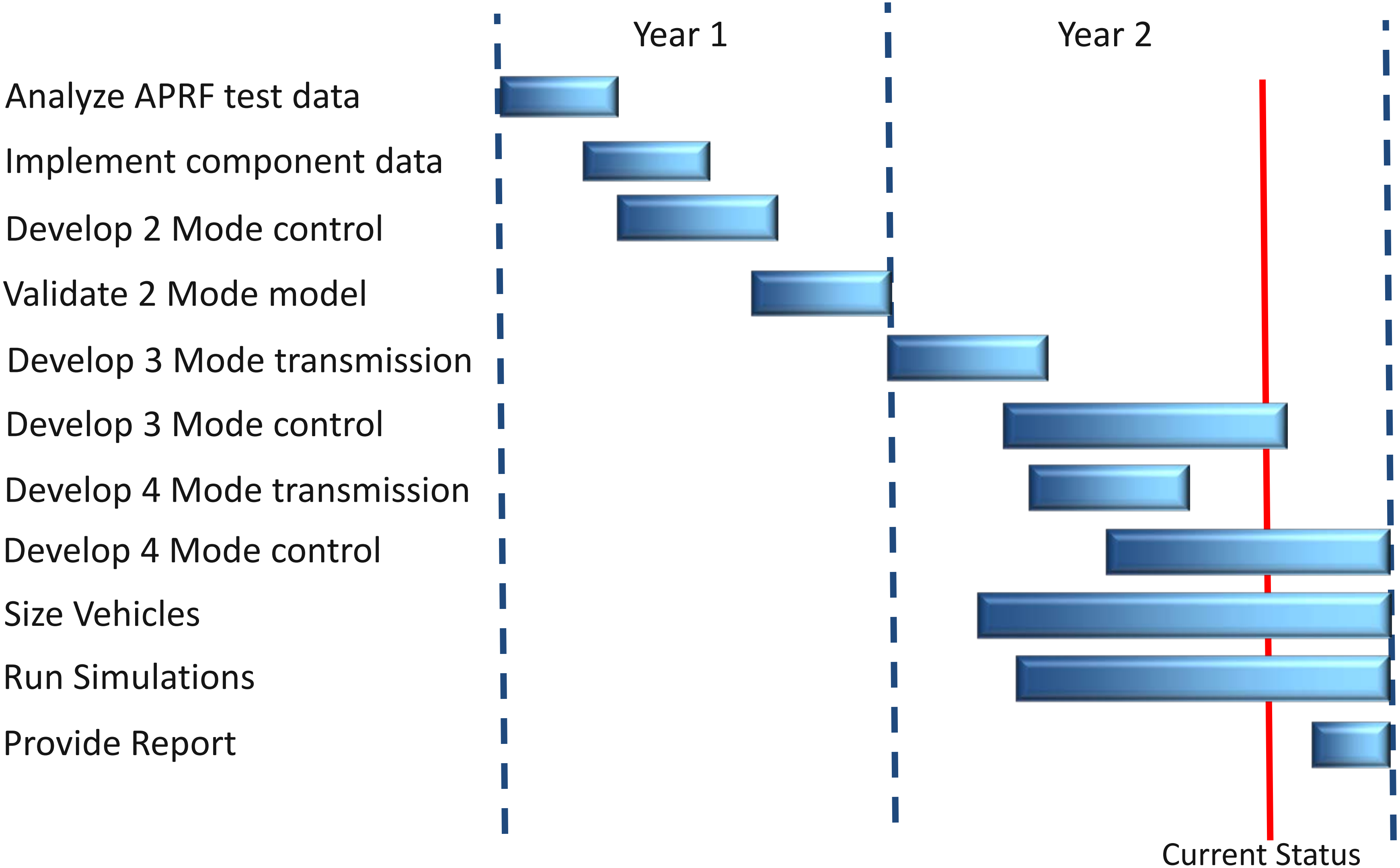



- An **EVT** hybrid uses differential gearing to split power into two paths:
  - **All-Mechanical**
  - **Electro-Mechanical**




- EVT gearing acts like an automobile differential, which uses gearing to split power between left and right wheels.
- Series – Engine Operates Independently
  - + Continuously Variable (CVT) Operation,
  - + Unlimited Transmission Speed Ratio
- Parallel – Mechanical Path Through
  - + Motors and Controllers Cost Less,
  - + Higher Transmission Efficiency.

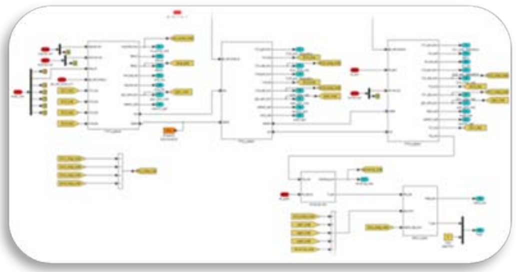
# Milestones


Year 1
Year 2
Analyze APRF test data
Implement component data
Develop 2 Mode control
Validate 2 Mode model
Develop 3 Mode transmission
Develop 3 Mode control
Develop 4 Mode transmission
Develop 4 Mode control
Size Vehicles
Run Simulations
Provide Report
Current Status

