# Modelling and Analysis of Plug-in Series-Parallel Hybrid Medium-Duty Vehicles

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## Background

According to the 2010 fuel efficiency and greenhouse gas (GHG) standards for MD and HD vehicles, the nation's fleet of MD and HD trucks will be required to meet fuel efficiency regulations for the first time beginning in model year 2014. Vocational vehicles including delivery trucks, buses, and garbage trucks will be required to reduce fuel consumption and GHG emissions by approximated 10 percent by model year 2018. In 2015, more stringent standards were proposed for the same classes of MD and HD vehicles for model year 2018 and beyond. In phase 2, the new fuel consumption standards would become 2.5% more stringent every year from model years 2021 to 2027. These regulations and standards will spur more innovation and the adoption of advanced vehicle technologies to comply with them. Various advanced vehicle technologies have been studied and advanced to improve fuel efficiency, including non-electrification efficiency-improving technologies and electrification and hybridization efficiency-improving approaches. There is a need to explore different powertrain architectures for the MD delivery vehicle over various duty cycles.

## Objective and Approach

This research studies the hybridization using electric motors and batteries in PHEVs with the conventional engines and explores various architectures for MD vehicles over different duty cycles in term of fuel economy. The baseline MD truck is a 2014 Class 4 conventional diesel delivery truck (stepvan). Series-parallel hybrid powertrains with pre- and post-transmission configuration for the plug-in hybrid medium-duty trucks were modelled and compared with a conventional diesel and a mild/full parallel hybrid with pre-transmission configuration to explore the fuel economy potential of each technology over a wide range of duty cycles.

