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

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ABSTRACT

The paper presents the fuel economy and performance capabilities of a switchable P2/P3 Hybrid Transmission for commercial and military use cases through modeling and simulation. An overview of the simulation model developed to analyze the vehicle performance and fuel consumption for a specified drive cycle is presented. The model includes the key components of the electrified powertrain including engine, hybrid transmission, electric motor and battery. Use cases were identified to represent Commercial vocational applications and military analogues. The results of P2/P3 Hybrid Powertrain model simulation are compared with that obtained from a model of baseline Conventional Torque Converter Automatic Transmission (AT). The comparison is made for both vehicle performance and fuel economy, and the results indicate that the P2/P3 Hybrid Transmission demonstrates better fuel economy with same or better performance than the baseline heavy-duty automatic transmission. Opportunities to achieve further improvements in fuel savings with the P2/P3 Hybrid Transmission are also identified.

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1. INTRODUCTION

The paper presents a concept multi-speed transmission based on conventional Automated Manual Transmission (AMT) 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 for (1) last-mile delivery where zero emission zones are directed in cities and ports, (2) high performance vocational applications where low speed, power-shifts, decoupled drive & PTO (Power Take-Off) functions are needed, and (3) 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 based Automatic Transmission (AT). 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 complete engine shutdown.

The paper is organized as follows: a concise description of the proposed hybrid powertrain concept and the details of the representative simulation model are presented in Section 2. Section 3 describes the commercial and military vehicle use cases across which the hybrid powertrain will be evaluated in simulation. Section 4 presents the results of the simulation for both commercial and military vehicle applications, followed by conclusions in Section 5.

2. SWITCHABLE P2/P3 HYBRID POWERTRAIN CONCEPT

The P2/P3 Hybrid Powertrain is a parallel hybrid system capable of propelling the vehicle using the engine alone in conventional engine mode, or the motor alone in EV mode, or combined engine and motor 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. The P3 hybrid mode provides 'torque-fill' during AMT gear shifts where the engine torque transfer to the vehicle is interrupted. The various powertrain modes for different vehicle functions are described in Table 1.

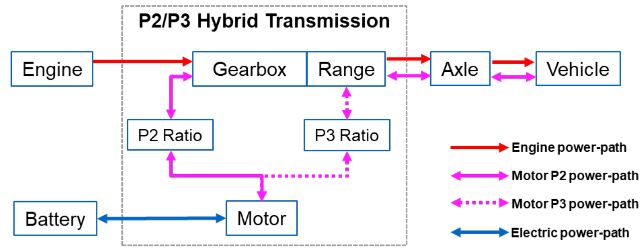

Figure 1: Schematic Representation of P2/P3 Hybrid Powertrain.

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: Description of Hybrid Operation Modes.

2.1. Vehicle Performance Requirements

The vehicle performance requirements for the commercial (vocational) and military (cargo) applications are shown in Table 2.

Performance Requirement Metric	Commercial Vehicle - Vocational	HEMMT A4 M977 - Cargo
Max Speed: km/h [mph]	105 [65]	100 [62]
Gradeability @ Maximum Speed	1% @ 49,885 kg [110 klb]	2% @ 32,886 kg [72.5 klb]
Startability on Max Grade @ GCWR 110 klb	20%	NA
Startability on Max Grade (w/o towed load) @ GVWR 72.5 klb	NA	60%
Startability on Max Grade (w/ towed load) @ GCWR 109 klb	NA	30%

Table 2: Vehicle Performance Requirements

2.2. Simulation Model

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, shown in Figure 2, was developed in MATLAB/Simulink and comprises the main powertrain components: engine, master clutch, AMT, electric motor, high voltage battery, vehicle, and a controller. The model also includes peripheral components such as environment, driver and data logger. The model can simulate the longitudinal vehicle dynamics for tracking a desired vehicle speed cycle.

A brief explanation along with the assumptions used in modeling each component or subsystem is presented below.

The environment subsystem generates the desired vehicle speed for a drive cycle and road percent grade information.

A typical Proportional-Integral (PI) vehicle speed feedback controller is implemented in the driver subsystem to enable tracking the desired vehicle speed in a drive cycle. The driver subsystem generates two important signals: the percent acceleration pedal and the brake pedal that will be used extensively by the controllers. It also generates the brake torque command signal which is directly sent to the wheel in the vehicle subsystem.

The P2/P3 Hybrid Powertrain and Vehicle subsystem comprises the engine, the P2/P3 hybrid transmission, the controllers, the high-voltage battery, and the vehicle. A first-order dynamics heavy-duty diesel engine model is developed to capture important characteristics such as torque, speed, fuel and energy consumption. The engine subsystem can be configured to represent two engine specifications: a 500 HP engine with 1800 rpm governed speed for commercial applications, and a 500 HP engine with 2100 rpm governed speed for military applications. The fuel consumption data used in the model was generated by mapping the engine on a dynamometer.

