ELECTRIFIED ACCESSORIES STUDY FOR 48 V HYBRIDS

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ABSTRACT

Electrification of accessories (*i.e.*, engine water pump, air-conditioner) in electrified vehicles is an enabler for increased system efficiency and higher fuel economy. This is achieved by eliminating the front-end accessory drive (FEAD), a source of engine friction, and more efficiently operating the devices that would have been driven by the FEAD at constant speeds relative to engine speed. Offsetting the efficiency benefit is a potential increase in cost. In this work, we investigate implementation of a dual-function e-Accessory drive that can independently drive an accessory component and also supplement the capability of the electric drive system for propulsion. The potential CO2 benefit of such a system relative to other propulsion configurations is assessed via simulation for the case of a 48V hybrid vehicle. An experimental system is also developed to demonstrate and assess basic functionality.

Keywords: Hybrid; Vehicle; Propulsion; Electric; Accessories; 48 V

ÉTUDE D'ACCESSOIRES ÉLECTRIFIÉS POUR LES HYBRIDES 48V

RÉSUMÉ

L'électrification des accessoires (c'est-à-dire la pompe à eau du moteur, le climatiseur) dans les véhicules électrifiés est un catalyseur pour une efficacité accrue du système et une plus grande économie de carburant. Ceci est réalisé en éliminant l'entraînement des accessoires frontaux (FEAD), une source de frottement du moteur, et en faisant fonctionner plus efficacement les dispositifs qui auraient été entraînés par le FEAD à des vitesses constantes par rapport au régime moteur. La compensation de l'avantage d'efficacité est une augmentation potentielle des coûts. Dans ce travail, nous étudions la mise en œuvre d'un entraînement e-accessoire à double fonction qui peut entraîner indépendamment un composant accessoire et également compléter la capacité du système d'entraînement électrique pour la propulsion. Le bénéfice CO2 potentiel d'un tel système par rapport à d'autres configurations de propulsion est évalué par simulation pour le cas d'un véhicule hybride 48V. Un système expérimental est également développé pour démontrer et évaluer les fonctionnalités de base.

Mots-clés : hybride; véhicule; Propulsion; Électrique; Accessoires; 48V

NOMENCLATURE

CO2	*Carbon Dioxide*
M/G	*motor-generator*
ICE	*Internal Combustion Engine*
S/S	*Start/Stop*
AWD	*All-Wheel-Drive*
PTO	*Power Take Off*
Px	*x = 0,1,2,3,4: Hybrid Configuration*
FEAD	*Front End Accessory Drive*
FTP	Federal Test Procedure (U.S.)

1 INTRODUCTION

A critical and ongoing task for vehicle manufacturers today is the development of technologies to reduce the CO2 emissions from their products. While the electric vehicle is seen as the long-term solution by many, the internal combustion engine (ICE) will remain a propulsion option, representing a significant portion of vehicle sales over the next ten to fifteen years, particularly in the U.S. [1]. For ICE-equipped vehicles, electrification of the propulsion system is a common strategy for improving ICE efficiency. The simplest electrification option is a start/stop (S/S) system with a more robust starter motor to stop the engine to avoid idling while the vehicle is stopped and restarting it when needed [2]. A mild (or light) hybrid system goes one step further, using a more powerful motor and dedicated battery to provide some level of engine-torque assist and vehicle kinetic energy recuperation in addition to start/stop [3]. Maximum electric motor power is typically under 20 kW. A strong hybrid system improves on the benefits offered by the mild hybrid by permitting some level of engine-off electric driving and greater kinetic energy recuperation via a yet larger motor system [4]. Maximum electric motor power can often exceed 50 kW in such systems.

While electrification is beneficial for reducing CO2, the cost of adding this capability is not without cost, which generally rises as system electric power increases. With this in mind, options were studied for maximizing the CO2 reduction benefit of a mild hybrid system by looking at 48V motor technology to try to provide the greatest benefit relative to system cost. For mild hybrid systems, motors are generally an add-on to the conventional powertrain rather than a unique integrated design as in [4]. The position of the electric motor assisting or providing propulsion is typically denoted as P0, P1, P2, P3 or P4. Table 1 provides working definitions of these terms.

