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The Electrified Control Technology for Toyota's L4A0 and L580

- Electrification Control Technologies for Motor-Generator -

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ABSTRACT: Toyota has developed the L4A0 and L580 hybrid units to electrify its full-size and midsize pickup trucks. These electrified powertrains aim to achieve optimal environmental performance in line with Toyota's goal of Carbon Neutrality, while exceeding customer expectations for drivability across diverse conditions, including on-road, off-road, and towing situations. In these hybrid units, a motor-generator and a K0 disconnect clutch are integrated into a single module, positioned between the conventional engine and automatic transmission. Hybrid capabilities are realized through various control functions for the motor-generator and disconnect clutch. Electric motor torque is utilized to enhance dynamic acceleration by reducing turbo lag and increasing total system torque. A smooth transition between EV driving and HEV driving is achieved through sophisticated control of the K0 disconnect clutch. Engine power suppression control has been developed to improve emissions, and anti-vibration control has been implemented to reduce powertrain surge.

KEY WORDS: 1-Motor, hybrid vehicle, motor-generator, control, L4A0, L580

1. INTRODUCTION

Toyota's strategy toward carbon neutrality involves a multi-pathway approach that includes a comprehensive lineup of electrified powertrains, such as Battery Electric Vehicles (BEV), Fuel Cell Electric Vehicles (FCEV), Hybrid Electric Vehicles (HEV), and Plug-in Hybrid Electric Vehicles (PHEV).

To achieve the goal of carbon neutrality, Toyota is preparing a diverse range of electric vehicles. In regions like the West Coast of North America, which are abundant in renewable energy, zero-emission vehicles (ZEVs) such as BEVs and FCEVs are considered ideal options. On the other hand, Toyota emphasizes the importance of reducing CO2 emissions by providing HEVs for popular models without compromising purchasing and production capabilities. Full-size and mid-size trucks are examples of vehicles expected by users to have excellent towing capability and off-road performance.

However, the requirements for full-size and compact trucks differ. While both require high torque at low speeds for heavy-duty and off-road use, full-size trucks emphasize high power for premium towing performance.

This paper describes the architecture and new motor-generator control technologies adopted in the L4A0 and L580 1-Motor hybrid units. The L4A0 hybrid units are designed for full-size truck applications such as the Tundra and Sequoia, while the L580 hybrid units are designed for compact truck applications like the Tacoma and Land Cruiser Prado. Throughout this paper, we will refer to the powertrains as 1-Motor hybrid units. Table 1 lists the control technologies covered in this paper.

Table 1. Control Strategies Covered in This Paper

No.	Control Technology
1	Hybrid Control Mode
2	MG Assist and Boost Control
3	MG Assist for Towing and Off-Roading
4	Engine Start Control
5	Engine Power Suppression Control
6	MG Anti-Vibration Control

2. POWERTRAIN CONCEPT AND TARGET

2.1 Powertrain Concept

The 1-Motor hybrid units are designed for Toyota's global truck platform, targeting both demanding off-road and heavy towing capabilities, while maintaining daily drivability and a fun-to-drive experience. The core powertrain development concept focuses on maximizing efficiency to comply with stringent emission regulatory standards, while simultaneously exceeding customer expectations for on- and off-road performance through improved fuel economy, enhanced drivability, and ride comfort. These concepts are achieved through advanced system architecture and sophisticated integration of hardware and controls.

2.2 Powertrain Target

When Toyota began designing the 1-Motor hybrid units, several key considerations were prioritized. The units needed to meet strict emission regulations, deliver stronger system power and torque for daily driving, off-roading, and towing, and provide better fuel economy compared to previous generations, all while maintaining performance aspects such as noise and vibration. The target of the 1-Motor hybrid units was to improve acceleration, response, fuel economy, emissions, off-road, and towing performance over the previous generation model, as shown in Figure 1.

