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EVALUATION OF THE EFFECTS OF ADVANCED HYBRID TRANSMISSION CONTROL TECHNOLOGIES ON HEAVY-DUTY COMMERCIAL TRUCK APPLICATIONS

Emircan Beşler, Orkun Özener

Department of Mechanical Engineering, Yıldız Technical University, 34349, Istanbul, Turkey

ABSTRACT

Hybrid powertrain topologies are in the consideration for heavy-duty commercial truck applications for better energy management and emission reduction possibilities. Different hybrid powertrain architectures were already evaluated by engineers to see potential benefits, improvements on driving performance and fuel economy. Having said these, potentials of complex hybrid transmission control capabilities need to be evaluated to see where the gain is and what these can bring to the table. A one-dimensional vehicle model was developed in combination with an advanced hybrid transmission control unit to perform co-simulation runs on different regulatory drive cycles. The main objective of the present study is to investigate the potential benefits of P2-P3 mixed hybrid automated manual transmission with advanced transmission control techniques can provide in transient drive cycles in terms of fuel economy and engine out emission with simulation methodology. The analysis results have shown that P2-P3 mixed hybrid transmission can provide significant improvements on fuel economy (up to %15+) and reduction on engine out emissions (up to %10+) on transient drive cycles for heavy-duty commercial truck applications.

Keywords: *Hybrid Powertrain, Heavy-duty Trucks, Commercial Vehicles, Fuel Economy, Emissions, Automated Manual Transmission, Internal Combustion Engine*

INTRODUCTION

Heavy-duty commercial transportation is playing a key role in today's world for global warming threat, air quality and environment. However, it is also crucial for satisfying todays and future transportation demands to continue living like we humans all do, achieving the things that we all desire in a faster and cheaper way. Not only passenger cars or motorcycles, but heavy-duty trucks are also in the talks for many years by the authorities for decreasing their emission output and increasing the fuel economy. OEMs are continuously searching for better overall powertrain efficiency by introducing innovative architectures with their new products into the heavy-duty commercial truck market. Battery electric vehicles have been introduced by Volvo Trucks; hydrogen combustion engines are at a very advanced development stage for Daimler Trucks. Having said that, almost all truck manufacturers are searching for the best powertrain option for future heavy duty commercial transportation.

While there are still development areas that exist on the exterior of the vehicle (e.g., aerodynamic efficiency, rolling resistance reduction, etc.), the limits of the conventional powertrain concept of diesel internal combustion engine (ICE) are almost reached. In addition, the technologies that can be applied to the exterior of the truck are irrespective of the powertrain layout. Lots of different techniques are developed to increase powertrain efficiency, with the very first trend that came into mind is improvements on internal combustion engines with; combustion process enhancements, turbocharging, downsizing of the engine, etc. Another trend is to reduce emissions via focusing on the fuel by either using alternative fuel types or additives. Even though these developments are good for reducing the emission output and increasing the fuel economy, more dramatic improvements will be required to reach the desired levels.

[1] *Department of Mechanical Engineering, Ozyegin University, Istanbul, Turkey*
[2] *Department of Materials Engineering, University of Technology, Baghdad, IRAQ*
**E-mail address: layth.ismael@ozu.edu.tr, 130006@uotechnology.edu.iq*

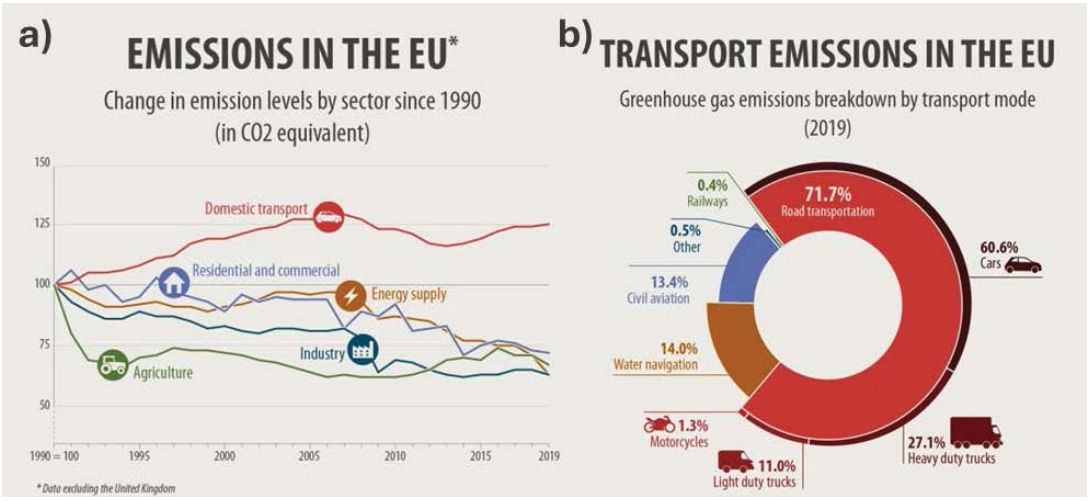


Fig 1. CO2 emissions in the European Union (EU): (a) evolution of CO2 emission in the EU by sector (*manufacture and construction industry) and (b) transport CO2 emissions in the EU [1].