Table 1. Hybrid System Definitions

Hybrid Configuration	Electric Motor Location
P0	Engine Starter Position (typically next to the engine flywheel)
P1	Front of the Engine, often connected to the engine accessory drive
P2	Between the engine and transmission, often coupled with an engine disconnect clutch to allow the motor to drive the vehicle
P3	At the output of the transmission
P4	Connected to the non-engine axle of the vehicle

The GM R&D 48V P2-hybrid project [5] demonstrated an engine-disconnect hybrid electric vehicle with a 15 kW P2 motor in a Sport Utility Vehicle (SUV). An estimated 14% reduction of gCO2/km was found over a baseline vehicle with engine start/stop, based on simulation as shown in Fig. 1. To limit hybridization cost and implementation, an electric air-conditioner compressor was not initially considered. Thus, the HVAC behaviour as found in a vehicle with engine start/stop was deemed acceptable. As an adjunct to the P2 project, alternatives to further reduce the predicted fuel consumption were investigated. As shown in Fig. 1, a 25 kW P2 motor system could further reduce the estimated CO2 by 5%. This could be implemented with a larger P2 motor without adding electric air-conditioning, as before, or other options could be considered, the genesis of the e-Accessories work described in this paper.

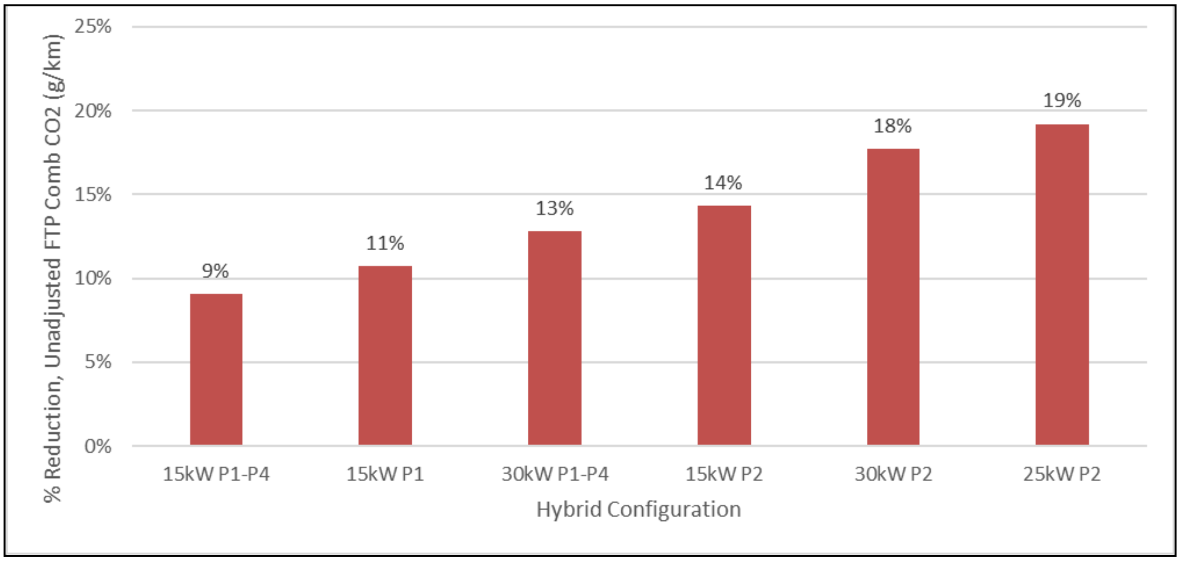

Fig. 1. 48V Hybrid Vehicle FTP CO2 for Various Propulsion Architectures.

2 SYSTEM DEFINITION

Reference [6] demonstrated a concept in which the P2 electric motor served double duty in driving the air-conditioner compressor while acting as the main electric propulsion unit, shown schematically in Fig. 2. In this case, the entire P2 motor and air-conditioner can be decoupled from the driveline when the vehicle is at standstill, facilitated by the automated manual implementation; it incorporates a disconnect clutch (the automated manual's starting or input clutch) downstream of the P2 motor package in addition to the engine disconnect clutch upstream of the P2. By using one motor for many tasks, system add-on cost is kept to a minimum. The limitations of this configuration are a) the air-conditioner compressor always runs at a constant speed relative to the P2 motor; b) when running in standstill mode, a large motor driving the A/C compressor will be more lightly loaded (and therefore less efficient) relative to a dedicated smaller unit. A dedicated unit can also operate at the optimal speed for the A/C compressor demand, regardless of other demands on the electrical propulsion system, maximizing system efficiency.