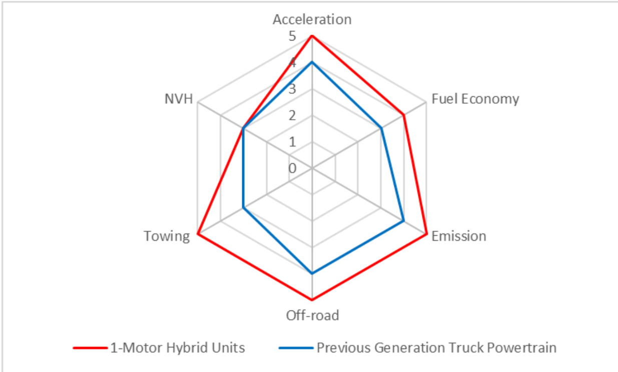


Figure 1. Powertrain Target

2.3 Powertrain Architecture

Based on the powertrain targets we established, Toyota selected the appropriate architecture for the powertrain. In choosing the system structure for the hybrid units, our primary focus was to meet the high power and high torque requirements for truck applications. Unlike Toyota's existing Toyota Hybrid System (THS) used in models like the Prius and Camry, which is a series-parallel hybrid system, the 1-Motor hybrid unit is a parallel hybrid system. The THS faces limitations under high power output conditions, such as towing, because the majority of power is delivered to the wheels by the electric motor MG2. As a result, the MG2 can reach its maximum current, generating significant heat and requiring a reduction in its output to prevent overheating. Conversely, parallel systems, such as the 1-Motor hybrid units, offer advantages in continuous rating and superior thermal performance. The comparison of the 1-Motor Hybrid System and the THS is shown in Figures 2 and 3.

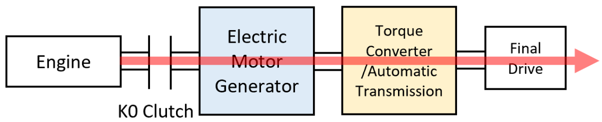


Figure 2. 1-Motor Hybrid System

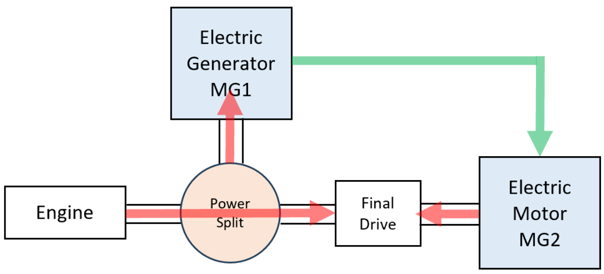


Figure 3. Toyota Hybrid System

Several structural options exist for the parallel system. In selecting the structure for the new parallel system, we assessed system efficiency, complexity, regenerative capability, and electric vehicle (EV) driving capability. Ultimately, we chose a structure that supports full EV driving capability and allows the motor generator (MG) to function as the engine starter in normal operating condition.

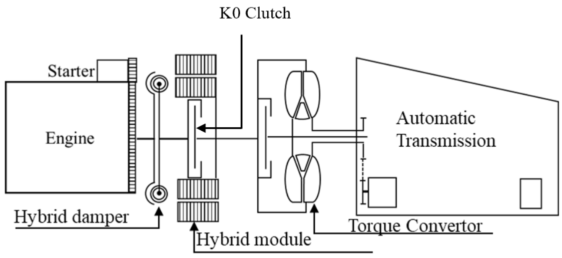


Figure 4. 1-Motor Architecture

Figure 4 illustrates the powertrain architecture. The hybrid module, equipped with a K0 disconnect clutch, is positioned between the engine and the automatic transmission (AT) with torque converter to facilitate engine disconnection during EV operation. The K0 clutch enables the engine to be disengaged from the drivetrain when necessary. A starter is incorporated into the powertrain and is used to start the engine when the temperature is extremely cold. A hybrid damper is incorporated to enhance noise and vibration (NV) performance, while a torque converter is included to improve low-speed acceleration. A conventional step AT is utilized for better efficiency.