An important option which can help to lower emissions and fuel consumption demands of heavy-duty road transportation is the use of battery electric powertrain layouts. Rather than using internal combustion engines for power generation, energy stored in a battery is converted to mechanical energy via electric motor(s) (EM). A single ratio gearbox can be used to optimize torque-speed characteristics at wheel level. Even though these types of powertrain concepts have shown their potential and are currently in use for the passenger car market, lack of long-range driving capability is the main backfoot for introducing this strategy into the heavy-duty commercial transportation sector. High energy demand due to high power and traction requirements, combined with longer distance travel needs is one of the primary focus areas of the heavy-duty truck market. For example, 10 kW drive power would be enough to a passenger car at 80 km/h on a flat road condition, whereas a loaded heavy-duty truck would need >100 kW drive power to perform the same maneuver [2]. In addition, this power demand difference increases even more during grade climbing scenarios. This means that larger batteries will be required to provide higher power demands while covering long range driving requirements. Larger batteries will come back with cost handicap and more importantly weight of these batteries will lower the amount of cargo that the tractor can transport.

Hybrid powertrain technologies are also in the discussion in recent years. There are multiple options to use at least one electric motor integrated into the powertrain of the truck, especially to the transmission. Different hybrid electric powertrain architectures for heavy duty commercial truck applications are investigated in terms of fuel economy and overall efficiency. Overall, study has shown that the parallel hybrid option is best one for covering varying scenarios, even though power-split is slightly better for fuel economy. [3]. Another article also evaluated the capabilities that hybridization can offer to the heavy-duty commercial vehicle market. It claimed that hybrid powertrains are best suited to drive cycles with frequent acceleration-deceleration maneuvers to reach higher system efficiencies. However, it also suggested that more advanced hybrid powertrain technologies should be evaluated to see potential benefits that can be explored [4].

THEORY

As already mentioned in previous sections, different hybrid powertrain topologies were already evaluated to see the potential in fuel economy gains for heavy-duty commercial truck applications. The aim of this study, however, is to investigate the effects of using advanced transmission control technologies to see the benefits in fuel efficiency and engine out CO_2 emissions.

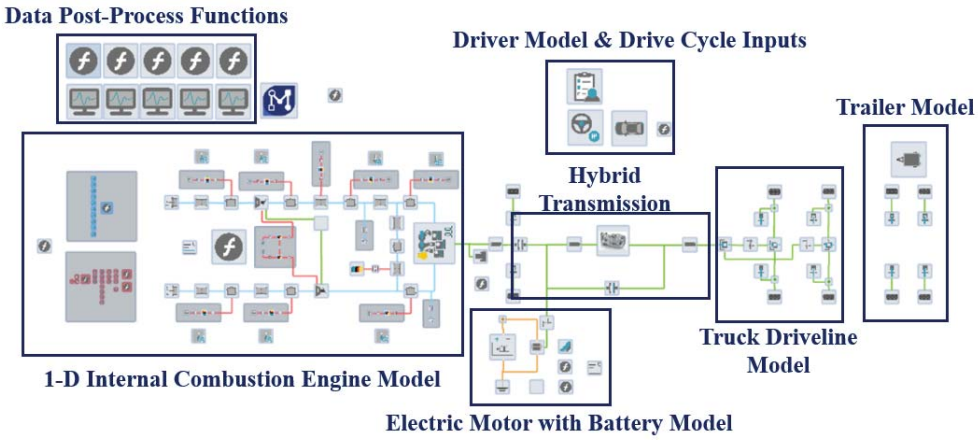


Figure 2. Heavy-duty commercial truck powertrain model (AVL Cruise M)

A detailed one dimensional (1-D) heavy-duty truck model that can provide P2 and P3 hybrid powertrain capability has been developed on AVL Cruise M modeling and simulation software tool. The model consists of a detailed 1-D diesel internal combustion engine, an electric motor and a battery model, 16-speed automated manual transmission (AMT) with friction clutch, a separator clutch to disconnect internal combustion engine and P3 enabling clutch to provide P3 hybrid power flow, differential and tires for tractor and a trailer to simulate extra cargo load. Hybrid Transmission Control Unit (HTCU) is also developed in the MATLAB/Simulink environment for load management of ICE and EM, transmission demand gear selection, clutch position and service brake pressure controls.