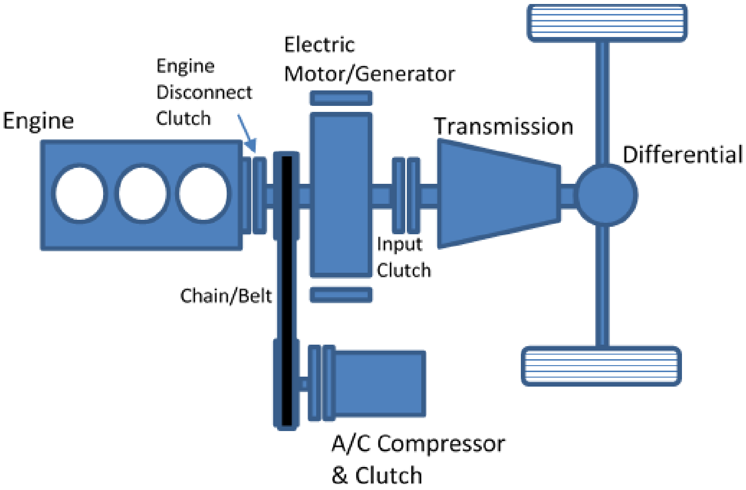

Fig. 2. P2 System with 1 Motor Used for Propulsion Assist and A/C drive

As an alternative to a single large P2 motor, a P2-P3 option for configuring an e-Accessory drive was studied, as shown in Fig. 3. The P2-P3 configuration was thought to provide a more packaging friendly option, given the existing space limitations with the 48 V P2 implementation. In the P2-P3 configuration, the main hybrid motor remains the P2 motor connected to the transmission input as shown schematically in Fig. 3. The P3 motor is clutched to the transmission output via a power takeoff (PTO) mechanism (transfer gearing shown). The A/C compressor unit is clutched to the P3 motor via a direct clutch connection as shown, or other offset gearing. The P3 option keeps the A/C compressor located in the front engine compartment. With this layout, the primary operating modes are shown in Table 2. C0 is the engine disconnect clutch, which may be internal to the transmission as in the R&D P2 implementation. C1 is the P3 drive clutch connecting the transmission output to the P3 motor and C2 is the clutch connecting the P3 motor to the A/C compressor. Based on the possible combinations of C0, C1 and C2, there are up to 9 clutch modes and therefore 27 motor modes (P2-only, P2-P3, P3-only). We can discount the P3-only modes since the P2 motor is always spinning so that it makes sense to utilize it; a P3-only electric mode is feasible but less useful because of the smaller P3 motor and the limited mechanical advantage of the motor in the P3 position.

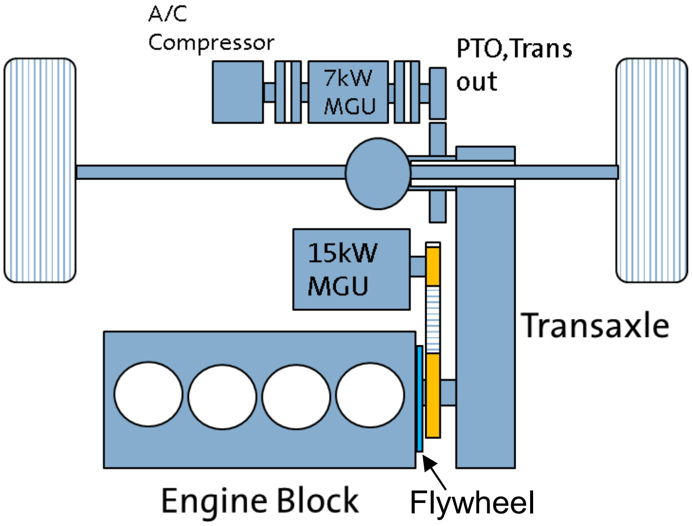

Fig. 3. e-Accessory P2-P3 Architecture Schematic.

Table 2. P2-P3 e-Accessory Modes

	C0	C1	C2
Electric Launch 1, P2-P3	Off	On	Off
Electric Launch 2, P2, electric A/C	Off	Off	On
Standstill electric A/C	Off	Off	On
Engine On, P2-P3 Assist, No A/C	On	On	Off

2.1 Sizing the P3 Motor and components

Typical electric AC compressors in GM applications like the Chevy Bolt use high-voltage (300 V) motors and have a displacement significantly smaller than typical engine driven units. For this study, an engine-driven unit was assumed, as a way to keep cost down and allow use of a lower cost 48V motor to fit the overall system voltage. The disadvantage of this approach is that compressor size makes packaging more difficult if the compressor is relocated from its usual location near the front of the engine. Maximum power consumption for large engine-driven compressors is approximately 10 kW. In most cases, maximum power on a thermal durability cycle would be in the range of 5-7 kW. The C2 clutch between the compressor and the P3 motor is the existing built-in electromagnetic compressor clutch. The P3 motor peak power choice is a tradeoff between cost and capability, as cost increases with power. In the case of a hybrid vehicle, we do not expect extended electric-only AC operation since the engine should be on under high power demand conditions, given that useable battery energy is under 1 kWh. When clutches C1 and C2 are connected, it is possible to drive the compressor with the engine alone. Consequently, it is not necessary for the P3 motor to drive the compressor at maximum power. For the 48 V hybrid project we had studied a 25 kW P2 system (Fig. 1 results) in consideration of available supplier components and “reasonable” battery current limits (about 520 A for 25 kW in a nominal 48 V battery pack). In the case of a 48 V system with a 15 kW P2, a P3 motor of 5-10 kW keeps total system power at or below the 25 kW peak power limit.