Key highlights of the 1-Motor hybrid unit include:

(1) Full EV System for Optimal Fuel Economy: K0 clutch is integrated into the hybrid module, positioned between the engine and the AT. This allows the engine to disconnect from the drivetrain, enabling full EV driving.

(2) Simplified System Complexity: The MG is designed to serve dual functions as both a power source and the primary engine starter. The torque required to crank the engine is provided by the electric motor and transmitted through the K0 clutch, eliminating the need for a starter under normal operating conditions. An engine starter is used only when temperature is extremely low when friction increases. The K0 clutch is controlled sophisticatedly to ensure rapid response and smooth engine starts. The K0 control is explained in Chapter 3 in detail.

(3) HEV Mode Operation: In HEV mode, both the engine and motor provide power to the vehicle. This collaborative operation compensates for each component's weaknesses. At low engine RPMs, the motor's instant torque mitigates the engine's delayed torque response, enhancing overall system responsiveness. Conversely, under high-load conditions, the engine serves as the primary power source once the electric motor reaches its peak power output. During powertrain warm-up, the motor can provide torque to reduce engine load and emissions through engine power suppression control. Engine power suppression control is discussed in Chapter 3 in detail.

(4) Mechanical Power Transfer: A torque converter and AT are employed in this hybrid system to enable direct mechanical power transfer from both the engine and electric motor to the wheels. The torque converter also multiplies system torque, aiding acceleration in off-road and towing scenarios.

Table 2 summarizes the merits and demerits of different parallel hybrid system architectures. Compared to other parallel system layouts, the 1-Motor hybrid unit's P2 layout offers the most balanced overall performance. Unlike the P2 layout, the P0 layout cannot achieve full EV operation because it lacks a K0 clutch and the capability to disconnect the engine from the drivetrain. Additionally, in comparison to the P3 layout, where the MG is positioned after the transmission, the P2 layout allows the MG to start the engine. In contrast, the P3 layout has difficulty to perform this function especially for overlapping with the shifting, and it may require integrated starter. Furthermore, the P2 layout enables the torque converter to multiply the MG's torque at low speeds during slip conditions, which enhances truck drivability.

Table 2. Comparison of Parallel Hybrid Architecture

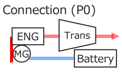
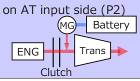
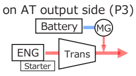
Architecture		Trans	Fuel Economy Function: Engine FE Efficiency	Fuel Economy Function: Power Transfer Efficiency	Fuel Economy Function: Regen	Fuel Economy Function: EV Driving	High Power Engine Compatibility	MG as Engine Start Device	SOC management
Parallel Hybrid	Belt Connection (P0) 	Step	△	○	△--	×	○	○	○
		Variable	○	△	△-	×	△	○	○
	MG on AT input side (P2) 	Step	△	○	○-	○	○	○	○
		Variable	○	△	○	○	△	○	○
	MG on AT output side (P3) 	Step	△	○	○	○	○	×	△--
		Variable	○	△	○	○	△	×	△--

Table 3 is a comparison of two 1-Motor hybrid units, L4A0 and L580.

Table 3. Comparison of L4A0 and L580

Category	L4A0	L580
Engine	3.4L V6-T	2.4L L4-T
Motor-Generator	36kW	36kW
K0 Clutch	With	With
Transmission	10AT	8AT
Application	Full-size Truck	Compact Truck

3. MOTOR-GENERATOR CONTROLS

This section discusses the key motor-generator control technologies that work seamlessly with the hybrid architecture discussed in the previous chapter, enabling the hybrid system to achieve its target performance. These controls are essential for managing motor torque requests under various operating conditions. Therefore, it is important to clarify the purpose and context of each control.

3.1 Hybrid Control Mode

This paper will focus on three hybrid operation modes based on the power transfer: EV mode, HEV mode, and Engine Start/Stop mode, as they are directly related to the control technologies discussed herein. Figure 5 illustrates these three modes. Based on driver input and vehicle condition, the powertrain electronic control unit (ECU) calculates the required total system torque for both the engine and the electric motor, determining which hybrid control mode to activate.