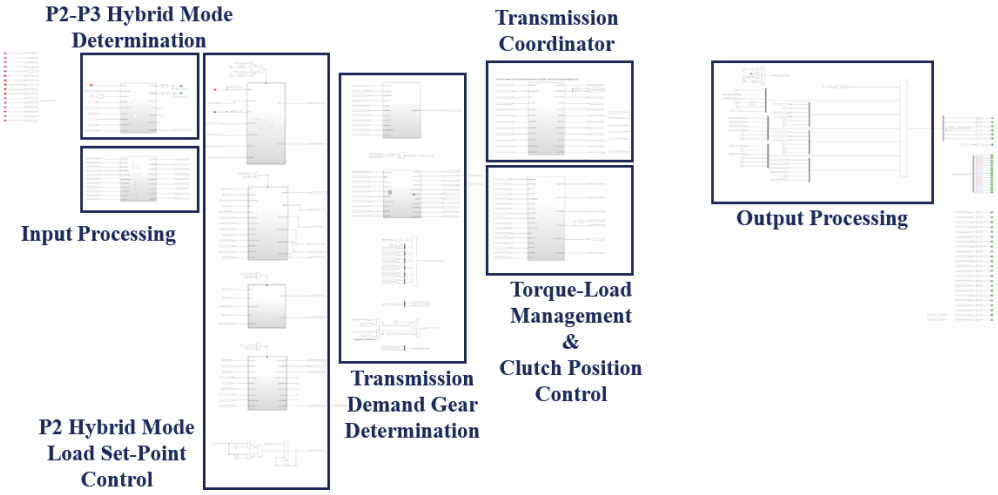


Figure 3. HTCU structure for P2-P3 Hybrid AMT control (MATLAB/Simulink)

Model Connect model integration and co-simulation platform of AVL Advanced Simulation Technologies (AST) is used to perform data communication and transfer between powertrain models developed with AVL Cruise M and HTCU developed on MATLAB/Simulink. Co-simulation with Tool-Interface (ICOS) is used, and data transfer connection is established.

POWERTRAIN COMPONENT SPECIFICATION

Inline 6-cylinder (I6) 13-liter diesel ICE with 2600 Nm maximum torque starting from 1000 rpm and 530 PS maximum power at 1700 rpm is used. EM maximum torque is 882 Nm at 3000 rpm with maximum power of 355 PS

between 3000 & 6000 rpm is selected and electrically connected to a 40 kWh capacity battery. A single gear ratio (1:3) gearbox is placed between EM output and AMT input to adjust EM torque-speed profile to ICE operation range. ICE and EM (with single gearbox ratio) full load torque-speed profiles are given below:

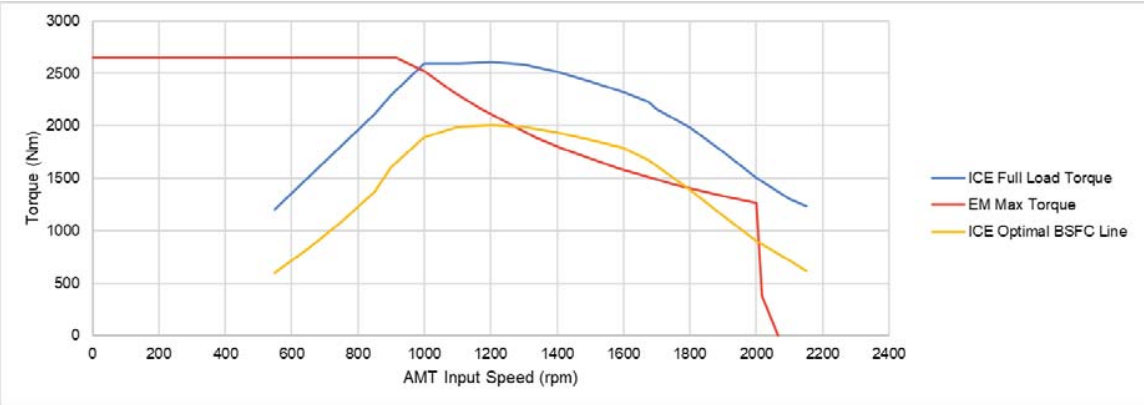


Fig 4. Full load torque curves of ICE and EM used in powertrain model

A 16-speed AMT is used in this powertrain model with 1st gear ratio of 1:15 and last gear ratio of 1:0,8 with power transfer efficiency of %97. Geometric gear ratio step methodology is used for internal gear ratio determination with gear ratio span of 1:1,215. In addition to this, gear engagement durations are adjusted according to the difference between next gear and current gear. For example, gear engagement time for single gear upshifts is 400 ms, whereas it is 600 ms for double upshifts and 800 ms for triple or more upshifts. For downshifts, however, shift durations are 100ms higher compared to upshifts.

Final drive ratio of the differential is 1:2.7 with %96 efficiency, tire radius is 0.472 m. Truck frontal area is 9,8175 m^2 and aerodynamic drag coefficient of 0.6 is used. Truck curb weight is 9 tons and, load of the trailer is adjusted depending on the drive cycles.