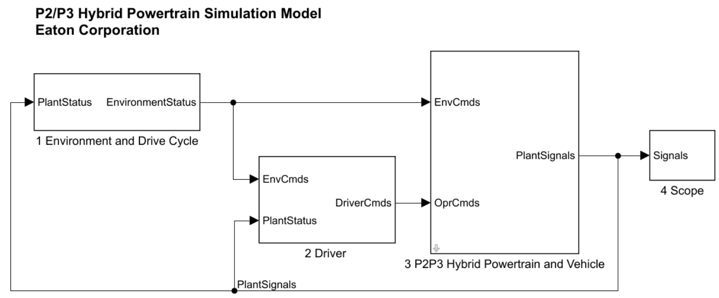

Figure 2: Top-Level Simulink Implementation of P2/P3 Hybrid Powertrain Model.

The P2/P3 hybrid transmission features the master clutch, AMT gear box with an additional electric motor and P2/P3 gear ratios. The model provides the important transmission characteristics affecting fuel economy such as input torque/speed, output torque/speed, gear ratios, and energy loss calculation.

The P2/P3 Hybrid Powertrain can operate in any of the following modes: P2 electric-only, P3 electric-only, P2 hybrid, P3 hybrid, and engine-only mode. The specific mode of operation is determined dynamically by a controller based on driver demand, vehicle dynamics, available battery energy, and system power. The controller also performs scheduled gear shifts of the transmission to meet the driver demand while simultaneously optimizing fuel economy.

The high-voltage battery subsystem is 600 V with 27 kWh capacity. It provides crucial signals such as battery voltage, current, SOC, and energy loss.

The longitudinal first-order vehicle dynamics model is developed to represent the vehicle subsystem. The vehicle model parameters, specifically the frontal area, rolling resistance and aerodynamic drag, were chosen for a commercial vocational truck application. The vehicle mass can be configured to represent either a vocational truck (commercial application) or a representative HEMMT A4 M977 Cargo truck (military application). The selected key parameters used in each vehicle configuration and the various subsystems are shown in Table 3.

Finally, the Scope Subsystem provides data for post-processing analysis.

A model of a conventional heavy-duty automatic transmission (AT) based on the EPA Greenhouse Gas Emission Model (GEM) [1] was previously developed for evaluating the performance and fuel economy of the baseline powertrain system.

Model Parameter	Units	Commercial	Military
Vehicle Mass (GCWR)	kg [klb]	49,885 [110]	49,442 [109]
Vehicle Mass (GVWR)	kg [klb]	NA	32,886 [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 3: Key Model Parameters and Values

3. VEHICLE USE CASES

The purpose of use case analysis is to identify the drive cycles that will be used to evaluate the fuel savings from the P2/P3 Hybrid Transmission. The fuel consumption is evaluated over a drive cycle for the vehicle with the P2/P3 Hybrid Powertrain and compared with the baseline Automatic Transmission powertrain. Five drive cycles were selected from the NREL DriveCAT database [2] to analyze commercial heavy-duty vocational applications. The details of the cycles are listed in Table 4. The time-series plots of the five commercial vehicle drive cycles are shown in Figure 3 – 7 along with a brief description.

Drive cycle	Distance	Max speed	Avg. speed	Stops	Drive time	Idle time
	[mi]	[mph]	[mph]	[#]	[%]	[%]
Los Angeles Port Drayage Composite Cycle	35.2	64.2	17.6	27	53%	47%
Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles (UDDS HD)	5.6	58.0	18.8	14	67%	33%
CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Composite Cycle	26.1	59.3	26.0	13	73%	27%
Miami-Dade Refuse Cycle	1.9	52.8	7.7	20	44%	56%
City Suburban Heavy Vehicle Cycle (CSHVC)	6.7	43.8	14.1	13	77%	23%

Table 4: Key Metrics of Commercial Vehicle Drive Cycles

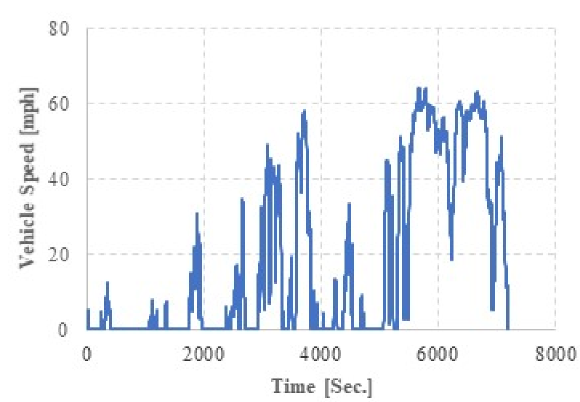

Figure 3: Los Angeles Port Drayage Composite Cycle

The Los Angeles Port Drayage Composite Cycle is a four-mode drive cycle developed by NREL utilizing drayage driving data from vehicles operating in and around the Ports of Los Angeles and Long Beach (POLA/POLB). The cycle is a composite of four NREL port drayage cycles, including creep queue, local, metro highway, and near dock.