The P3 power-take-off gear ratio is selected to maximize the efficiency of the P3 motor when the vehicle operates on the regulatory fuel economy cycles. At the same time, the maximum ratio may be limited by the maximum compressor speed of approximately 10,000 rpm if the motor is directly driving the compressor. An additional gear reduction between the compressor and the P3 would eliminate this restriction. Based on studying P4 and P3 options for the 48 V P2 R&D project, a motor/wheel-speed ratio in the range of 10-13 provides good motor efficiency for typical 48 V motors. This would imply a PTO ratio in the range of 3.2 to 4.0 relative to transmission output speed and maximum motor speeds of 13,000 to 16,000 rpm. To stay within the 10,000 rpm limit of a directly driven compressor would imply a maximum PTO ratio of 2.5. This indicates that a speed-reduction is required to allow maximum vehicle speed operation and best system efficiency.

Since the P2 and P3 motors will generally not be operating at the same speed when simultaneously connected to the driveline, there is an opportunity to tailor the overall motor system power output by manipulating the second motor’s peak power curve. Fig. 4 shows two different accessory (*i.e.*, P3) MGU power curves (orange and dark blue lines) and the main (P2) MGU power curve. When both motors are operating at the same speed (P3 orange power curve) and have the same corner speed (*i.e.*, the maximum speed at which the motor can still provide peak torque), the system peak power is the gray line. The system power peaks and rolls off immediately as speed increases. If the P3 corner speed is higher than that for the P2, the yellow total power curve results, where peak power is lower but is available for a wider speed band.

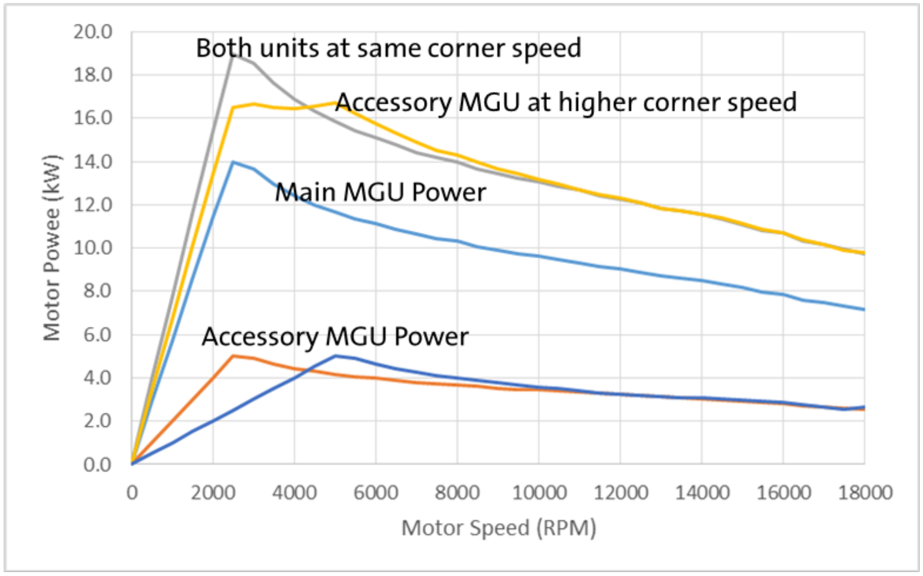

Fig. 4. Total System Motor Power

3 SIMULATION RESULTS

The benefits of a P2-P3 option were simulated using an internally developed propulsion simulation program. Results are shown in Fig. 5 for the baseline engine start/stop case, the R&D 48 V P2 configuration with revised engine (relative to Fig. 1) and two different P2-P3 options with different P3 motors. The P2-P3 cases assume the engine friction reduction benefit of removing the FEAD, given the P3-driven A/C compressor. A 25 kW 48 V P2 was also simulated. The last column shows the 25 kW P2 with the FEAD removed, assuming a dedicated electric A/C compressor. For this simulation, the P3 motor has a PTO gear ratio of 2:1. The P2 MGU runs at 2.5 times transmission input speed. The best result is achieved with the 25 kW P2 with no FEAD, which requires an electric A/C compressor. The best P2-P3 is a close second. The sensitivity of the reduction in CO2 to the P3 motor selection is evidenced by the difference in CO2 reduction for the two P2-P3 cases.