(1) EV mode. During vehicle launch or low system torque request conditions, MG is the only power source to drive the vehicle. K0 clutch is disengaged, and engine is turned off.

(2) HEV mode. In this mode, both engine and MG are providing power to the wheels. The powertrain ECU prioritizes EV mode if system torque request is low. HEV is activated when system torque request is high. K0 clutch is engaged, and engine is ON.

(3) Engine start/stop mode. This is the transition mode from EV mode to HEV mode. This mode activates based on vehicle condition and driver operation. MG torque control and K0 clutch pressure control work seamlessly to realize a smooth and fast transition.

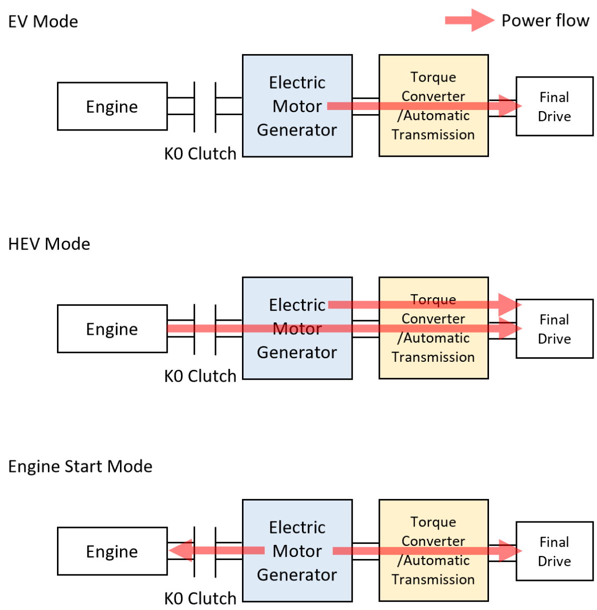


Figure 5. Hybrid Operation Modes

3.2 MG Assist and Boost Control

MG assist control is designed to use electric motor torque to fill the gap between the requested system torque and the engine torque, thereby reducing turbo lag when the driver presses the accelerator pedal. As a result, the system torque output can quickly respond to the driver's request. This allows the driver to experience fast acceleration without the delay typically associated with conventional engine-only systems, thanks to the instant torque delivery of the MG.

If driver continue to push accelerator and maintain requested system torque high that exceeds max engine capability, electric motor will continue to provide boost torque for stronger peak acceleration. This is known as MG boost. Figure 6 illustrates the flow of MG assist and boost control. Figure 7 shows the system torque compared to engine torque and MG torque.