DRIVE CYCLES

Two different drive cycles are used to evaluate potential gains on fuel economy and engine out CO_2 emission: Vehicle Energy Consumption Calculation Tool's (VECTO) Regional Delivery (RD) and Long-Haul (LH) driving cycles with both cycles having 100 km driving range. Each cycle must be run in two different total vehicle mass conditions:

- Regional Delivery: 18,1 and 24,8 tons
- Long-Haul: 18,1 and 34,8 tons

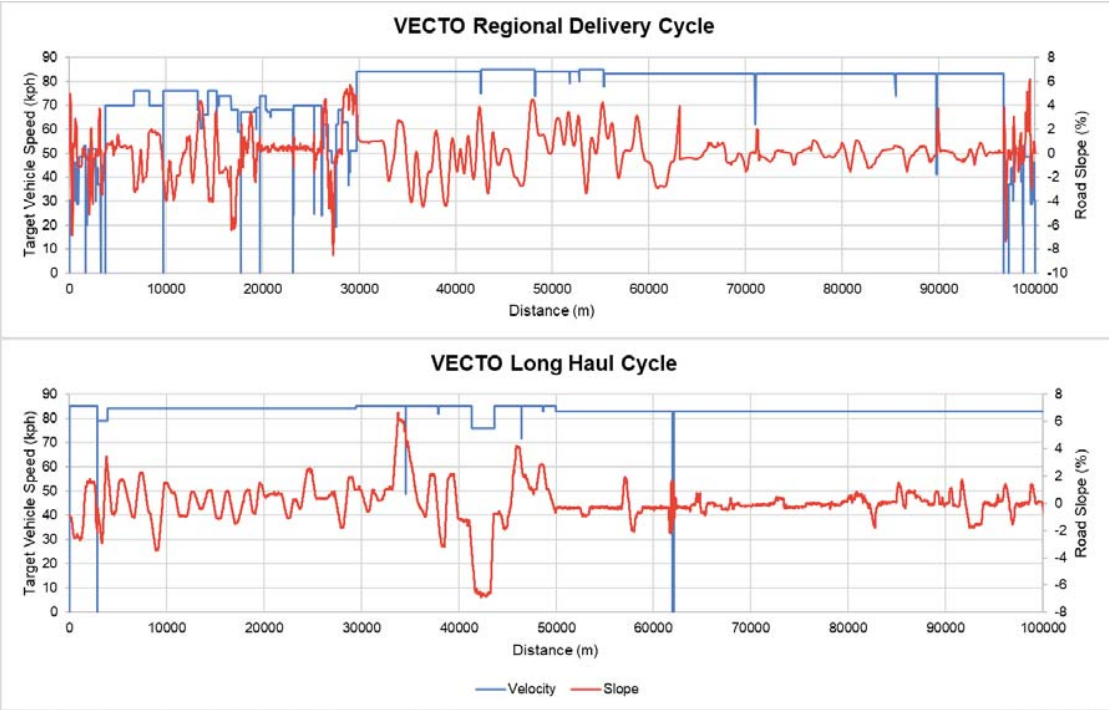


Fig 5. VECTO drive cycles

P2 & P3 Hybrid Control Modes of HTCU

HTCU provides six different hybrid control options for P2 hybrid option, these are: ICE Only mode, Electric Vehicle (EV) mode, Hybrid mode, Charge Sustaining mode, Battery Overcharge Protection mode, Braking mode with regeneration capability. EM and ICE load demand determination is calculated depending on active P2 hybrid mode. P2 hybrid mode is active during in-gear driving, meaning that once the transmission is engaged to a gear, then enabled mode will direct EM and ICE load demand. Each mode of P2 hybrid mode is to both provide the demand of the driver and keep the battery state of charge (SOC) at the desired level. EV mode provides EM only drive capability with ICE being inactive, whereas both ICE and EM are running in Hybrid mode with EM load being dependent on where the driver demand is placed on ICE fuel map. Charge Sustaining mode mainly aims to increase battery SOC level to target values while providing the driver's demand torque to the wheels. Battery Overcharge Protection mode on the other hand, as the naming suggests, allows more EM usage to consume battery energy while preventing SOC to go over higher thresholds. A detailed optimization is provided in Braking mode to adjust EM regenerative load demand with service brake demand to match driver's deceleration request by considering battery SOC level.

In addition, P3 hybrid control option is provided to cover speed loss that can occur during a gear shift process. EM load demand is calculated for the gear shift and then the P3 enabling clutch is closed to provide driving torque to the wheels while the gear shift is in progress.