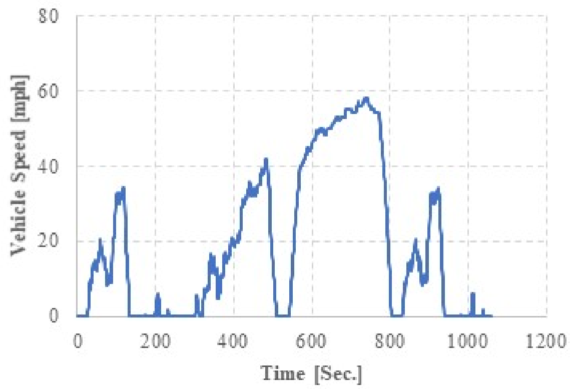

Figure 4: Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles - UDDS HD

The Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles is a test cycle for heavy-duty vehicles based on the Environmental Protection Agency's Urban Dynamometer Driving Schedule.

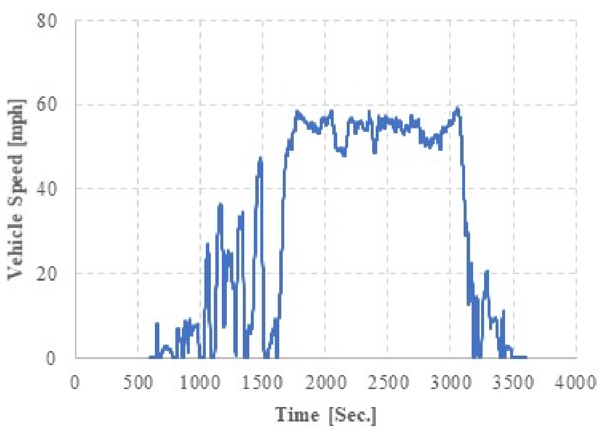

Figure 5: CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Composite Cycle.

The CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Composite Cycle is a composite of four-mode chassis dynamometer test cycle for heavy-duty vehicles developed by the California Air Resources Board (CARB) and West Virginia University. The four modes of the cycle are idle, creep, transient, and cruise driving.

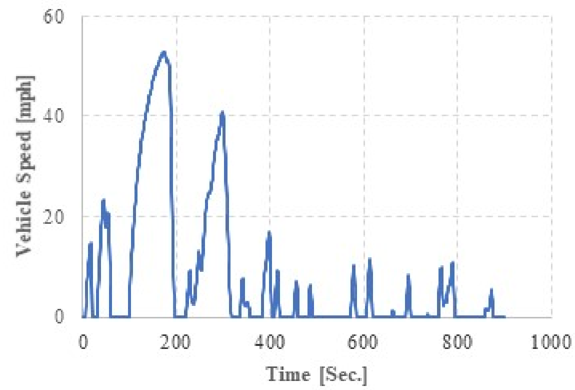

Figure 6: Miami-Dade Refuse Cycle

The Miami-Dade Refuse Cycle was developed by NREL from automated side-loader refuse truck data. The vehicles were operated by Public Works and Waste Management in Miami-Dade County, Florida.

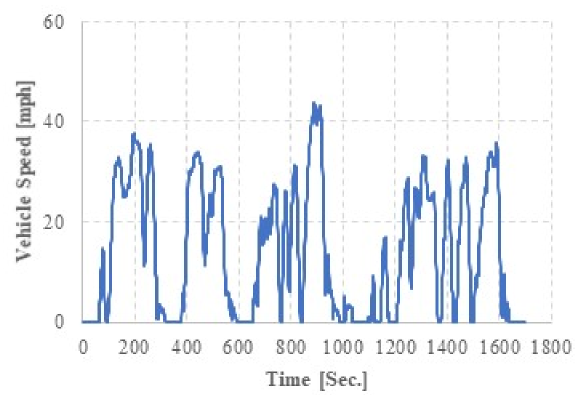

Figure 7: City Suburban Heavy Vehicle Cycle - CSHVC

The City Suburban Heavy Vehicle Cycle (CSHVC) was developed by West Virginia University using operating data from trucks in Richmond, Virginia, and Akron, Ohio. The cycle also known as the City Suburban Cycle (CSC).

For military vehicle applications, the UDDS HD cycle in Figure 4, and CARB HHDDT cycle shown in Figure 5 were modified to expand the vehicle idle time to 60% of the total drive cycle time. For example, the idle time for the UDDS HD cycle is 33% (see Table 4) while in the modified UDDS HD cycle it is 60% as shown in Table 5. The time-series plots of the two modified cycles are shown in Figure 8 and Figure 9.