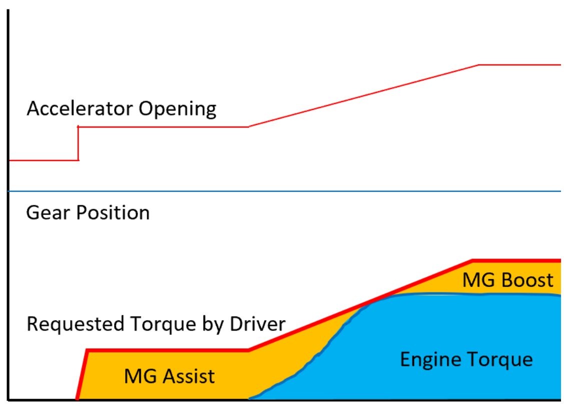


Figure 6. MG Assist and Boost Control

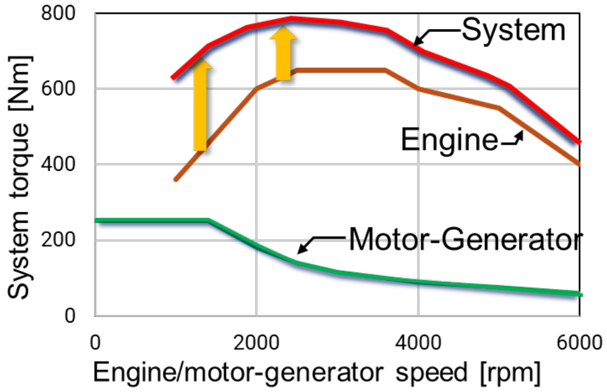


Figure 7. System Torque Curve

3.3 MG assist and boost for Towing and Off-roading

Toyota's truck models are often equipped with a drive mode switch, allowing customers to change the driving mode based on their preferred activity and control needs. Since towing, hauling, and off-roading are very common uses for these vehicles, Toyota has developed a tow/haul mode and multi-terrain modes specifically for these tasks.

When tow/haul and multi-terrain modes are selected, the powertrain ECU adjusts its control strategy to enhance towing, hauling, and off-roading performance. These conditions require high system torque, so HEV mode driving is prioritized over fuel efficiency. EV mode is prohibited to prevent frequent engine stops and restarts, ensuring uninterrupted torque transfer. With the implementation of a torque converter, the engine and electric motor torque are multiplied, providing strong acceleration capability for the customer.

When towing heavy trailers, customers often require strong torque at low speeds to launch and accelerate quickly. With MG assist and boost control, 1-Motor units can quickly achieve the requested system torque and provide stronger system torque than engine-only powertrains, as shown in Figures 6 and 7. This provides customers with an effortless feeling when towing a heavy trailer. Additionally, at highway speeds, customers can experience more responsive performance when trying to maintain speed, with less need for downshifting.

3.4 Engine Start Control

Engine start control is a key element to ensure smooth transitions between EV and HEV modes. It significantly impacts emissions, drivability, and NV performance. This control is frequently activated because, during on-road driving, EV and HEV modes switch frequently to maximize overall drivability and fuel economy.

Figure 8 demonstrates the engine start control sequence. The engine is first cranked by engaging the K0 clutch. During this period, the motor-generator provides additional counter torque to compensate for the K0 clutch torque, which tends to cause a decrease in vehicle acceleration. The counter torque provided by MG prevents the driver from feeling any changes in acceleration. Simultaneously, the engine must quickly fire and generate output torque. Therefore, the timing and duration of engine cranking and the accuracy of cranking torque delivered by the K0 clutch are crucial in the system.

The K0 clutch control algorithm was optimized by Model-Based Development to ensure consistency and robustness of K0 torque control delay and shape to ensure smooth and quick engine starts (Tan, G. et al., 2022). With the implementation of advanced engine start control algorithms, the L4A0 and L580 systems are capable of achieving smooth and quick engine starts without using any torque or oil pressure sensors.

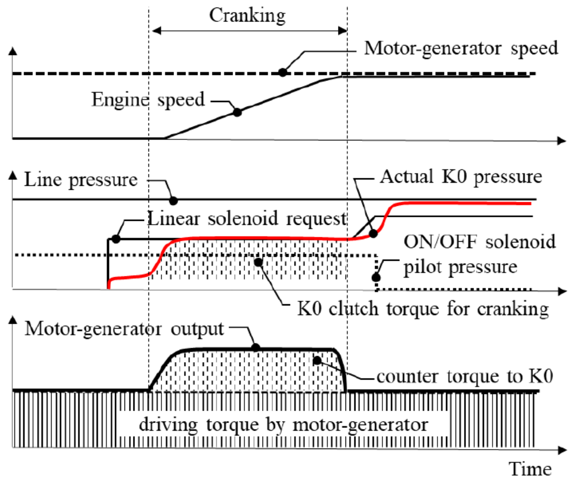


Figure 8. Engine Start Control Sequence

As a result, engine start control provides smooth EV to HEV mode transition performance when the engine turns on without noticeable acceleration change or interruption to the driver. It permits frequent mode switches between EV and HEV modes, allowing the system to maximize the advantages of the hybrid system.