Transmission Control Structure of HTCU

As state above, other than determining P2 and P3 hybrid mode activation and load set point management, HTCU also decides when to shift and calculates the demand gear for 16-speed AMT depending on multiple sources coming from powertrain sensors (i.e., accelerator pedal position, AMT output speed, ICE torque, etc.). Shift trigger maps used in HTCU for upshift and downshift events are dependent on active P2 hybrid mode state. In EV mode for example, ICE is not running, lower target AMT input shaft speeds can be aimed for selection of the next gear, whereas higher AMT input shaft speeds shall be aimed for ICE active cases. Desired gear selection is mainly dependent on shift speeds, target speeds and the calculated speed loss that will occur during the shift event. Speed loss during a shift event

is calculated for every possible shift scenario and then gear with optimum speed is selected. This strategy applies for both upshift and downshift events and continuously performed while driving.

Upshift Points ICE On (rpm)		AMT Current Gear																
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Accelerator Pedal Position (%)	0%	3000	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	5000
	10%	3000	1350	1350	1350	1350	1350	1350	1350	1350	1350	1350	1350	1350	1350	1350	1350	5000
	20%	3000	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	5000
	30%	3000	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	5000
	40%	3000	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	5000
	50%	3000	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	5000
	60%	3000	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	5000
	70%	3000	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	5000
	80%	3000	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1300	5000
	90%	3000	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1300	5000
	100%	3000	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1300	5000
Upshift Points ICE Off (rpm)		AMT Current Gear																
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Accelerator Pedal Position (%)	0%	3000	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	5000
	10%	3000	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250	1250	5000
	20%	3000	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	5000
	30%	3000	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	5000
	40%	3000	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	5000
	50%	3000	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1300	5000
	60%	3000	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1300	5000
	70%	3000	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1300	5000
	80%	3000	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1300	5000
	90%	3000	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1300	5000
	100%	3000	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1300	5000

Fig 6. Baseline upshift trigger points of HTCU depending on ICE on & off state. These shift points are later adjusted with respect to vehicle mass and road slope condition

Once the desired gear is determined in the shift logic, then all the clutch and torque controls specific to that shift are calculated in HTCU as well by considering the driving condition of the truck (i.e., vehicle mass, road slope, accelerator pedal position, etc.). Clutch closing and opening rates for example, are adjusted based on the truck's driving state to lower potential speed loss that can occur while opening and closing the friction clutch. An example illustration of an upshift event is given below for better visualization:

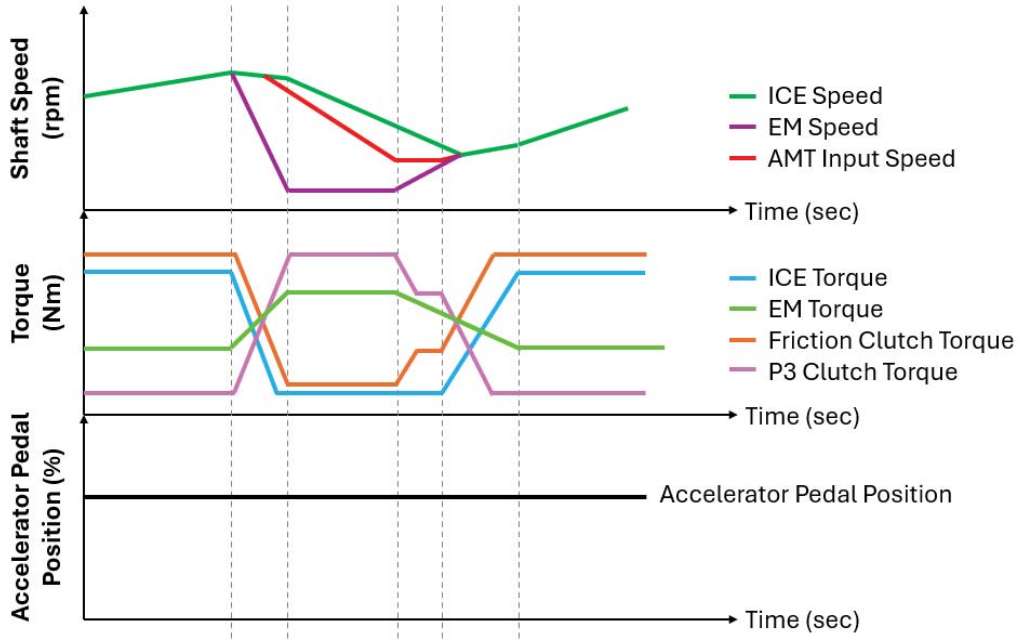


Fig 7. ICE-EM-clutch torque control strategies of HTCU during an upshift sequence

RESULTS AND DISCUSSION

Two different powertrain options which could be used in today's heavy-duty commercial trucks are compared in this study. First is the conventional one, 530 PS diesel internal combustion engine coupled with 16-speed traditional AMT with HTCU, second however, same diesel engine combined with 355 PS electric motor connected to hybrid P2-P3 capable 16-speed AMT. Vehicle simulation runs have been performed with initial %60 battery SOC capacity on above-mentioned VECTO RD and LH cycles.