Cycle	Distance	Max Speed	Avg. Speed	Stops	Drive time	Idle time
	[mi]	[mph]	[mph]	[#]	[%]	[%]
Modified UDDS HD	5.6	58	18.8	14	40%	60%
Modified HHDDT Composite Cycle	26.1	59.3	26	13	40%	60%

Table 5: Key Metrics of Representative Military Vehicle Drive Cycles

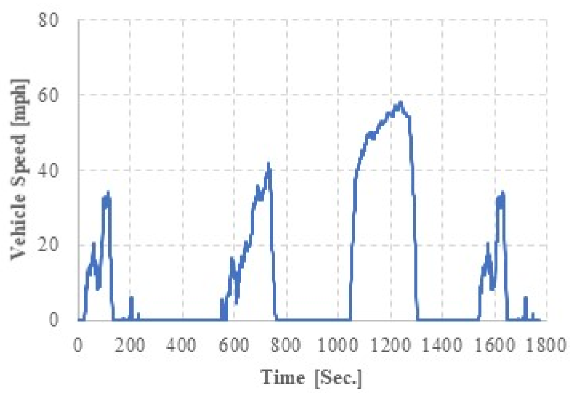

Figure 8: Modified UDDS HD Cycle for Representative Military Application.

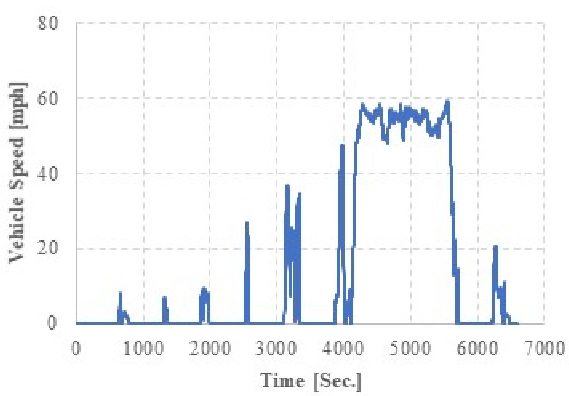

Figure 9: Modified CARB HHDDT Composite Cycle for Representative Military Application.

4. POWERTRAIN SIMULATION RESULTS AND DISCUSSION

The model of the P2/P3 Hybrid Powertrain system outlined in Section 2.2 was used to evaluate the vehicle performance criteria, namely, (1) ability to achieve top speed, (2) ability to maintain top speed on grade (gradeability), and (3) ability to launch on grade (startability), as specified in Table 2, and vehicle fuel economy for selected drive cycles shown in Table 4 and Table 5. A model of a heavy-duty automatic transmission (AT) was previously developed based on the EPA Greenhouse Gas Emission Model (GEM) [2] for evaluating the performance and fuel economy of the baseline powertrain system. The simulation results for commercial vehicle application are discussed in section 4.1, followed by military vehicle application results in section 4.2.

4.1. Commercial Vehicle Results

Figure 10 shows the 0-70 mph wide-open throttle vehicle response plots of the P2/P3 hybrid transmission and the baseline AT Transmission with GCWR of 110 klb. The P2/P3 hybrid transmission can meet the vehicle top speed requirement of 65 mph. Further, the P2/P3 hybrid transmission demonstrates better acceleration performance by reaching the top speed faster than the baseline AT Transmission.

The inset in Figure 10 demonstrates that during low vehicle speeds, the P2/P3 hybrid transmission matches the acceleration performance of the AT (which has the torque multiplication from the open torque converter). When the vehicle speed reaches 14.5 mph, the range box of the P2/P3 hybrid transmission shifts and causes a torque interrupt as seen in the dip in the vehicle speed at 15 s. During all other transmission shifts, the engine torque to the wheels is interrupted, but the electric motor continues to provide torque-fill causing the vehicle to continue to accelerate smoothly. Table 6 shows the time taken to reach different speeds by both the P2/P3 hybrid transmission and the baseline AT Transmission.

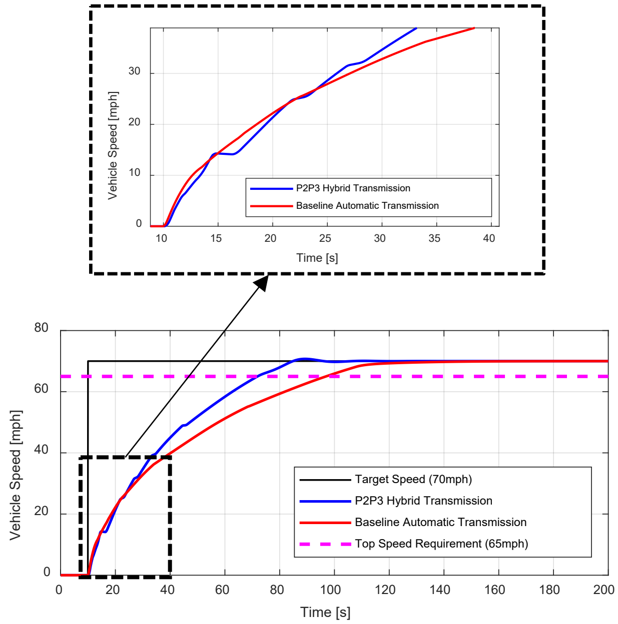

Figure 10: Commercial Vehicle 0-70 mph WOT Simulation: P2/P3 vs. Baseline

Transmission	Time to Reach [s]			
Speed	15 mph	30 mph	45 mph	65 mph
P2/P3	7.1	15.8	30.1	61.9
AT (Baseline)	5.4	17.1	38.6	86.9