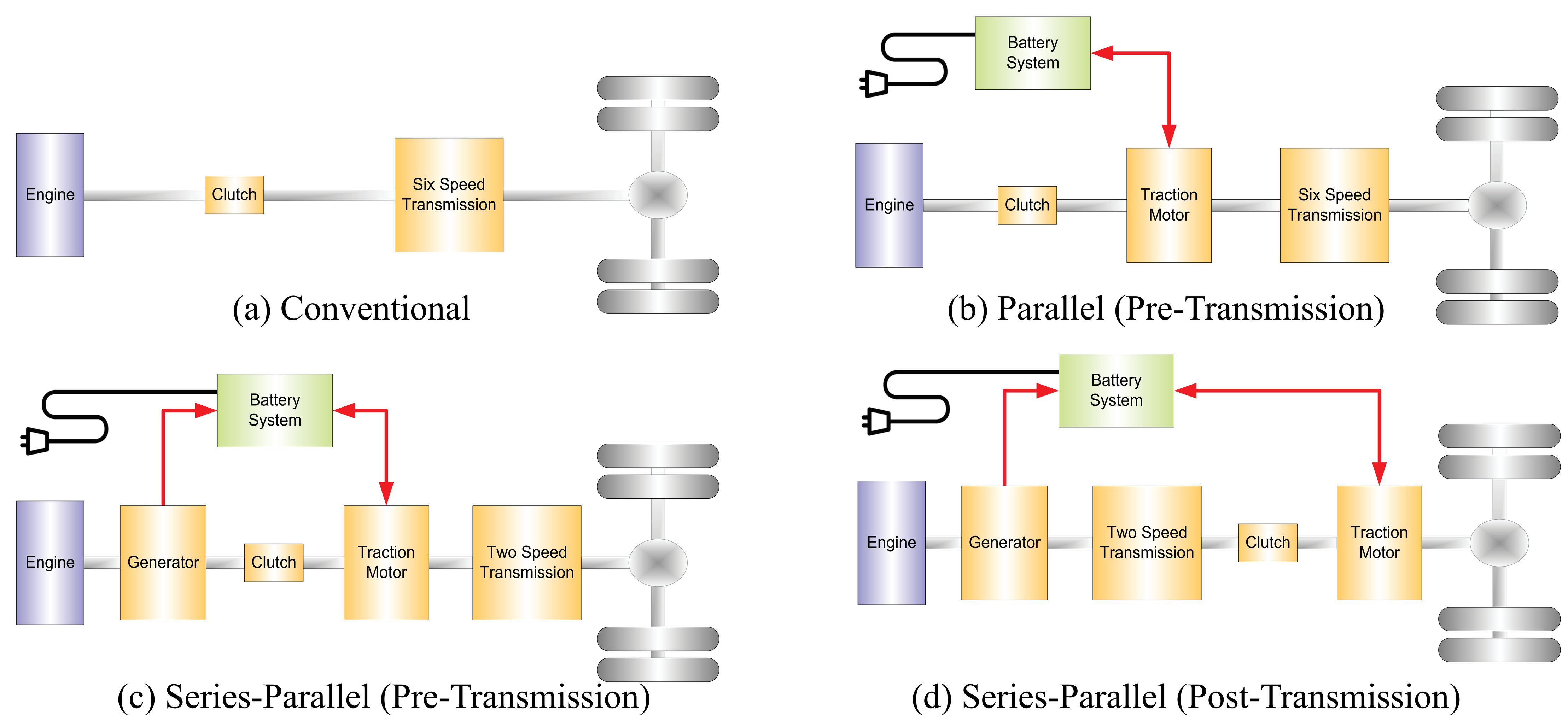



Figure 1: Delivery truck powertrain architectures

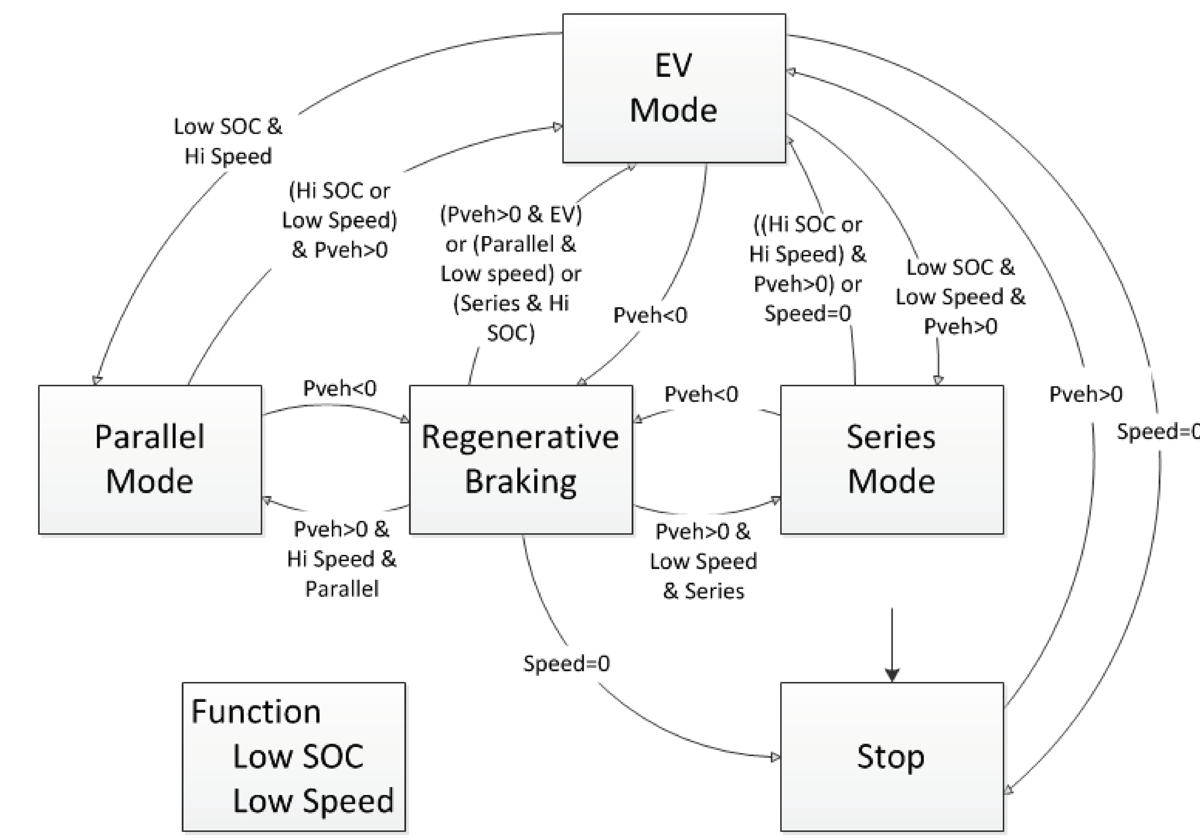
## Simulation Inputs

| | |
|---|---|
| Engine (2014) | CI Diesel, 7Liter 150 kW |
| Engine Peak Eff. | 0.43 |
| Frontal Area | 7.8 $m^2$ |
| Air Drag Coef. | 0.6 |
| Weight | 7,257 kg |
| Wheel Radius | 0.378 m |
| Rolling Res. Coef. | 0.006 |
| Traction Motor (PM) | 100kW cont. 150kW peak |
| | 45 kW for mild parallel |
| Generator | PM 71 kW |
| Energy Storage | 31 kWh (22 kW usable) |
| Gearbox | 6-Speed for conven. & parallel |
| | 2-Speed for series-parallel |
| Final Drive | 2.85 |
| Aux. Mech. / Elec. | 1 kW / 0.4 kW |

A Class 4 delivery truck is modelled. A 2014, 7 Litre, 150 kW diesel engine and a UQM PM motor with continuous power of 100 kW and peak power of 150 kW are selected to power the truck. A 45 kW PM motor is used for a mild parallel hybrid. A six-speed transmission is employed in the conventional powertrain and parallel hybrid architectures, and a two-speed transmission is used in the series-parallel hybrids. All hybrid powertrains use the same lithium battery pack of 31 kWh and the same engine without downsizing.

