MODEL-BASED ASSESSMENT OF FUEL ECONOMY AND PERFORMANCE OF A SWITCHABLE P2/P3 HYBRID POWERTRAIN FOR HEAVY TRUCK

Chinmaya Patil, Witt Thanom, Erik Dykes, Josh Kreucher, Thomas Genise,
Eaton Corporation

Martin Kummer, David Sarcona,
Eaton Cummins Automated Transmission Technologies ™

The proposed paper will present a concept multi-speed transmission for heavy duty vocational hybrid vehicles that would enhance vehicle performance and fuel economy for both commercial vocational and military applications. The commercial application is specifically designed to target last-mile delivery where zero emission zones are directed in cities and ports, high performance vocational applications where low speed, power-shifts, decoupled drive & PTO functions are needed, and fuel-efficient low NOx hybrid powertrains and electrical power export: e-PTO are required. The military application targets the added torque beyond the diesel powertrain, high on-board electrical power, and bi-directional Vehicle-to-Grid (V2G) / Micro-Grid integration. The addition of the hybrid features enables the vehicle-to-grid power export function while maintaining the same or better performance than the base conventional torque converter automatic (AT) transmission. In addition, significantly better fuel economy and emissions reduction are enabled with this concept. The hybrid transmission concept is also compatible with pure EV propulsion - where the vehicle has the necessary electrified accessories to enable it.

The P2/P3 Hybrid Powertrain is a parallel hybrid system that propels the vehicle using the engine alone in conventional engine mode, or the motor alone in EV mode, or both in the hybrid mode. Furthermore, in the hybrid mode, the motor torque can be transmitted to the vehicle in either the P2 configuration (connected to the transmission input shaft) or in the P3 configuration (connected to the transmission output shaft through the range section) as shown in Figure 1. This unique design of the system enables the motor to switch between the two hybrid configurations while the vehicle is in motion. The P2 hybrid mode offers the additional motor torque through the multiple gear ratios of the transmission, while the P3 hybrid mode enables the motor torque to be added to the transmission output torque providing torque-fill during gear shifts where the engine torque transfer to the vehicle is interrupted in the conventional AMT transmission. The hybrid modes for different vehicle functions are described in Table 1.

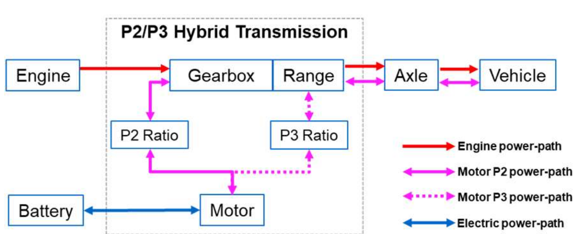

Figure 1 Schematic Representation of P2/P3 Hybrid Transmission

Vehicle Function	Hybrid Mode	Description
Launch Assist	P2 or P3	• E-motor assists engine for higher startability & gradeability
Low Speed Creep Mode	P2 or P3	• E-motor enables superior low speed maneuverability (<2mph)
EV Drive / Engine-off	P2 or P3	• E-motor only up to cruise speed • Transmission enables 6 EV ratios • Zero-emission/stealth operation for EV enabled vehicles
Hybrid Drive	P2	• E-motor provide driveline boost as well as braking regeneration • Used commonly in high range (gears 7-12)
Engine Crank	P2	• Start diesel engine with motor
Export Power Stationary	P2	• Vehicle connects to micro-grid • System exports up to 130kW power
Export Power Mobile	P2	• Diesel engine powers E-motor and driveline • E-motor powers vehicle accessories (fans, pumps, etc.)
Power-shift	P3	• E-motor provides vehicle acceleration during AMT shifts • Used commonly in low range (gears 1-6)
Diesel Drive	Neutral	• E-motor disconnected for efficiency when on level ground

Table 1 Hybrid Operation Modes Description

A forward-facing simulation model for analyzing the heavy-duty vehicle performance and fuel consumption under commercial use cases and their military analogues was developed. The P2/P3 hybrid powertrain model comprises the main powertrain components: engine, master clutch, AMT, electric motor, high voltage battery, and controllers and the peripheral components: environment, driver, vehicle, and data logger. Table 2 shows the numerical values of parameters of key subsystems of the P2/P3 Hybrid Transmission model. The entire model is developed in MATLAB/Simulink software tool. The model can simulate the longitudinal vehicle dynamics for tracking a desired vehicle speed cycle.

Model Parameter	Units	Commercial	Military
Vehicle Mass (GCWR)	kg [klb]	49,885 [110]	49442 [109]
Vehicle Mass (GVWR)	kg [klb]	NA	32886 [72.5]
Frontal Area	m^2	10.66	
Coefficient of Rolling Resistance	unitless	0.00564	
Coefficient of Aerodynamic Drag	unitless	0.465	
Transfer Case Ratio	unitless	NA	[2.66, 0.98]
Final Drive Ratio (Axle Ratio)	unitless	3.91	5.43
Tire Size	rev/mile	486	397
Engine Rated Power	kW [HP]	375 [500]	375 [500]
Engine Governed Speed	rpm	1800	2100
Motor Peak (Continuous) Power	kW	250 (180)	
HV Battery Voltage	V	600	
HV Battery Capacity	kWh	27	

Table 2 P2/P3 Simulation Model Parameters

For military vehicle applications, the Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles and CARB Heavy Heavy-Duty Diesel Truck cycles were selected from NREL DriveCAT database and modified to expand the vehicle idle time to 60% of the total drive cycle time. The fuel economy achieved from the P2/P3 Hybrid Powertrain for the two drive cycles were compared with that obtained from baseline Automatic Transmission powertrain and are shown in Table 3. The P2/P3 Hybrid Transmission demonstrates fuel savings in the range of 21% to 29% over the baseline AT Transmission for military vehicle applications, and 8% to 26% for commercial vehicle applications in simulation.

Powertrain	Cycle	Cycle Distance	Distance traveled	Fuel consumed	Fuel economy	Battery SOC change	SOC adjusted fuel economy	Fuel economy gain
		[mi]	[mi]	[gal]	[mpg]	[%]	[mpg]	[%]
Heavy-duty Automatic Transmission (Non-hybrid)	Modified UDDS Heavy Duty	5.55	5.44	2.14	2.54	0	2.544	0%
	Modified CARB HHDDT Cycle	26.05	25.94	7.06	3.67	0	3.672	0%
P2/P3 Hybrid Transmission	Modified UDDS Heavy Duty	5.55	5.49	1.66	3.32	2.50%	3.280	28.90%
	Modified CARB HHDDT Cycle	26.05	26.02	5.82	4.47	3.00%	4.449	21.20%

Table 3 Fuel economy comparison between P2/P3 Hybrid Powertrain and baseline Automatic Transmission

The proposed paper will discuss the details of the simulation model and results of fuel economy and vehicle performance analyses for both military and commercial vehicle applications. Future work includes detailed design and build of the P2/P3 Hybrid Transmission and evaluation in powertrain hardware-in-loop test setup to validate the simulation results.