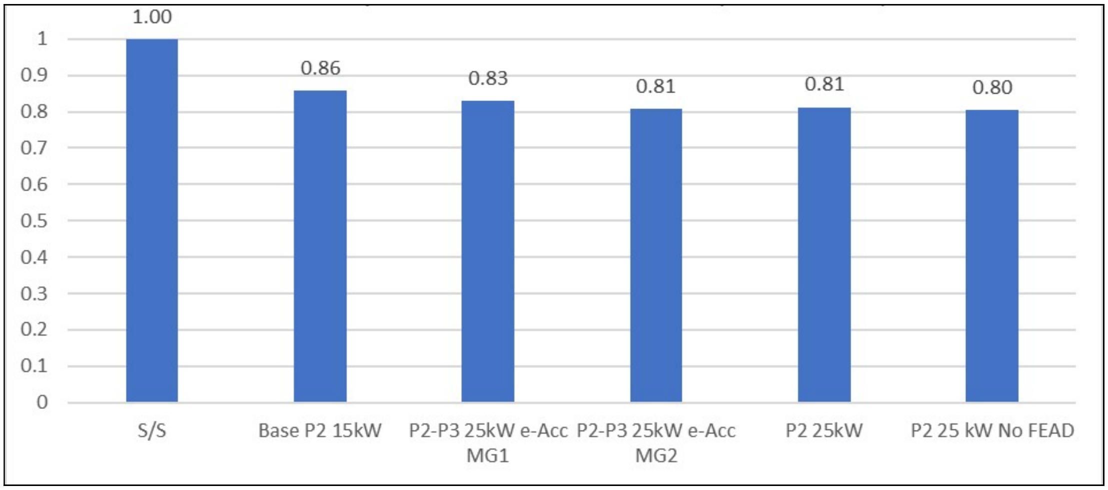

Fig. 5. Normalized gCO2/km for P2-P3 E-Accessories Configuration and Other Options

The 25 kW systems reduce gCO2/km by up to 7% relative to the 15 kW P2 system due to improved electric launch capability (eliminates inefficient engine operating points) and higher regenerative braking power. The difference in benefit is due to the relative size and efficiencies of the MG1 and MG2 electric motors in the P3 position. The addition of a 7 kW P3 to the 15 kW P2 system (not plotted) while keeping peak battery power constant at around 16 kW, still results in a 1-2 gCO2/km benefit from coupling the machines due to improved electric launch performance. This does not include the estimated 1 gCO2/km benefit of deleting the FEAD. The benefit of electric A/C on the SC03 cycle, which is the regulatory cycle using air conditioning, was also estimated. Assuming a standalone electric A/C compressor, there is a 4% reduction in gCO2/km over a mechanically driven compressor with the 15 kW P2 system. This is due to two effects: 1) the large reduction in engine fuel consumption due to the removal of the compressor load on the engine and 2) the elimination of the FEAD. The P2-P3 option at 25 kW provides an 8% reduction over the mechanically driven compressor due to greater hybrid capability, in addition to the reduction in engine loads.

4 EXPERIMENTAL IMPLEMENTATION

Experimental 'breadboard' hardware was developed, adapting the existing P2 hardware test system that had been developed for the 48 V P2 project. The existing 6-speed automatic transmission AWD module was removed and replaced by a custom-designed power take-off (PTO) module. A cross-section of the PTO module is shown in Fig. 6. The PTO interfaces with the transmission at axle speed, after the transaxle final drive, which is a limitation of the current implementation. This choice was made to avoid creation of a new transmission case and more significant tear up, given the operational limitations (the transmission output is unloaded except for reaction torque from the P3 motor) of using the existing setup. The total ratio speed-up is 2.8125, which means the motor is spinning at 2.8 times axle speed. Ideally, the PTO should connect to the transmission output before the final drive (3.17 ratio), which would imply a total ratio of 8.92 (3.17x2.8) times axle speed for the P3. Other notable features of the module are the drive clutch (C1), which is capable of absorbing the maximum P3 motor torque supplied (60 Nm). The clutch is an electromagnetic design drawing a maximum of 25 W at maximum torque.