Table 6: WOT Acceleration for Commercial Vehicle: P2/P3 vs. Baseline

Figure 11 shows the gradeability simulation results (the road grade increases to target value of 1% once the vehicle achieves the top speed of 65 mph) comparing the P2/P3 Hybrid Transmission with the baseline AT for a 110 klb commercial vehicle. The vehicle speed drops from its top speed momentarily as the road grade increases (as seen in the inset) but recovers much faster for the P2/P3 case as the hybrid system increases the torque to the wheels in response to the increased load using the electric motor that responds much faster than the diesel engine alone. It is noted that, in simulation the road grade is applied based on the distance traveled by the vehicle. As the vehicle speed for the two powertrains are different, they arrive at the

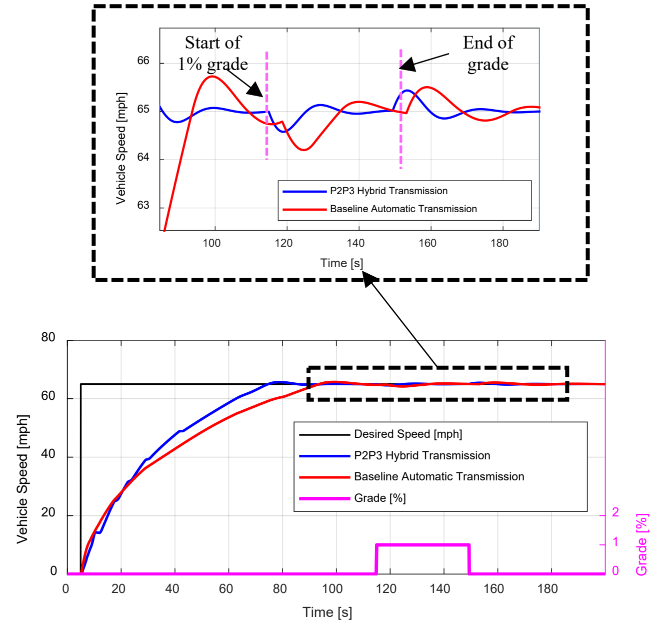

Figure 11: Commercial Vehicle Gradeability Simulation

'start of grade' at slightly different times, as seen in Figure 11 inset.

Figure 12 shows the startability simulation results for commercial vehicle. The P2/P3 system launches the 110 klb vehicle from rest to steady-state speed of 4.2 mph on a 20% grade.

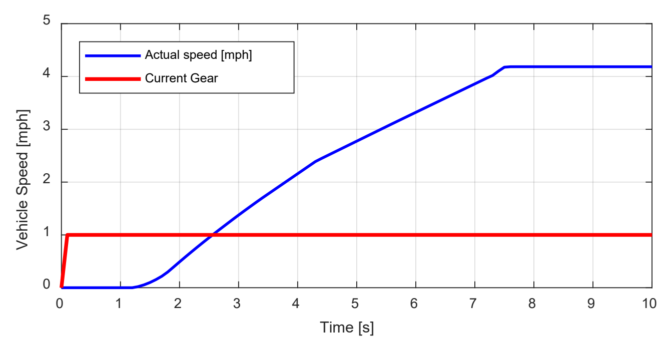

Figure 12: Commercial Vehicle Startability Simulation

Table 7 shows the fuel economy (FE) simulation results for commercial vehicle application using the baseline AT and P2/P3 Hybrid Transmission. The simulations were run with identical vehicle GCWR of 110 klb for both the powertrains to ensure fair comparison. The results show the fuel economy gain of the P2/P3 system over the baseline AT system. The distance traveled in the simulation is within 5% of the actual drive cycle distance for all the vehicle use cases.

Cycle	Cycle distance	Distance traveled	Fuel used	FE	ΔSOC	SOC adjusted FE	FE gain
	[mi]	[mi]	[gal]	[mpg]	[%]	[mpg]	[%]
Baseline Heavy-duty Automatic Transmission							
LA Port Cycle	35.21	34.64	9.17	3.79	0	3.79	
UDDS HD	5.55	5.44	1.65	3.31	0	3.31	
CARB HHDDT	26.05	25.96	5.07	5.12	0	5.12	
Refuse Cycle	1.94	1.91	1.00	1.91	0	1.90	
CSHVC	6.68	6.55	2.48	2.65	0	2.65	
P2/P3 Hybrid Transmission							
LA Port Cycle	35.21	34.93	8.08	4.32	8.6	4.29	13.2
UDDS HD	5.55	5.49	1.32	4.15	2.2	4.10	24.2
CARB HHDDT	26.05	26.02	4.70	5.54	-1.3	5.55	8.4
Refuse Cycle	1.94	1.93	0.76	2.55	7.4	2.39	25.5
CSHVC	6.68	6.59	1.93	3.42	7.7	3.33	25.6