Based on the simulation runs, it looks like hybrid transmission has around % 14-21 less fuel consumption, %17-24 less CO2 and 3-16 NOx engine-out emission output gains compared to conventional powertrain thanks to different shifting strategies used for varying hybrid driving modes and P3 hybrid driving capability during gear shifts. In terms of consumption advantage, hybrid transmission has the edge over conventional powertrain especially at 18.1-ton driving conditions of both VECTO RD & LH cycles thanks to EV mode capability. This also provides significant benefits at the emission side on these drive scenarios, again with the help of ICE-off driving option of EV mode. For both 28.4-ton VECTO RD and 34.8-ton VECTO LH cycles, again another very positive result can be seen for fuel consumption and CO2 engine-out emission outputs. However, an increase in vehicle mass resulted in a very low gain on NOx engine-out emission, reduced to %10 for 28.4-ton RD cycle and even %3 for 34.8-ton LH cycle. This can be explained with a high average accelerator pedal position driving requirement of 34.8-ton LH cycle compared to other drive cycles (%10 higher average accelerator pedal position). High accelerator pedal driving will result as more optimal line operation of ICE for hybrid transmission, hence the possibility of more NOx engine-out emission output.

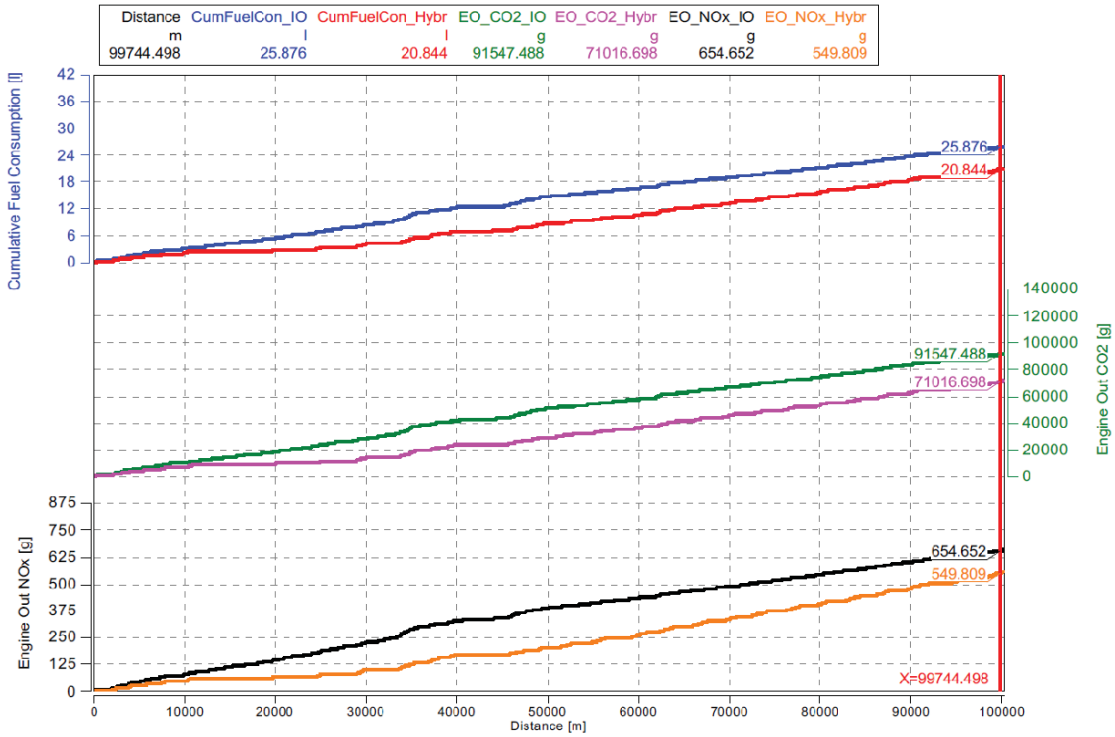


Fig 8. Fuel consumption, CO2-NOx engine-out (EO) emission outputs of ICE Only (IO) and P2-P3 mixed Hybrid Transmission (Hybr) on VECTO LH cycle with 18.1-ton truck