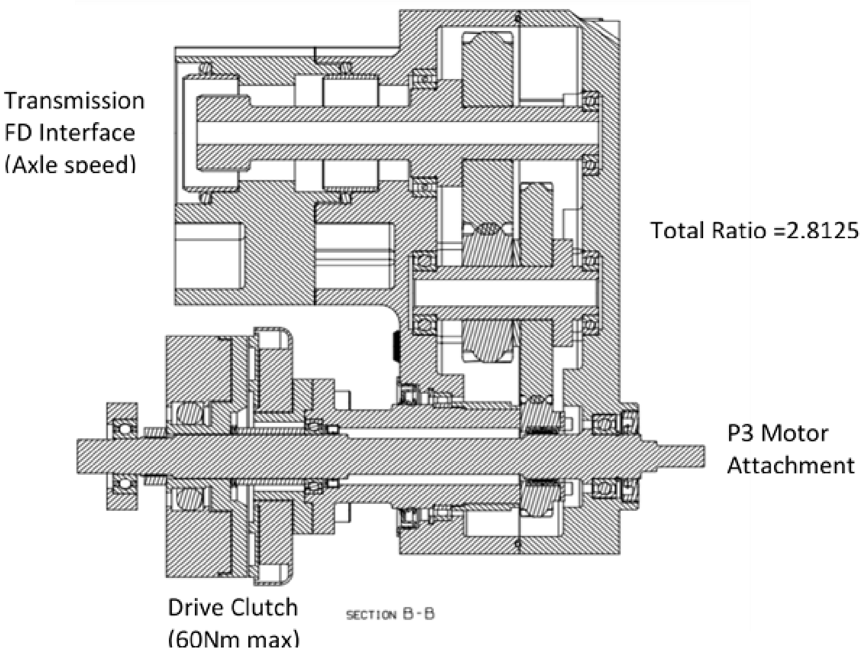

Fig. 6. P3 Experimental PTO Module Cross-Section Showing Gear Drive Layout

An external supplier of 48 V motor-generators was commissioned to modify one of its existing designs to allow a mechanical shaft connection at either end of the motor. To accomplish this, the motor case was modified by removing the inverter that had been integrated with the unit. The base motor specifications are listed in Table 3. At 12 kW, the motor peak capability is at the high-end of the design requirement for the P2-P3 e-Accessories application.

Table 3. Experimental P3 Motor Specifications.

P3 Motor Specifications	
Max Torque (Nm)	35
Max RPM (rpm)	22000
Max Power (kW)	12
Nominal Voltage (V)	48
Peak Motoring Efficiency (%)	> 94

The assembled PTO/P3/AC-Compressor hardware on a test stand is shown in Fig. 8. The motor is liquid cooled; the inverter was moved to the "SuperGen Control Box" shown in the picture. Since the torque loads on the A/C compressor drive section would be relatively low (primarily inertial, under 10 Nm), plastic gearing (white) was used for this experimental configuration.

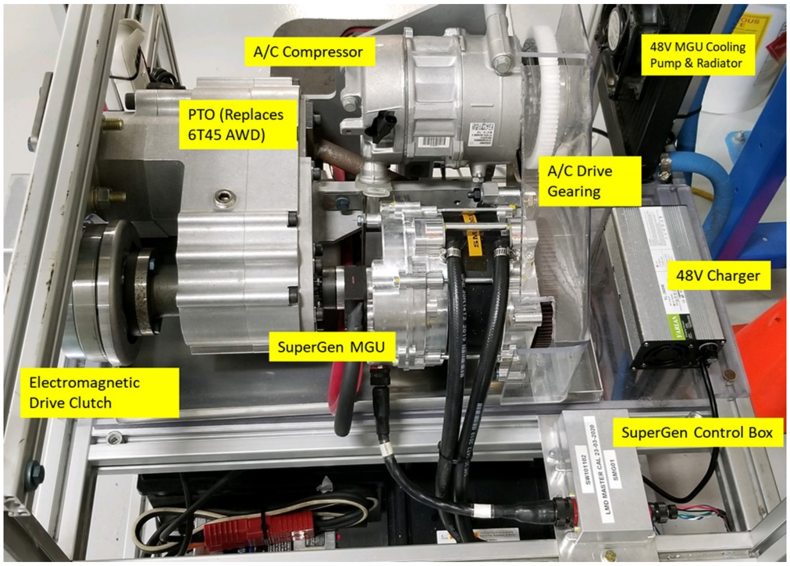

Fig. 7. PTO/P3/AC-Compressor Hardware

Fig. 8 shows a front view of the transfer gearing between the P3 motor and the AC compressor. The parallel axis layout for the motor and A/C compressor is the most practical, given the A/C compressor size. A side benefit is that the gear-ratio selection can be used to down-speed the compressor such that it doesn't exceed its speed limit, given typical maximum motor speeds of 16,000 rpm or more (22,000 rpm for the SuperGen unit).