## Series-Parallel Control Strategy

The series-parallel hybrid has three major operation modes: electric, series, and parallel. Initially the vehicle runs in the **electric mode** until the battery SOC reaches the lower limit. Then, the engine is turned on and the vehicle switches to either series mode or parallel mode depending on the vehicle speed. In the **series mode**, the clutch is disengaged. The traction motor is powered by the generator turned by the engine. The engine operates at its most efficient point and charges the battery if possible. When the vehicle exceeds the speed threshold in the series mode, the vehicle switches to the **parallel mode** via the electric operation mode. The clutch is engaged and the engine propels the vehicle and maintains the battery SOC at the same time.

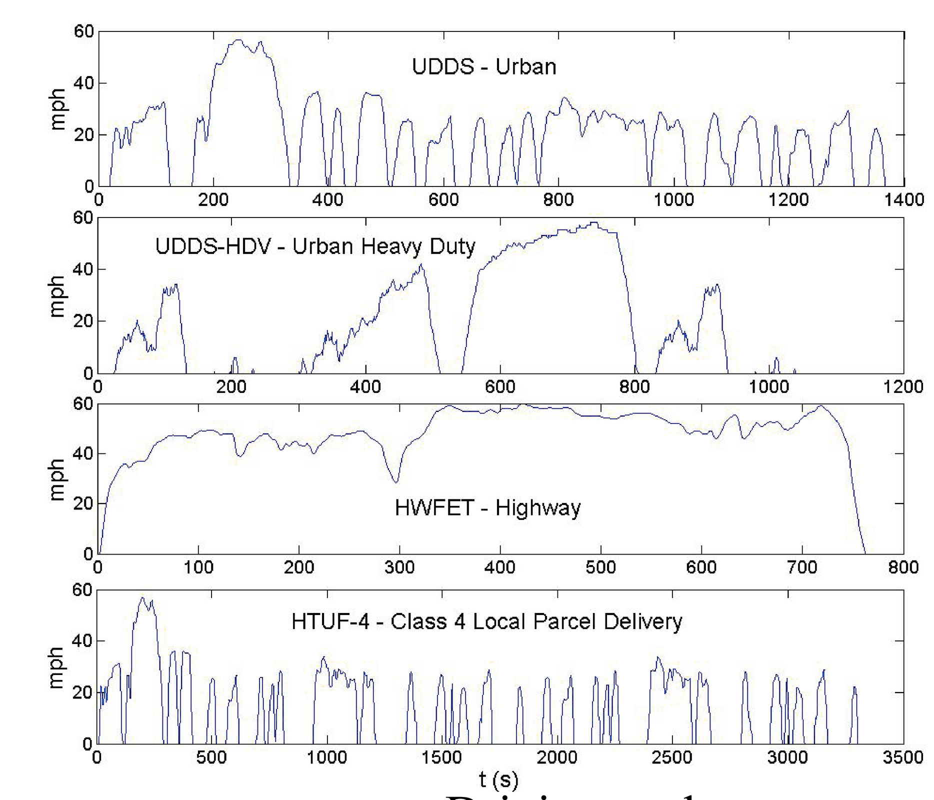



Operation mode migration of series-parallel hybrids

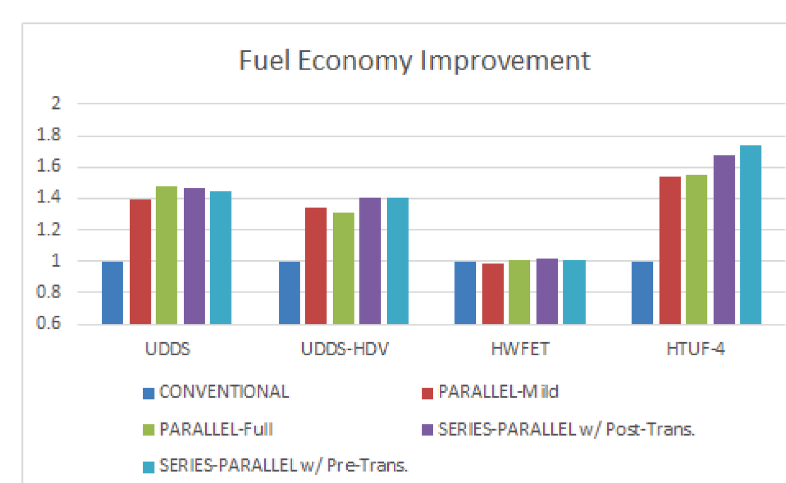
## Simulations

Simulations were performed on the Class 4 delivery vans over the UDDS, UDDS-HEV, HWFET, and the HTUF-4 driving cycles. The powertrain architectures simulated are conventional, mild parallel hybrid, full parallel hybrid, and series-parallel hybrid with pre- and post-transmission. The baseline vehicle is a Class 4 2014 diesel delivery truck.