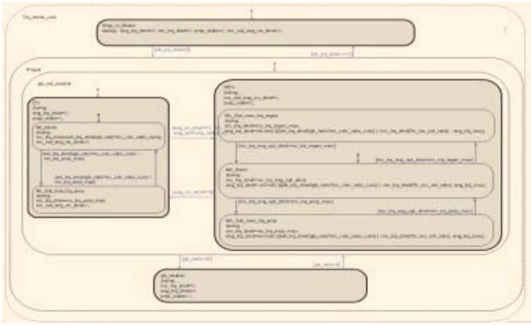
# Approach

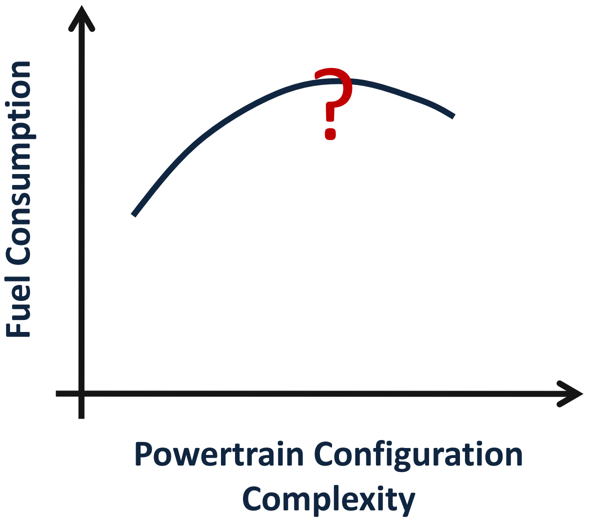
Search Existing Patents for Multi Mode HEV

Develop Transmission Models of Selected Patents



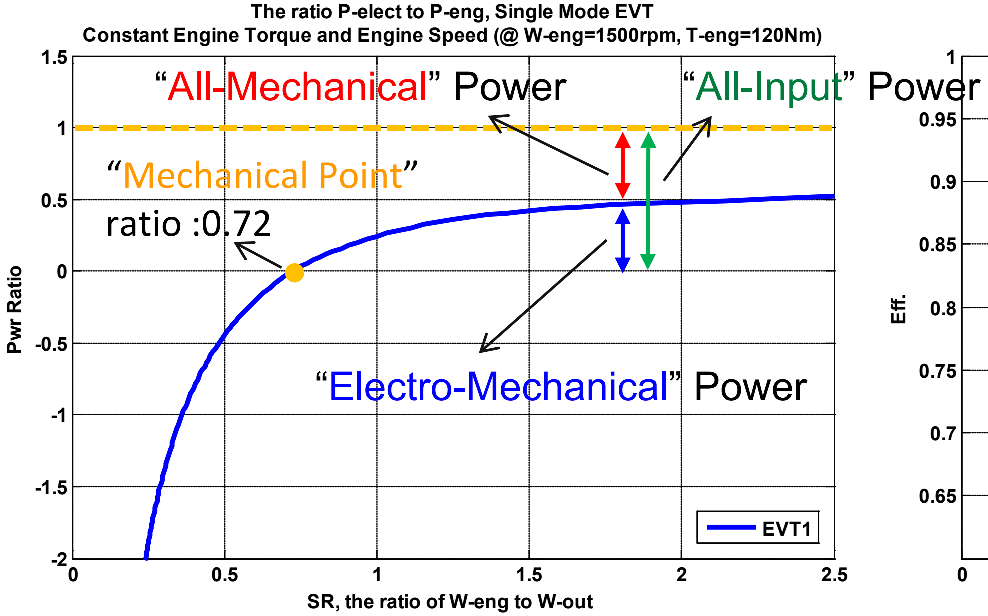
Develop Vehicle Level Control Based on Available Test Data and Literature