Table 7: Commercial Vehicle Fuel Economy (FE) Results

The SOC adjusted fuel economy for the hybrid powertrain was calculated using an approximation of the SAE standard for fuel correction of charge sustaining hybrid vehicle drive cycle tests [3], shown in equations (1-2). The battery SOC change over the course of the drive cycle is calculated as the difference between the SOC at the start of the cycle and the SOC at the end of the cycle.

$$FE' \,[mpg] = \frac{D\,[mi]}{(F\,[gal] + F'\,[gal])} \quad (1)$$

$$F'\,[gal] = \frac{\Delta SOC\,[\%] * E\,[kWh]}{FHV\,[kWh.kg^{-1}] * \rho\,[kg.gal^{-1}]} \quad (2)$$

In equations (1-2), *FE'* is the fuel economy adjusted for battery state-of-charge (SOC) change in miles per gallon, *D* is the distance traveled in miles, *F* is the actual fuel used by the engine in gallons, *F'* is the ΔSOC equivalent fuel used in gallons, *E* is the battery energy capacity in kWh, *FHV* is the diesel fuel heating value in kWh/kg, and *ρ* is the diesel fuel density in kg/gal. The equations do not include any charging efficiency term to avoid different biasing for the cases where the SOC change over the drive cycle is positive or negative.

4.2. Military Vehicle Results

Figure 13 shows the 0-70 mph wide-open throttle vehicle response plots of the P2/P3 hybrid transmission and the baseline AT Transmission for military vehicle. The P2/P3 hybrid transmission meets the top speed requirement of 62 mph. Further, the P2/P3 hybrid transmission demonstrates better acceleration performance by reaching the top speed faster than the baseline Automatic Transmission system. Table 8 shows the times taken by the two transmissions to reach different intermediate speeds.

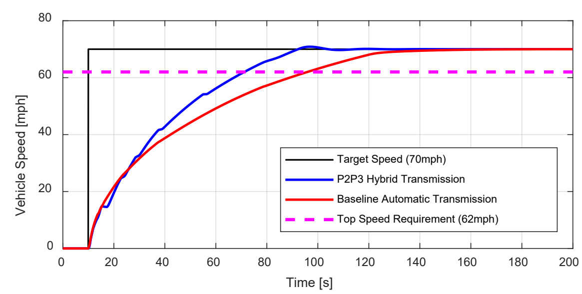

Figure 13: Military Vehicle 0-70 mph WOT Simulation: P2/P3 vs. Baseline

Transmission	Time to Reach [s]			
Speed	15 mph	30 mph	45 mph	65 mph
P2/P3	7.8	17.2	32.7	61.2
AT (Baseline)	5.5	18.1	41.5	85.9

Table 8: WOT Acceleration for Military Vehicle: P2/P3 vs. Baseline

Figure 14 show the gradeability results for military vehicle. The vehicle speed drops from its top speed momentarily as the road grade increases to target value of 2%, but the vehicle with the P2/P3

Transmission recovers quicker than the baseline AT as seen in the inset. This is due to the fact that the P2/P3 Transmission uses a combination of motor torque (which responds very fast) and engine torque (which responds much slower) to respond to the grade disturbance and regulate the vehicle top speed much better than the baseline AT. It should be noted here that the driver model parameters for both the powertrain simulation models were kept identical. Further, in comparison with Figure 11, the AT responds much slower in the military vehicle because the diesel engine is operating at its peak speed and is torque limited to respond to the increased vehicle load.

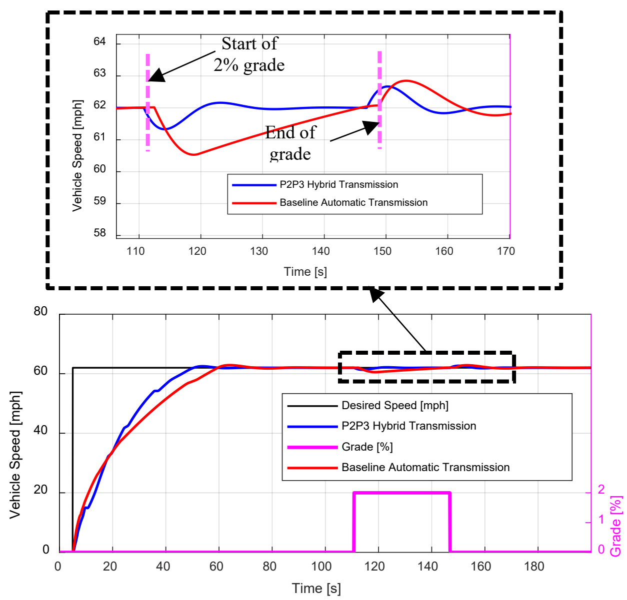

Figure 14: Military Vehicle Gradeability Simulation

Figure 15 shows the startability result for a 109 klb military vehicle launching on a 30% grade. The vehicle achieves steady-state speed of 4.5 mph. Figure 16 shows the startability result for a 72.5 klb military vehicle launching on a 60% grade, with the vehicle reaching steady-state speed of 2.8 mph. The results indicate that the P2/P3 Hybrid Transmission can meet the startability requirements for the military vehicle.