3.5 Engine Power Suppression Control

Rapid activation of the catalyst is essential for ensuring clean emissions, particularly in vehicles with high inertia, such as trucks (Endo M. et al., 2024). To achieve quick catalyst activation, the engine must generate heat to warm up the catalyst. Hybrid powertrains offer an advantage over conventional gasoline-only powertrains by reducing emissions through MG assist capability.

Engine power suppression control has been developed to limit engine operation at low temperatures, thereby reducing emissions by utilizing electric motor torque to support the vehicle's driving requirements. During this control, engine output power is limited, and any additional power requested by the driver is provided by the electric motor, prioritizing electric motor torque to meet the driving force demand. When the driver demands strong acceleration, power suppression allows the engine power to increase, ensuring smooth acceleration as requested by the driver as shown in Figure 9.

With power suppression control, a balance between emissions, drivability, and energy management is achieved, enabling vehicles equipped with the 1-Motor hybrid unit to meet emission target.

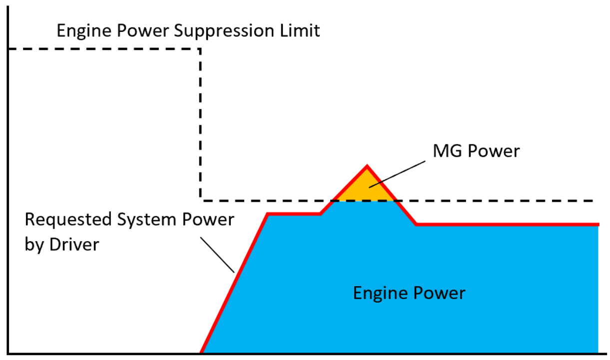


Figure *9*. Engine Power Suppression Control

3.6 MG Anti-vibration Control

Powertrain surge is a low-frequency vibration phenomenon resulting from torque fluctuations generated by power units such as the engine or motor. This phenomenon is further amplified by torsional driveline resonance, suspension resonance, and cabin resonance. In a parallel hybrid system, the engine, MG, torque converter, and AT are connected in series, which introduces additional challenges in managing powertrain surge. In the 1-Motor hybrid system, surge occurs in two frequency zones: torsional resonance of the driveline below 10 Hz and near 23 Hz (Okaya S. et al., 2022). Figure 10 demonstrates the frequency characteristics based on data of L4A0 powertrain in 7th gear.

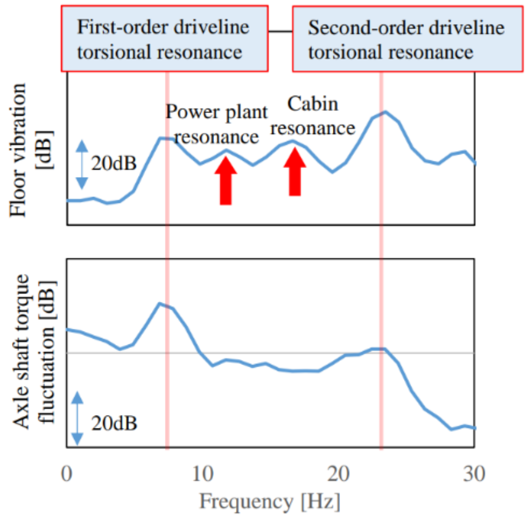


Figure *10*. Frequency of Surge (L4A0, 7th gear)

The powertrain resonance characteristics exhibit two different modes depending on the torque converter lockup condition and the AT gear position. A vibration below 10 Hz is observed when the torque converter is locked up, resulting in a resonance frequency that is affected by the gear position, as the equivalent inertia increases with lower gears. Conversely, a 23 Hz vibration occurs when the torque converter is in a slip condition, where the resonance frequency is primarily influenced by the engine and motor connection through the damper. Figure 11 illustrates the eigenfrequency trend of the driveline with the torque converter lockup ON and OFF in each gear. Figure 12 shows the mechanism of these two vibration modes.