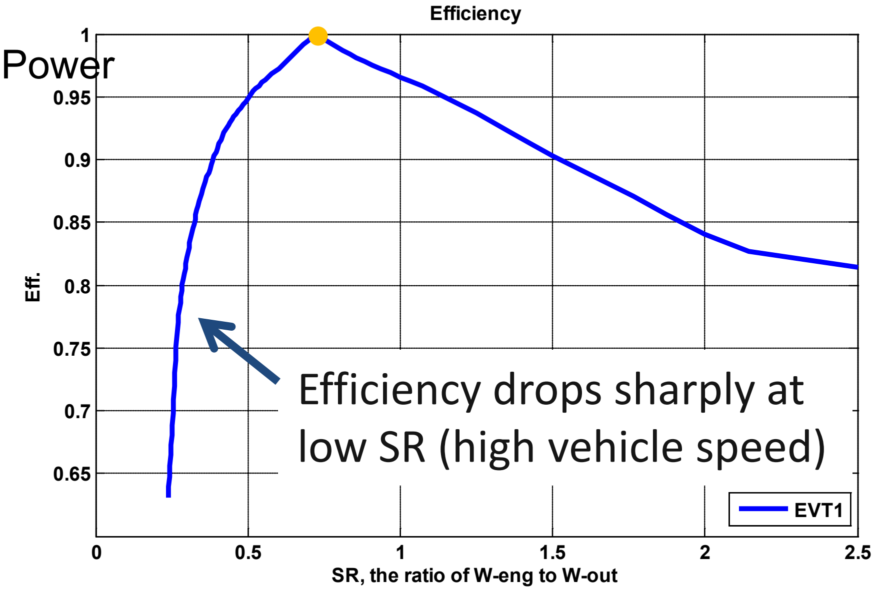




# Technical Accomplishments
## Understand Efficiency Potential of Each Multi-Mode

### Input Split



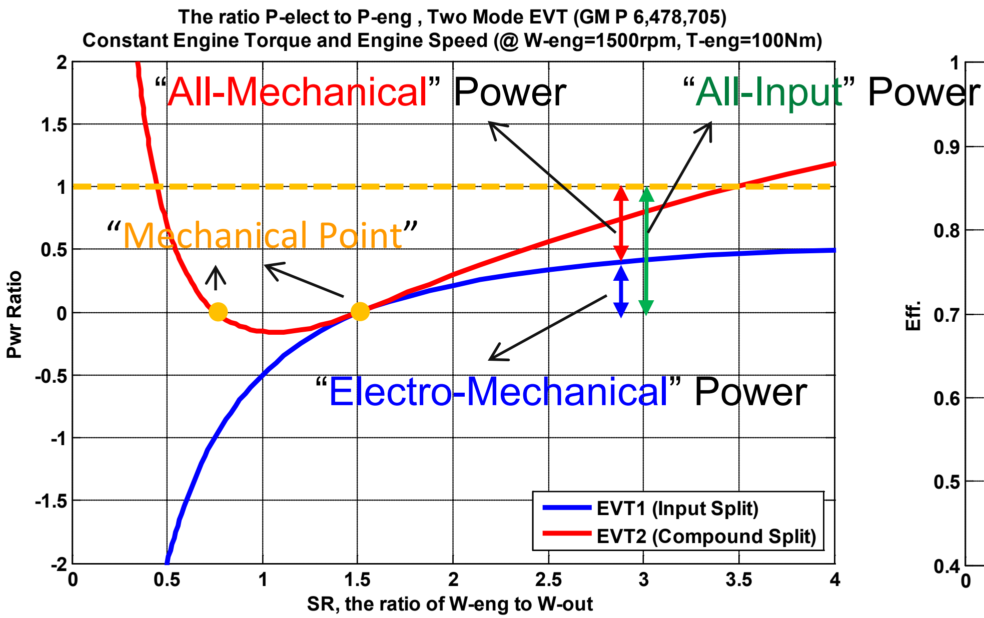



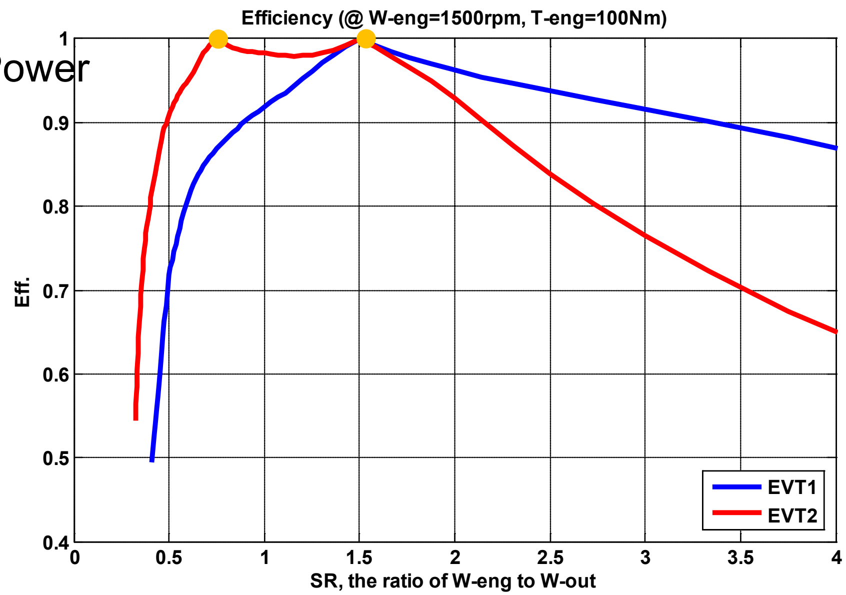

- Power ratio = electro-mechanical power / all-mechanical power (small values mean little recirculation, higher efficiencies)