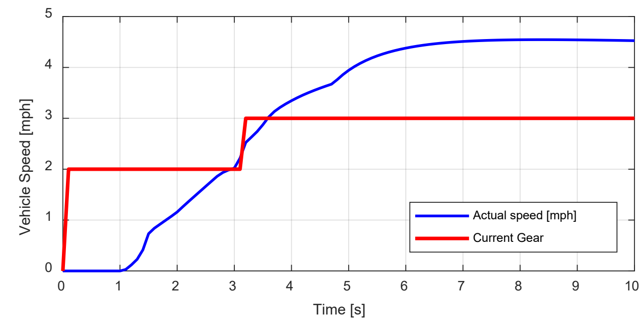

Figure 15: Military Vehicle Startability on 30% Grade Simulation

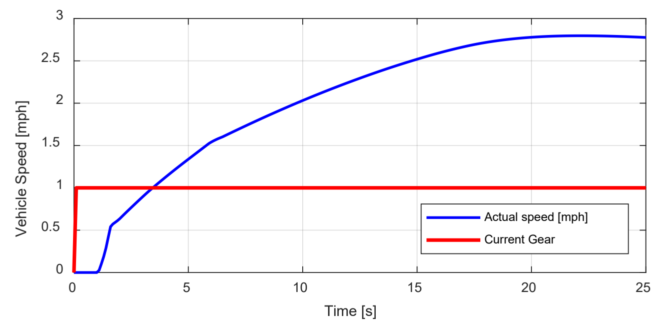

Figure 16: Military Vehicle Startability on 60% Grade Simulation

Table 9 shows the fuel economy (FE) results for a 109 klb military vehicle application. The P2/P3 Hybrid Powertrain demonstrates fuel savings of 28.9% and 21.2% over the baseline AT

Cycle	Cycle distance	Distance traveled	Fuel used	FE	ΔSOC	SOC adjusted FE	FE gain
	[mi]	[mi]	[gal]	[mpg]	[%]	[mpg]	[%]
Baseline Heavy-duty Automatic Transmission							
Modified UDDS HD	5.55	5.44	2.14	2.54	0	2.54	
Modified CARB HHDDT	26.05	25.94	7.06	3.67	0	3.67	
P2/P3 Hybrid Transmission							
Modified UDDS HD	5.55	5.49	1.66	3.31	2.5	3.28	28.9
Modified CARB HHDDT	26.05	26.02	5.82	4.46	3.0	4.45	21.2

Table 9: Military Vehicle Fuel Economy (FE) Results

Transmission for the modified UDDS HD and CARB HHDDT drive cycles, respectively.

To discuss the fuel savings achieved by the P2/P3 Hybrid Transmission, time-series plots of key model variables are shown in Figure 17 for simulation of the Modified CARB HHDDT Cycle. Figure 17 (a) shows the target and actual vehicle speeds, the transmission gear number and the battery SOC, Figure 17 (b) shows the engine and motor speeds, Figure 17 (c) shows the engine fuel rate and Figure 17 (d) shows the engine and motor torque values. The P2/P3 Hybrid Transmission achieves significant reduction in fuel consumption while meeting the drive cycle power demands primarily through the following features:

1. Electric only vehicle operation during low-speed portions of the drive cycles. The P2/P3 hybrid transmission uses the electric motor to propel the vehicle for low speed maneuvers on flat ground when the battery SOC is sufficiently high thereby saving fuel. As shown in Figure 17, the low speed excursions of the vehicle (in the time window [0-2000 s] of the drive cycle) are accomplished using only the electric motor, while the engine remains at idle (evidenced by the engine fuel rate remaining near zero).
2. Improved engine operation over the entire drive cycle due to hybrid torque blending. The P2/P3 hybrid transmission can blend the electric motor torque with the engine torque to ensure the drive cycle torque demand is met. By strategically implementing torque blending, the P2/P3 system can reduce the load on the engine and thus its fuel consumption. The torque blending feature is highlighted in Figure 18 (in the time window [3050-3400 s] of the drive cycle) where the motor assists the engine in accelerating the vehicle resulting in lower fuel consumption.
3. Vehicle brake energy recovery to charge the battery. The P2/P3 hybrid transmission absorbs some of the vehicle brake energy via regeneration into the battery to maintain the battery SOC throughout the drive cycle. This is highlighted in Figure 19 (in the time window [5550-5750 s] of the drive cycle) where the electric motor applies braking torque to decelerate the vehicle resulting in the battery SOC rising from 40% to nearly 50%.