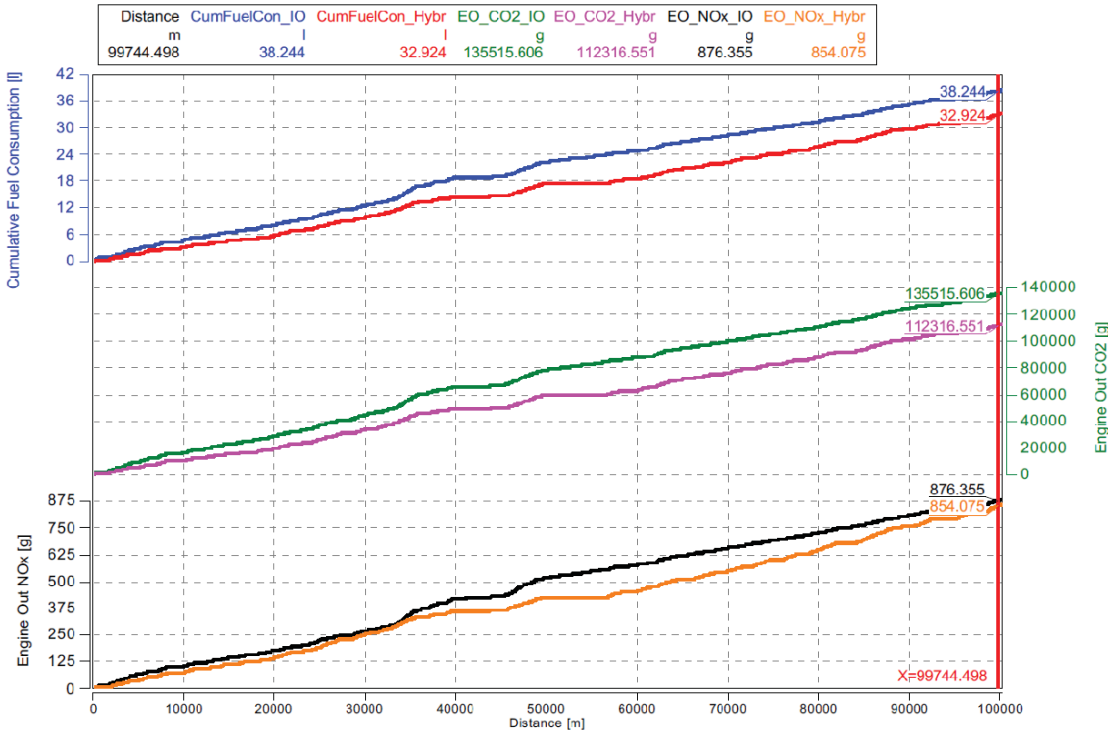


Fig 9. Fuel consumption, CO2-NOx engine-out (EO) emission outputs of ICE Only (IO) and P2-P3 mixed Hybrid Transmission (Hybr) on VECTO LH cycle with 34.8-ton truck

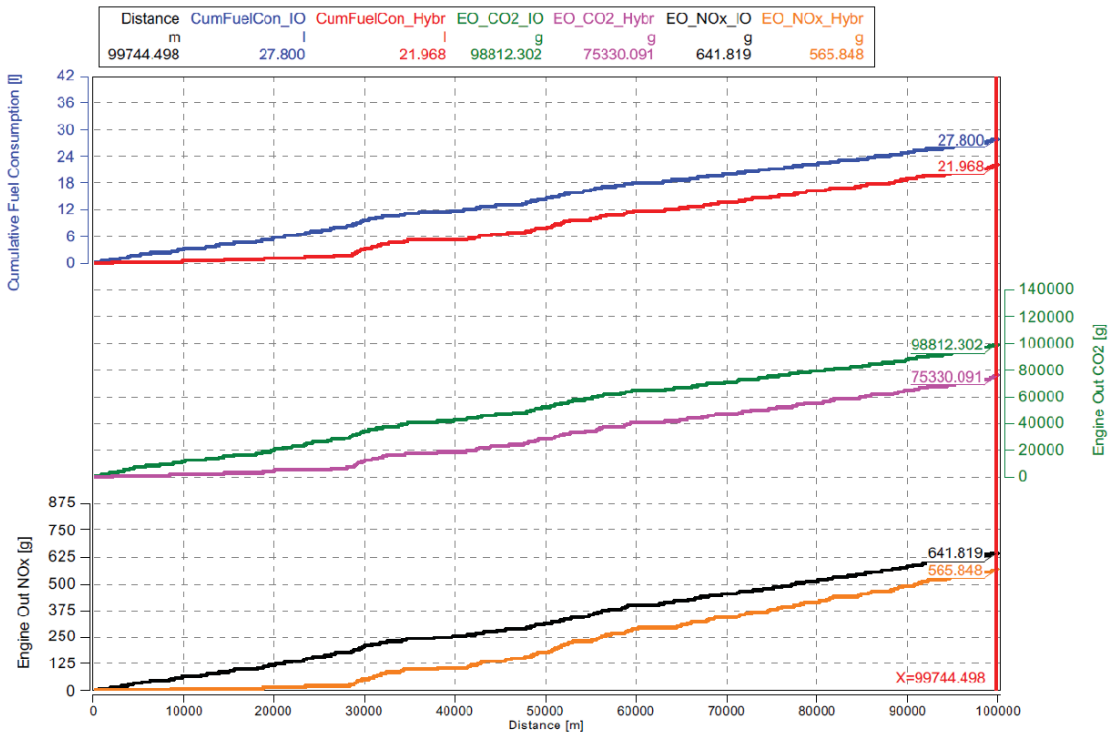


Fig 10. Fuel consumption, CO2-NOx engine-out (EO) emission outputs of ICE Only (IO) and P2-P3 mixed Hybrid Transmission (Hybr) on VECTO RD cycle with 18.1-ton truck