Patented in the US in 1969

# Technical Accomplishments
## Understand Efficiency Potential of Each Multi-Mode

### Dual Mode



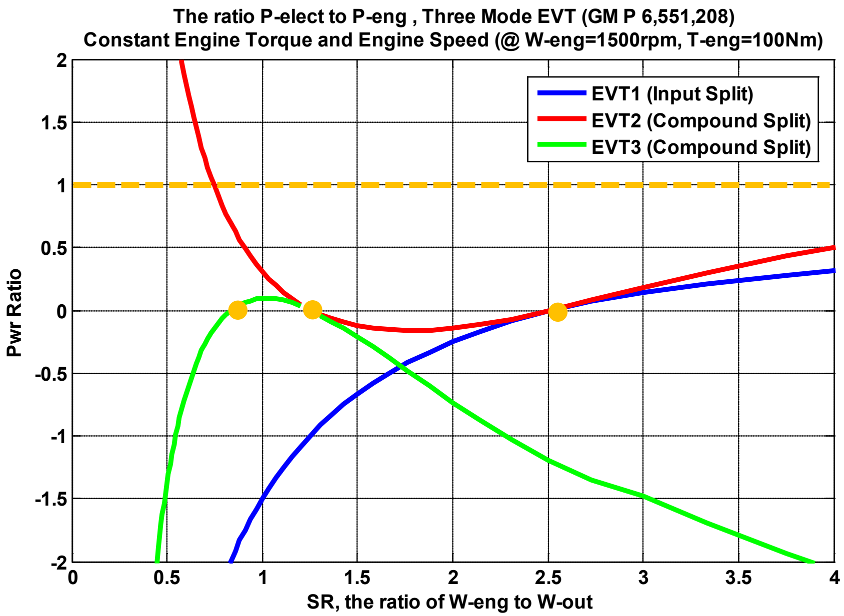



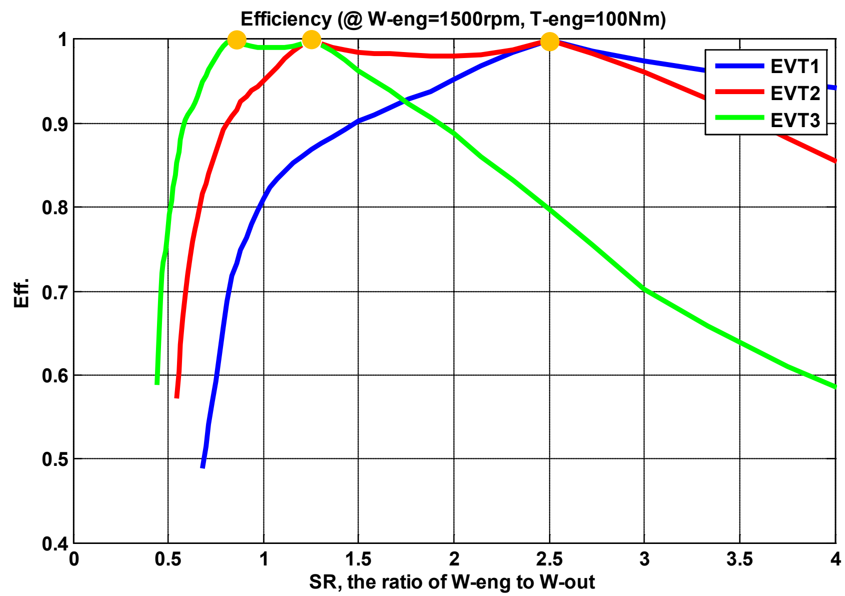

- The objective is to minimize the power ratio, to minimize recirculation
- Power through the transmission (engine to output) is the sum of all-mechanical power and electro-mechanical power.
- Transmit more power mechanically, which is **more efficient**.
- Two mechanical points allow higher efficiency over wider range

*GM patent no. 6,478,705*

# Technical Accomplishments
## Understand Efficiency Potential of Each Multi-Mode

### Three Mode




- Power through the transmission (engine to output) is the sum of all-mechanical power and electro-mechanical power.
- Transmit more power mechanically, which is **more efficient**.
- Maintain high efficiency over a wider range

GM patent no. 6,551,208

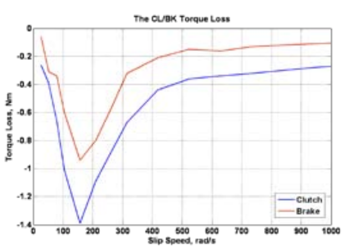
# Technical Accomplishments
## Multi-Mode Efficiency Potential Summary

| | Single | Two | Three | Four |
|---|---|---|---|---|
| Eff. of electro-mechanical power path | **0** | **+** | **++** | **+++** |
| Electro-mechanical capacity | **0** | **+** | **++** | **+++** |
| Cost | **0** | **-** | **--** | **--** |
| Oil pump loss | **0** | **-** | **-** | **-** |
| Planetary gear spin loss | **0** | **-** | **--** | **--** |
| Clutch drag loss | **0** | **-** | **--** | **--** |

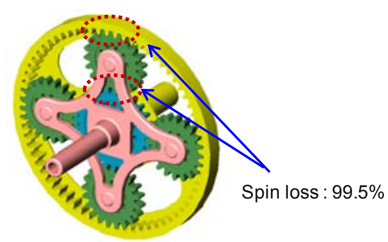
**Key: Baseline = 0, Better = +, Worse = -**

- Transmission model needs to include:

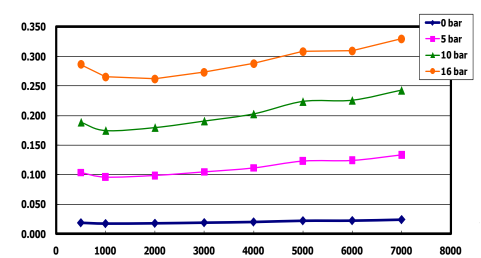
Clutch drag losses



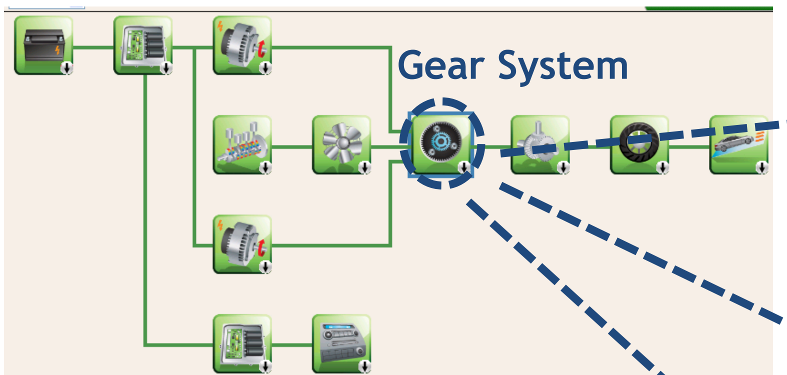

Planetary Gear Spin Losses

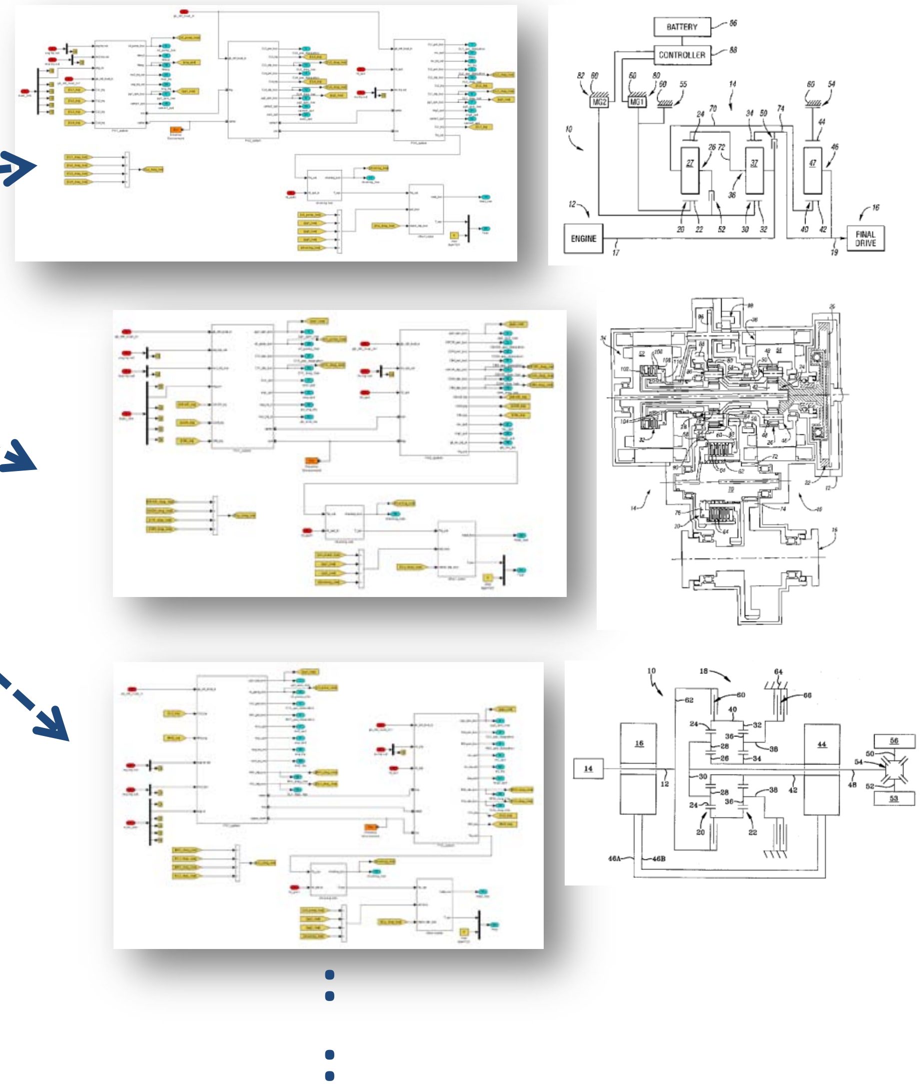



Oil Pump Loss



# Technical Accomplishments
## Modeled Different Transmissions



- Transmission models developed in SimDriveline to allow for modeling of detailed losses (oil pump, spin, clutch drag).
- Low level control developed for each transmission

# Technical Accomplishments
## Developed Single, 2 and 3 Mode Controls

### Control Logic Philosophy

- Controller objective: Find the power split between mechanical components (ICE, MC2, MC1) that meets the driver request for the current speed of the vehicle, while maintaining acceptable battery SOC and minimal fuel consumption
  - Use a compound split mode
  - Electric power should stay low with wide ratio coverage
- Mode selection rule is defined by maps which are computed in Matlab using a brute-force algorithm (similar to instantaneous optimization)
- The SOC correction and engine ON/OFF conditions have to be properly defined

*Candidate Fuel Consumption* ← $T_e$ ← $\omega_{MC1}, \omega_{MC2}$, $T_{MC1}, T_{MC2}$, $\eta_{transmission}$ ← **Equations** (Two modes & fixed gear modes) ← $T_{out}$ $\omega_{out}$, candidate $\omega_e$

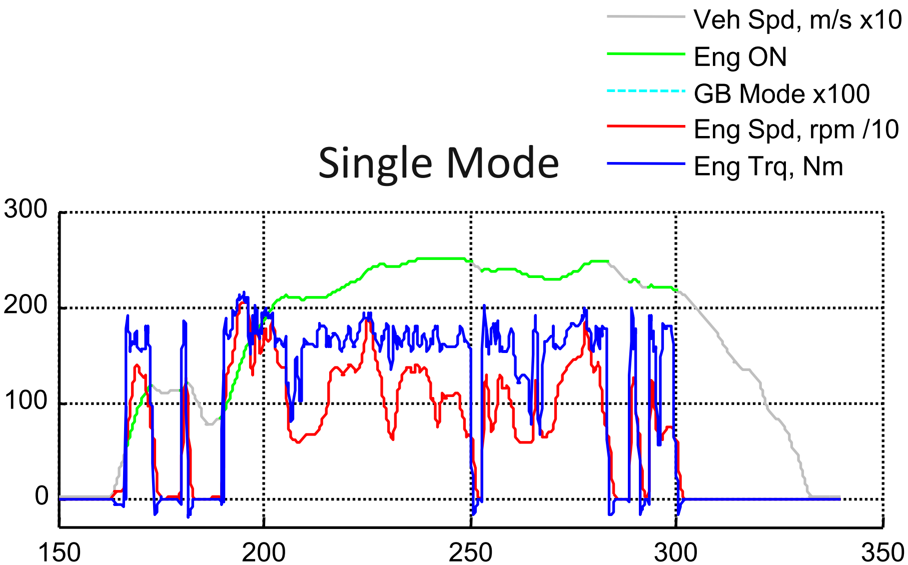
**Note: an instantaneous optimization has also been defined for the 2Mode**