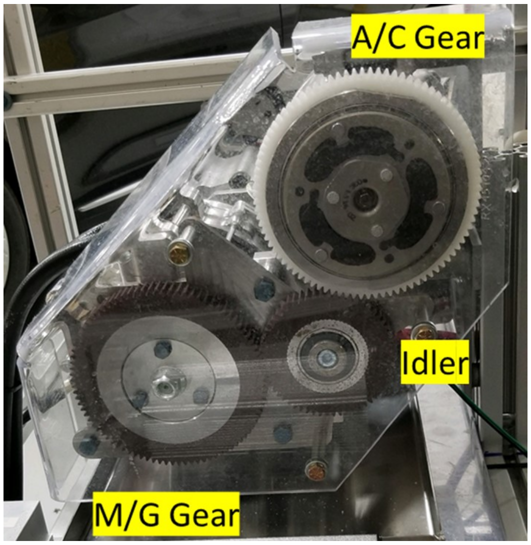

Fig. 8. Front View of P3 Motor/AC Compressor Transfer Gear

An example test result from the start cart is shown in Fig. 9. The P2-P3 system was run open-loop with both motors in speed control mode. This substantially simplifies the test process since each motor controller has its own internal speed control system; however, this system control state requires that the transmission torque converter remain unlocked to compensate for any kinematic differences in speed between the transmission input and output when the P3 is clutched to the transmission output (C1 locked). The engine disconnect device for the P2 was not operational when testing was carried out, resulting in the P2 motor spinning the unfired engine for these tests. The oscillatory engine compression torque was reduced by removing the spark plugs but the torque to spin the engine and transmission (grey) is still substantial, resulting in the P2 speed variation around the commanded speed value (approximately the middle of the speed variation band shown in orange). The plot shows the different modes demonstrable on the start cart, with: a) the P3 starting and accelerating the A/C compressor in the first 100 s with the P2 at zero speed, b) the P2 accelerating and driving the transmission with the P3 driving the A/C compressor separately (C1 open) up to 400 s; c) the C1 clutch applied after 400 s, resulting in the P3 loading the transmission due to the kinematic speed difference—the P2 tries to accelerate the P3 motor but P3 speed control prevents this, with the P3 generating in the process and d) the C1 clutch unlocking after 490 s, which unloads the transmission again, reducing P2 torque. After 550 s, C1 is relocked briefly, again causing the P3 to briefly generate. Since the P2 and P3 are operating off the same battery pack, the generated P3 power is essentially recirculating in the 48 V system. The plot also shows calculated axle speed based on the transmission output speed and assumed final drive ratio. One can see that the axle speed changes in steps as the transmission is manually slewed through lower gears to get the output to 4th gear or higher, where the P3 speed is a reasonable match to the transmission output speed. The P3 PTO being connected after the final drive results in a relatively low P3 speed (under 500 rpm).