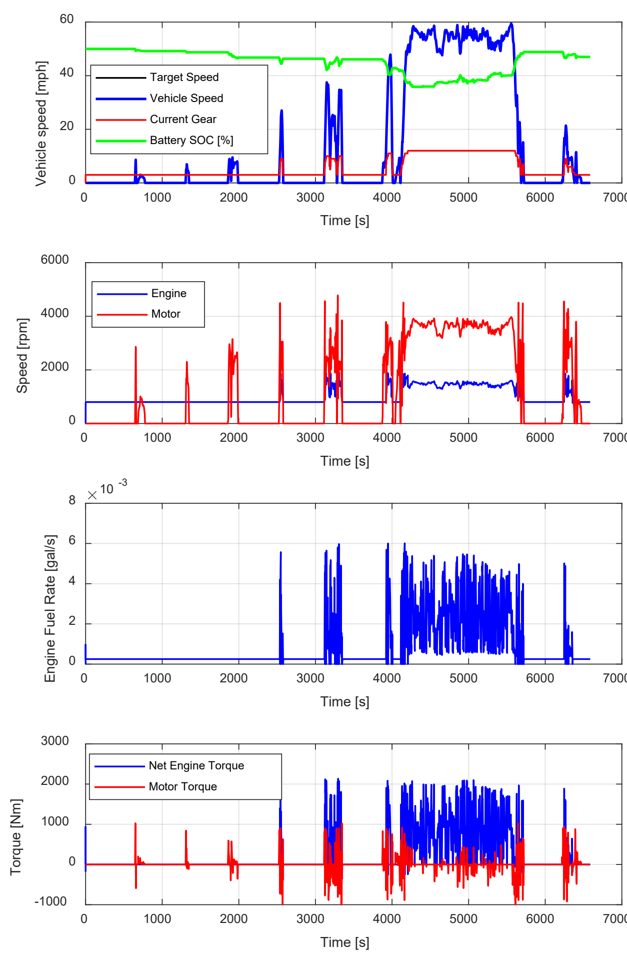

Figure 17: P2/P3 Hybrid Transmission Simulation Results for Modified CARB HHDDT Cycle

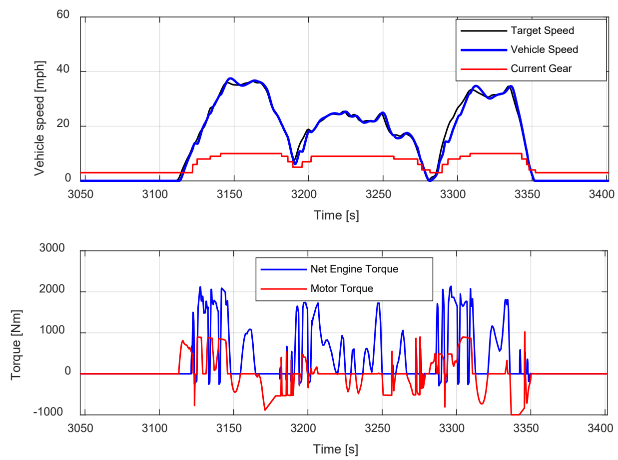

Figure 18: Torque Blending in P2/P3 Hybrid Transmission

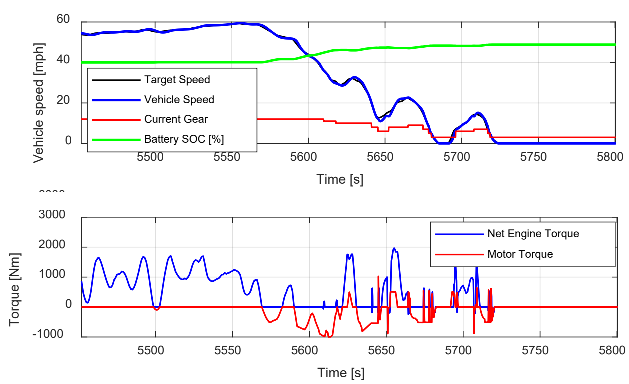

Figure 19: Vehicle Brake Energy Recovery in P2/P3 Hybrid Transmission

5. CONCLUSIONS

The paper presented the efforts to evaluate the fuel economy and performance of the P2/P3 Hybrid Transmission for commercial and military use cases through modeling and simulation. An overview of the modeling approach and assumptions were presented along with details of the P2/P3 Hybrid Powertrain model. The requirements for vehicle performance and vehicle use cases were identified. The simulation results using the developed model showed that the P2/P3 Hybrid Powertrain has better acceleration performance compared to the baseline Automatic Transmission system and met the gradeability and startability requirements for both commercial and military applications. The simulation results also showed fuel economy improvement for commercial vehicle between 8% to 26% depending upon the drive cycle over the baseline system. For the military vehicle, the fuel economy improvement was 21% to 28% for the two drive cycles evaluated. Further optimization of the design of the P2/P3 Hybrid Powertrain (including engine sizing, appropriate selection of final drive ratio, battery sizing) can improve both the vehicle performance and fuel economy.

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