# Technical Accomplishments
## Impact of Powertrain on Component Sizing and Operation

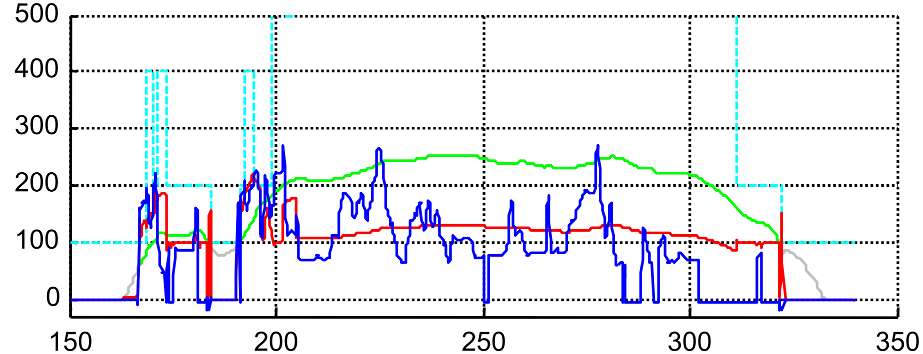
Small SUV Vehicle Sizing

| | Unit | Single Mode | Dual Mode |
|---|---|---|---|
| Engine Power | kW | 195 | 191 |
| Motor 1 Power | kW | 110 | 49 |
| Motor 2 Power | kW | 90 | 60 |
| Vehicle Weight | kg | 2026 | 1983 |

Single Mode




Dual Mode




- Dual mode allows smaller electric machines
- Mode selection also impact the component operating conditions (e.g., engine speed and torque)

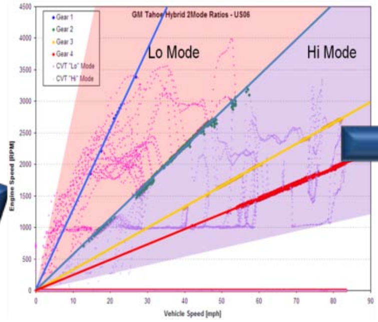
Cycle is UDDS Hill 2

# Technical Accomplishments
## Validate Single and Dual Mode Controls

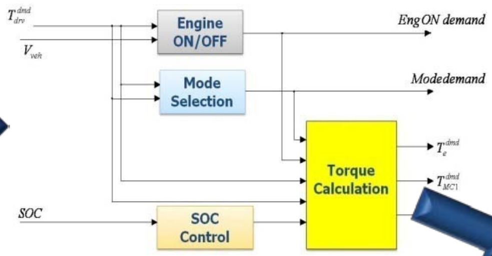
Collect Test Data

APRF

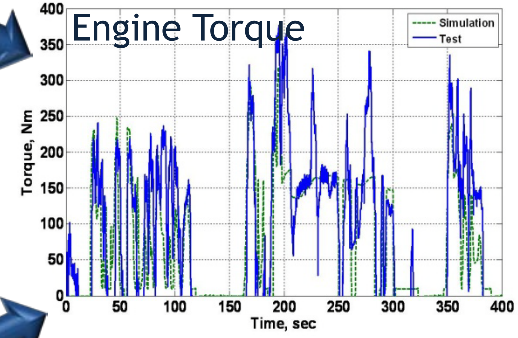
Analyze Data



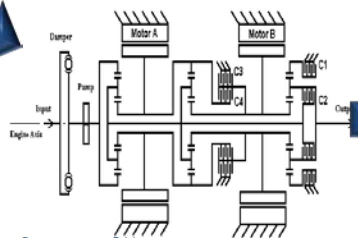

Develop Control




Validate Model

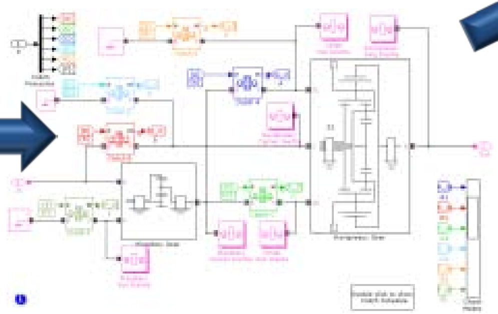



Understand Gearbox




Source : GM

Model Gearbox



Example of GM 2 Mode Tahoe

# Future Activities

- Multi-mode analysis completion
  - Refine / develop the design options and control of three and four mode powertrains
  - Complete fuel efficiency comparison and analysis study based on a small SUV
  - To ensure fair comparison, several control parameters will be simulated and/or heuristic optimization algorithm will be used to tune the parameters
  - Several drive cycles, include RWDC might be considered
  - Net Present Value (NPV) will also be considered
- Expand study
  - Additional vehicle classes (e.g., compact, midsize car, midsize SUV…)
  - Additional multi-mode (e.g., 5, 6…) if the tip not reached
  - Other configurations options (e.g., for series, compare series vs. GM Volt vs. BYD…)