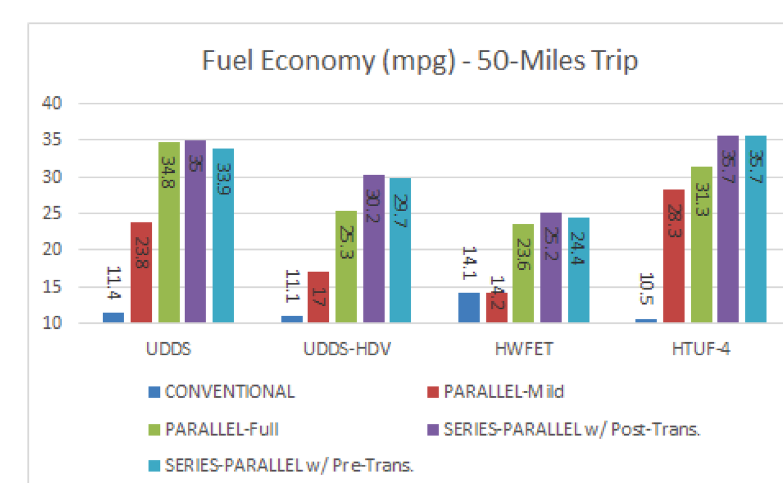
First, to compare the driveline efficiency of different hybrid powertrain architectures, the simulation is first done with initial battery SOC starting at 0.3 in charge sustaining mode. Then, the daily drive of a Class 4 truck is broken up into two scenarios: short daily distance – up to 50 miles and long daily distance – up to100 miles or longer. The simulations were performed with the initial battery SOC starting at 1.0 for both scenarios. The actual fuel economy (distance travelled / fuel used) for the 50-mile and 100-mile trips is simulated.



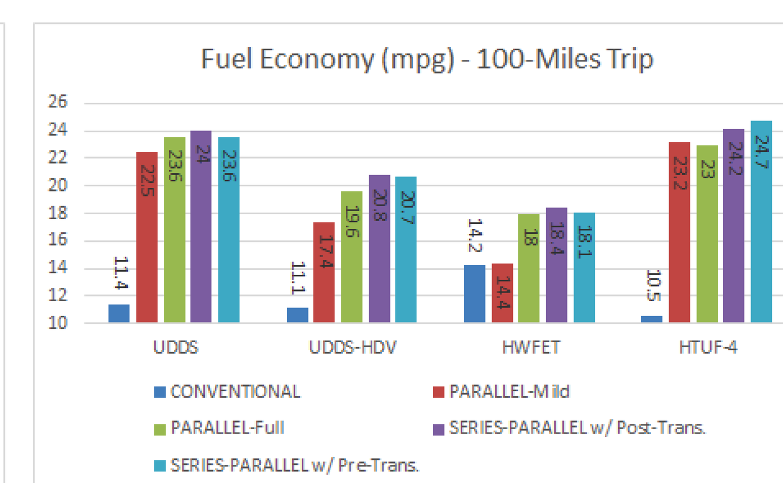

Driving cycles




Normalized fuel economy in CS mode




Fuel economy for a 50-mile trip




Fuel economy for a 100-mile trip

## Findings*

- ❑ The series-parallel powertrain achieves higher efficiency over the UDDS-HDV and the HTUF-4 drive cycles that feature stop-go with a short distance of high speed drive and is well suited for a typical Class 4 delivery truck.
- ❑ Compared to the parallel hybrid, the series-parallel hybrid achieves 10 – 20 percent improvement in driveline efficiency over the UDDS-HDV and the HTUF-4 drive cycles. There is no apparent difference between the mild parallel, full parallel, and series-parallel architectures for a Class 4 delivery truck operating in the charge sustaining mode over the light duty urban drive cycle and the highway drive cycle.
- ❑ Compared to the conventional truck, the series-parallel PHEVs with a 30 kWh battery shows improved fuel economy by a factor of 3-3.5 for the UDDS-HEV and HTUF-4 drive cycles. With the increase of the daily distance travelled, the improvement in fuel economy levels off for the series-parallel hybrids.

* Hengbing Zhao, Andrew Burke, Modelling and Analysis of Plug-in Series-Parallel Hybrid Medium-Duty Vehicles, European Battery, Hybrid and Fuel Cell Electric Vehicle Congress, Brussels, Belgium, 2nd - 4th December 2015

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