To mitigate the vibration, MG anti-vibration control was developed. Figure 13 shows the flow of the anti-vibration control. The control includes an observer model that calculates the predicted prop-shaft speed versus the actual prop-shaft speed, as well as the actual MG speed, then adds a counter torque with a gain factor to reduce the vibration.

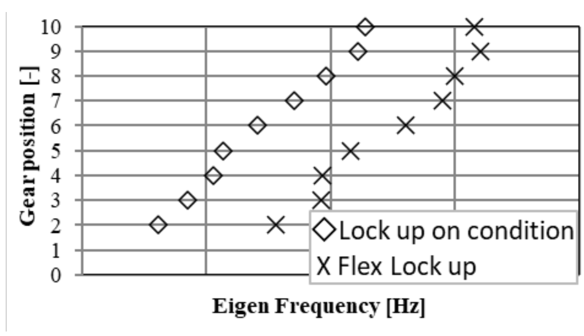


Figure *11*. Driveline Eigenfrequency

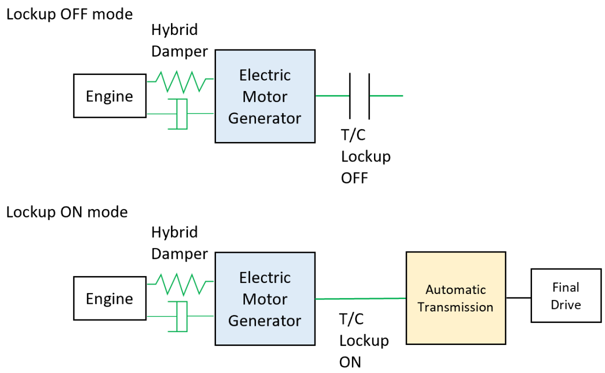


Figure *12*. Driveline Model

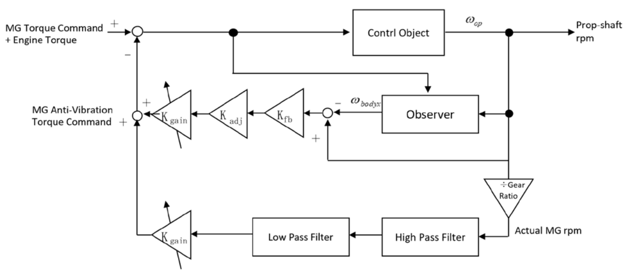


Figure *13*. Anti-Vibration Control Flow

With MG anti-vibration control, vehicle NV performance is maintained at the level of previous models, even though a more complex system is adopted.

4. CONCLUSION

As previously mentioned, L4A0 and L580 were engineered to improve acceleration, responsiveness, fuel economy, emissions, off-road capability, and towing performance compared to the previous generation model and its competitors.

With the control strategies outlined in this paper, customers can enjoy optimal, linear, and delay-free acceleration with MG assist both on-road and off-road. This system delivers strong peak acceleration at low engine speeds, superior fuel economy compared to the previous generation vehicle, and enhanced driving performance as shown in Figure 14. Additionally, the anti-vibration control ensures a comfortable riding experience.

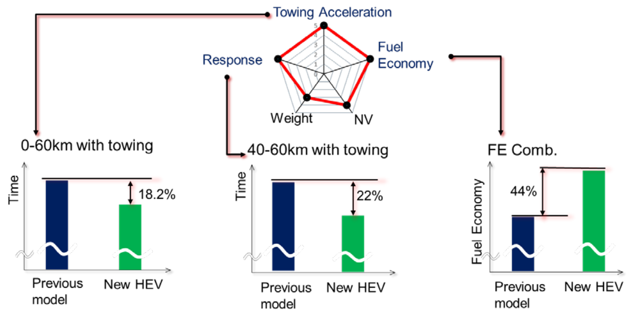


Figure 14. Performance Improvement

ACKNOWLEDGEMENT

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