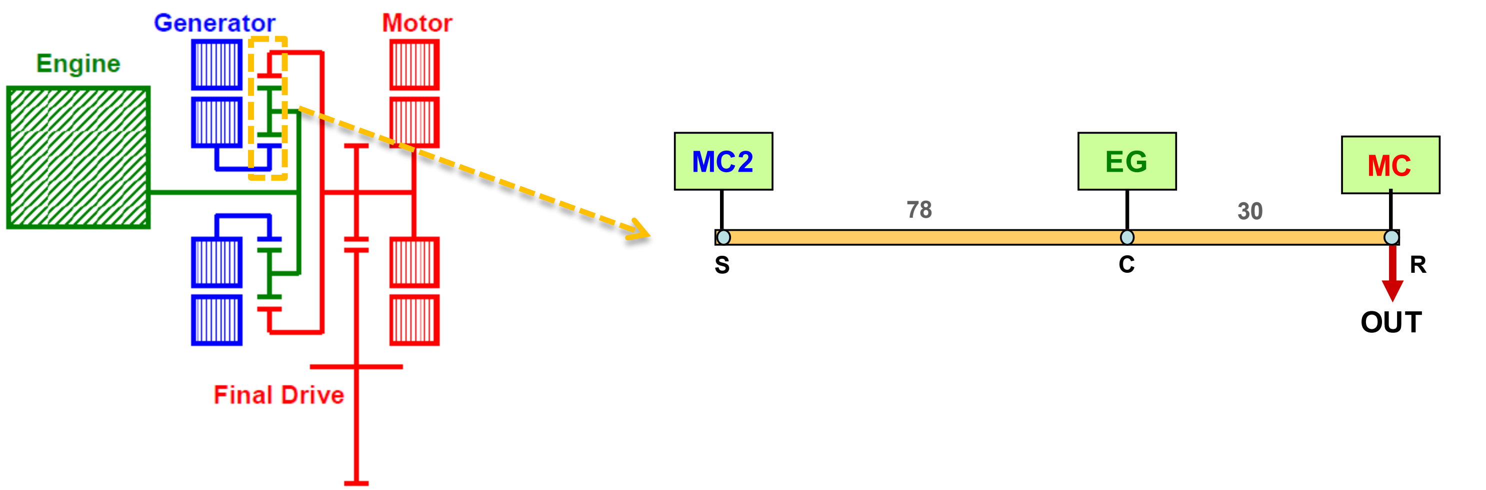
# Summary

- The fuel efficiency potential of several multimode systems (1 to 4 modes) has been defined.
- Detailed transmission models, including spin losses, clutch drag and oil pump losses have been developed along with their low level controllers.
- Vehicle level control strategies have been defined for several multi-mode systems (1, 2 and 3).
- For the small SUV application considered, preliminary results show impact on component sizing and component operating conditions
- Future work will address the four selected multi-mode systems to assess their impact on fuel consumption and component sizing.

# Additional Slides

# Single Mode EVT :

- Lever and stick diagrams for a simple planetary EVT (Input split):



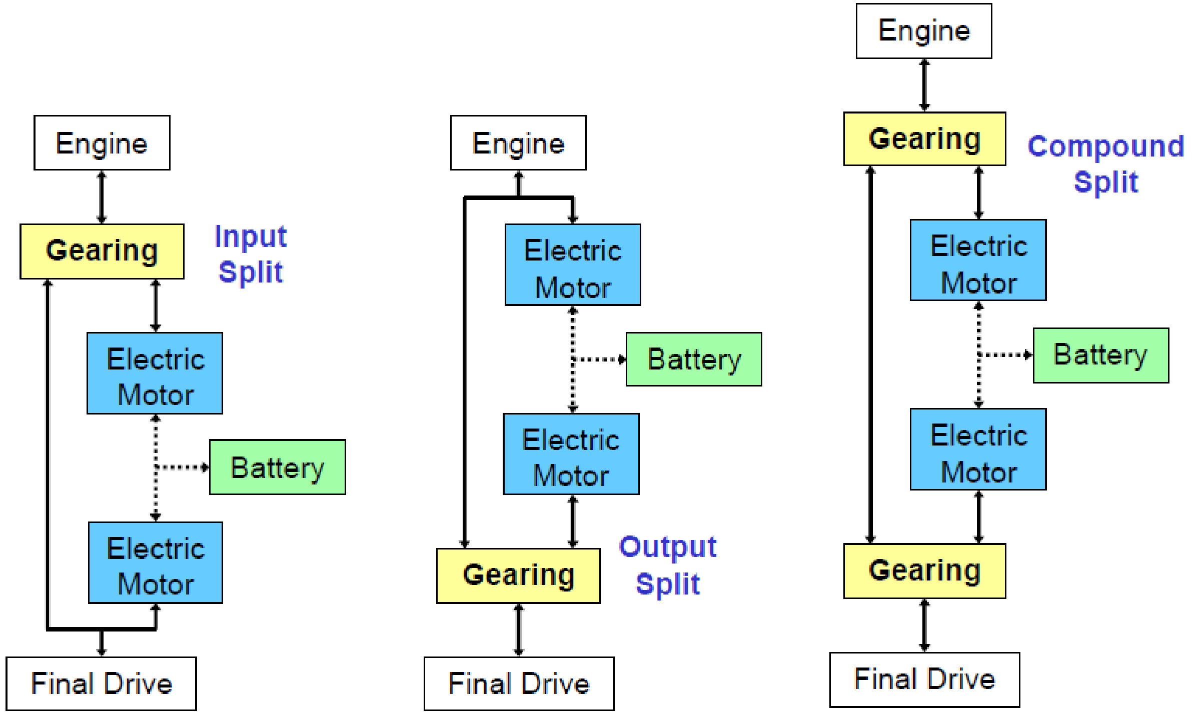

- A lever can be drawn in the same orientation as planetary “sticks”.
  - Patented in the US in 1969!
  - Toyota Prius uses this same basic gear schematic and power flow
- Engine torque is split unequally, based on ring-to-sun gear ratio.
- Final drive receives most of the engine torque directly.
- Generator receives a small fraction of engine torque (e.g. 1/3) but must be able to turn much faster than the engine.

# Single Mode EVT Limitations

- Electro-mechanical (continuously variable) power path is less efficient due to electrical power recirculation.
- EVT gear ratio or “mechanical point” must be chosen for high drive-cycle fuel economy (no recirculation).
- With high engine speed, transmission uses high speed ratios, with high electro-mechanical power.
- High electro-mechanical component power has high cost.
- High electro-mechanical use increases “real-world” fuel consumption.

# EVT Power Split Design Options:

- Input Split (IS), Output Split, and Compound Split (CS) EVT hybrids use gearing in different places:
  - I.S. : One electric motor is geared at the input, and the other motor turns with the output
  - C.S. : One electric motor is geared at the input, and the other is geared at the output.