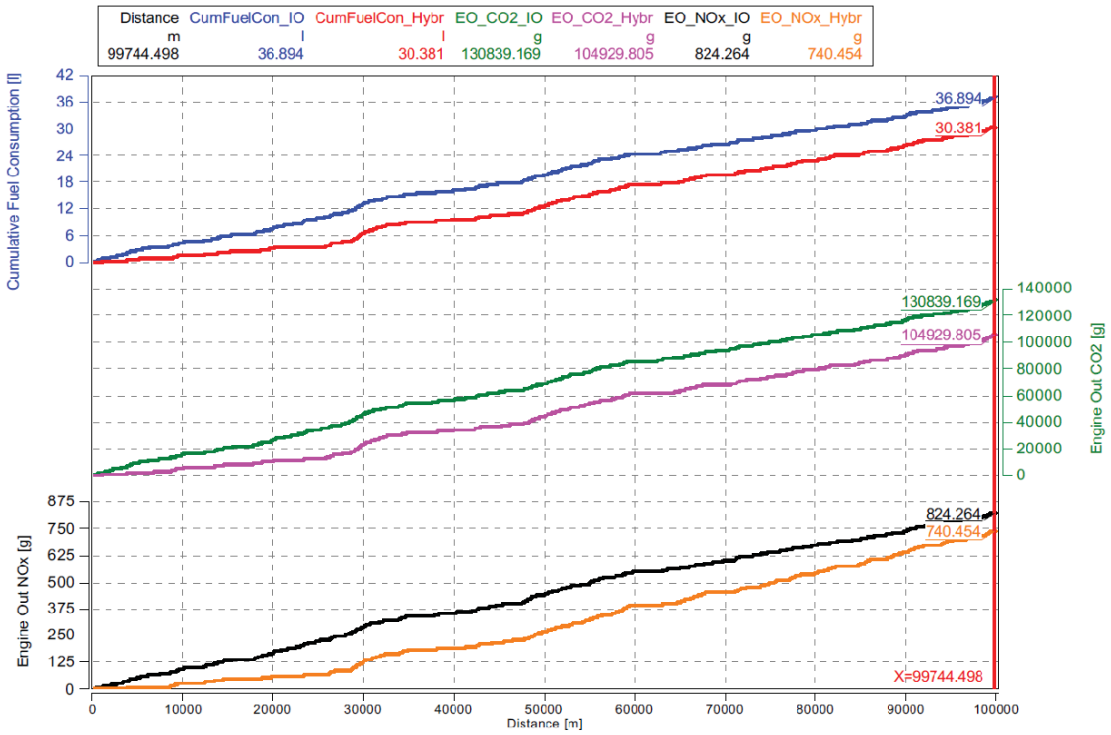


Fig 11. Fuel consumption, CO2-NOx engine-out (EO) emission outputs of ICE Only (IO) and P2-P3 mixed Hybrid Transmission (Hybr) on VECTO RD cycle with 28.4-ton truck

CONCLUSION

A hybrid P2-P3 mixed transmission with advanced control features is compared with a conventional powertrain on heavy-duty commercial trucks at VECTO cycles. 2 different vehicle mass conditions, as offered at VECTO simulations have been considered on 2 VECTO cycles (RD & LH). Hybrid P2-P3 mixed transmission with developed HTCU controller showed up to %20+ fuel economy advantages and %15-20 engine-out emission gains compared to conventional powertrain options. Further upgrades on HTCU controller capability and calibration improvements can provide even more increase in fuel economy and can lower engine-out emissions even more.

NOMENCLATURE

$CumFuelCon_IO$	Cumulative fuel consumption for ICE Only powertrain, l
$CumFuelCon_Hybr$	Cumulative fuel consumption for P2-P3 mixed hybrid transmission powertrain, l
EO_CO2_IO	Engine-out CO2 emission for ICE Only powertrain, gram
EO_CO2_Hybr	Engine-out CO2 emission for P2-P3 mixed hybrid transmission powertrain, gram
EO_NOx_IO	Engine-out NOx emission for ICE Only powertrain, gram
EO_NOx_Hybr	Engine-out NOx emission for P2-P3 mixed hybrid transmission powertrain, gram

ACKNOWLEDGEMENT

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