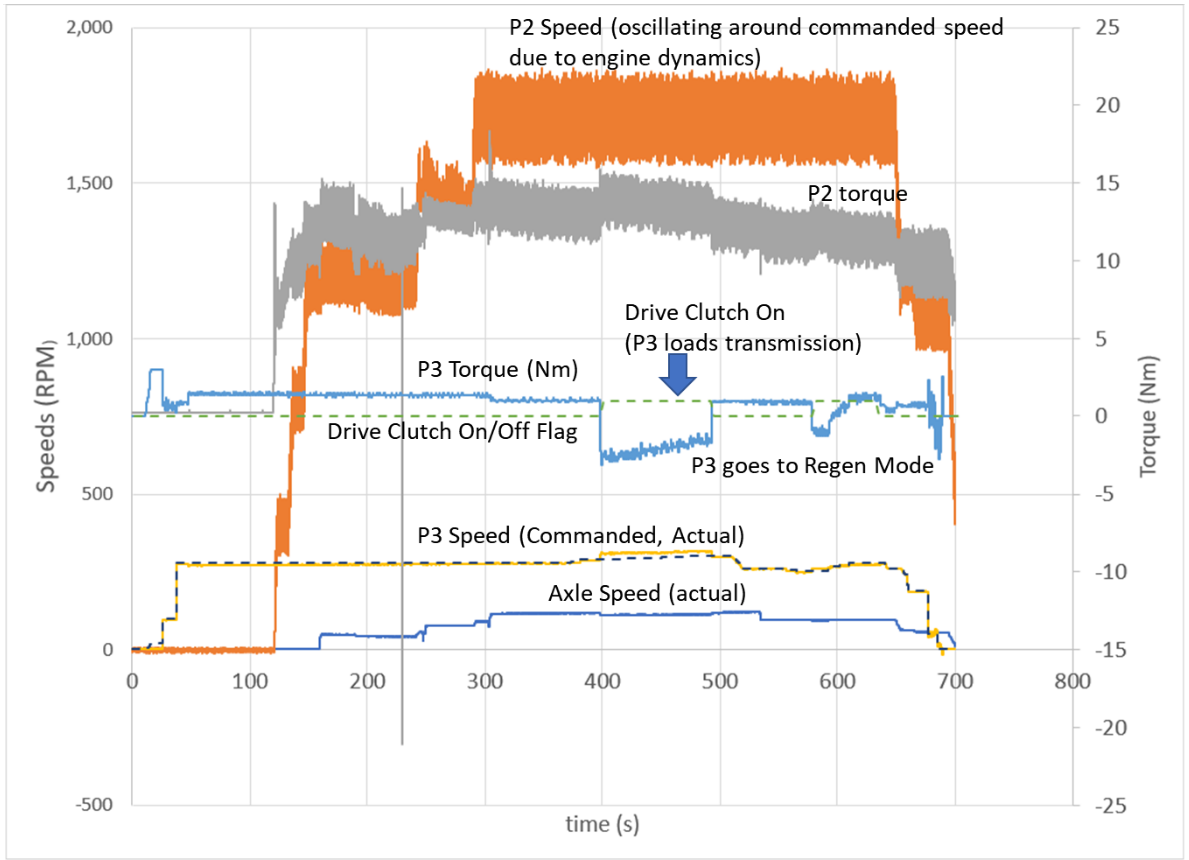

Fig. 9. P2-P3 Start Cart Test Result

5 DISCUSSION

The e-Accessories dual motor concept shows promise from a CO2 perspective but is challenging to implement due to packaging space constraints. Limited start cart testing indicates that the available motor controls and electromagnetic clutch technology are capable of managing the various mode switching options. In preliminary packaging analyses, it was not possible to fit a second motor and the A/C compressor in the space available in a production application. A best-case scenario would involve a complete redesign of the engine transaxle to accommodate the additional electric motor and the A/C compressor on the same side of the engine block. Elimination of the FEAD in the vehicle studied would free up approximately 20-25 mm of cross-car space, which may not be sufficient to accommodate the P3 transmission modifications needed.

One emerging potential application is in the electric vehicle space. In a system where the main electric A/C compressor is of the conventional high-voltage type, a secondary ICE-type A/C compressor driven off a motor PTO could be useful in applications where supplementary A/C performance is required, as in high power applications such as racing where significantly more cooling capacity is required but nominal electric compressor options are unavailable or add significant cost. Additional work is needed to confirm potential benefits.

6 SUMMARY & CONCLUSIONS

A dual-use drive system for driving an accessory device and providing propulsion was investigated via analysis and testing. The aim was to increase 48 V hybrid vehicle fuel economy by eliminating the engine FEAD, while offsetting the cost of electrified accessories by making the required electric drive serve dual functions.

1. Simulation of the proposed system indicates a 7% gCO2/km benefit is achievable with a 25 kW P2-P3 configuration over a 15 kW P2 system. 1% of the gain is attributable to the removal of the FEAD, reducing net engine friction. The remainder of the gain comes from the supplementary hybrid system power provided by the second electric motor.
2. On the SC03 cycle, the 15 kW P2 system sees a 4% reduction in gCO2/km, when using a stand-alone electric A/C compressor, instead of a mechanically driven A/C compressor.
3. On the SC03 cycle, the 25 kW P2-P3 system sees an 8% reduction in gCO2/km, when using a stand-alone electric A/C compressor, instead of a mechanically driven A/C compressor. This is due to greater hybrid capability, in addition to the reduction in engine loads.
4. The primary challenge in developing the dual-drive system arises from packaging the additional motor in the P3 position with connection to the A/C compressor. This was found to be impractical without a complete revision of the powertrain.
5. A demonstration hardware property was developed for experimental assessment, with the system working as expected in power-sharing mode.
6. A potential spin-off application in the battery electric vehicle space is the case where a purely electric large single A/C compressor would be costlier than a combination A/C compressor comprised of a smaller dedicated electric unit, plus a PTO-driven A/C compressor powered by the traction motor.

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