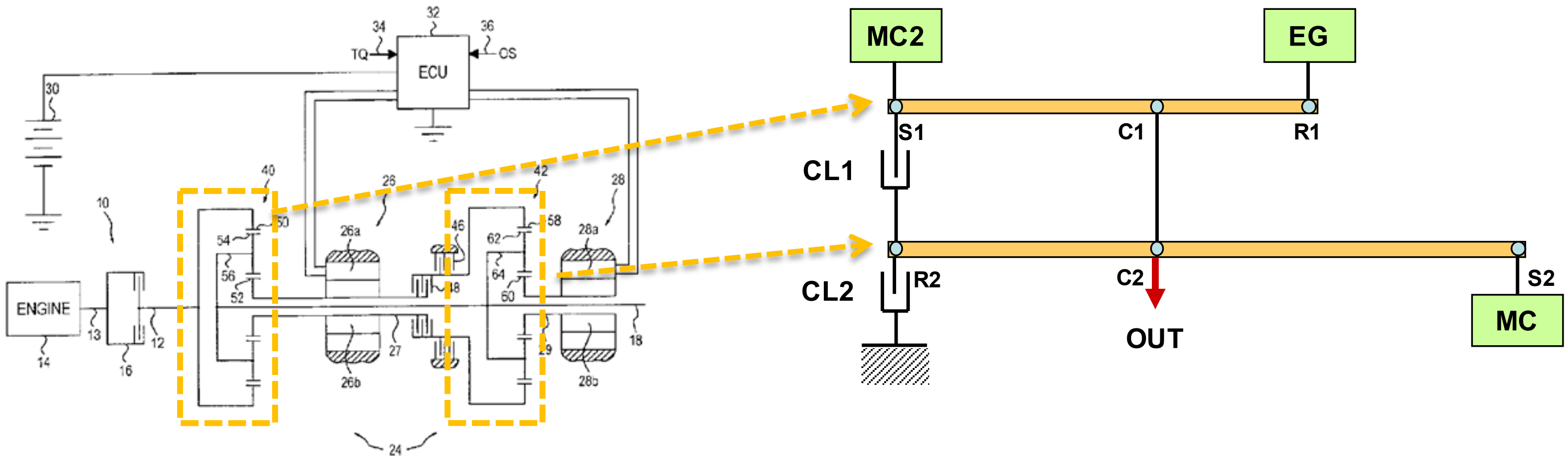



→ Input split, output split and compound split can be combined to form a multi-mode EVT

# Two Mode EVT :

- Lever and stick diagrams for a two mode EVT;  for example

*GM patent no. 6,478,705*

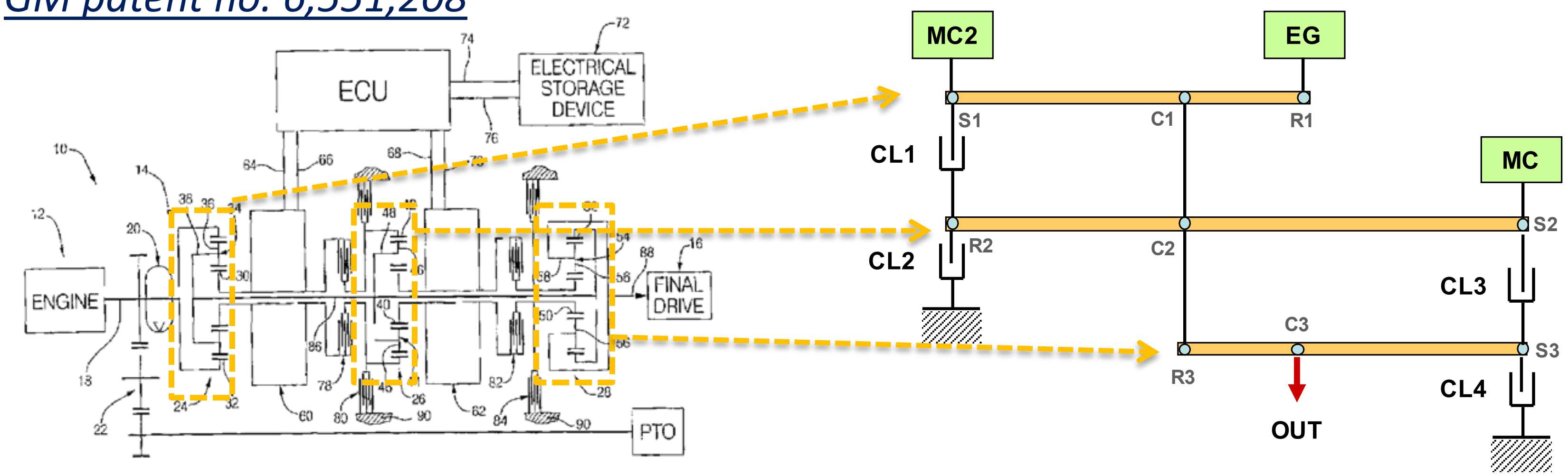



- Engine is connected to the 1st ring gear.
- Generator is connected to the 1st sun gear.
- Motor is connected to the 2nd sun gear.
- Final drive is connected to the planet carrier
- Two clutches are provided, one for each EVT range or “mode”. (Mechanical loss)
- Needs two planetary gear sets for EVT2 mode. (Mechanical loss)

# Three Mode EVT :

- Lever and stick diagrams for a three mode EVT;  for example

GM patent no. 6,551,208




- Engine is connected to the 1st ring gear.
- Generator is connected to the 1st sun gear.
- Motor is connected to the 2nd sun gear.
- Final drive is connected to the 3rd planet carrier
- Four clutches are provided, two for each EVT range or “mode”. (Mechanical loss)
- Needs three planetary gear sets for EVT2, EVT3 mode. (Mechanical loss)