

Performance-Oriented P3 and P4 HEV Solutions for Consumer Uptake with Long-Term CO₂ Compliance

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Summary

The proliferation of hybrid architecture is reviewed to show historic developments and identify the current leading solutions in respective segments. U.S. vehicle data is analyzed to identify gaps with respect to impending CO₂ requirements. Strengths and challenges of P3 and P4 hybrid configurations are identified with emphasis on customer-demanded capabilities like dynamic performance. Prime platforms to be brought into compliance using P3 or P4 hybrid configuration while maintaining customer-demanded performance are identified. Hybrid vehicle simulation for performance and fuel consumption is completed for one exemplary application.

Keywords: electric drive, emissions, parallel HEV, powertrain, torque

1. INTRODUCTION AND HYBRID PROLIFERATION

Early leadership is already established among HEV architectures with the Electric Variable Transmission (EVT) configuration dominating the front-wheel-drive segment and other architectures making inroads within the longitudinal powertrain and higher performance segments. Figure 1 illustrates the US market leadership achieved for EVT or power-split hybrid configuration over the past decade implemented first by Toyota [1] and notably early by Ford. Other automakers are also developing EVTs, especially in FWD transverse configuration where success has long been evident. The plot also illustrates the longstanding market experience of Honda with the P1 (electric machine on crankshaft or belt-driven) Integrated Motor Assist (IMA) mild hybrid architecture. Honda appears to be exiting the P1 architecture [2] in favor of a transmission-less, serial-parallel, P1-P3 configuration as implemented on the 2014 Accord Hybrid. Other automakers have also curtailed use of the P1 hybrid configuration as shown in Figure 1 where the BAS (Belt-Alternator-Starter) mild hybrid system developed by GM and used on the Saturn Vue and other models over the decade [3]. P2 configuration (with electric machine between a clutch and transmission input) recently debuted and is on the rise, especially in rear-wheel-drive applications.

While EVT configuration has experienced healthy growth over the decade, significant untapped growth potential exists for P3 (post-transmission) and P4 (secondary axle) hybrid configurations for both

longitudinal and transverse powertrain applications where they offer benefits of seamless recuperation and dynamic performance. This latter aspect produces the crucial consumer appeal to help OEMs reach their CO₂ compliance objectives.

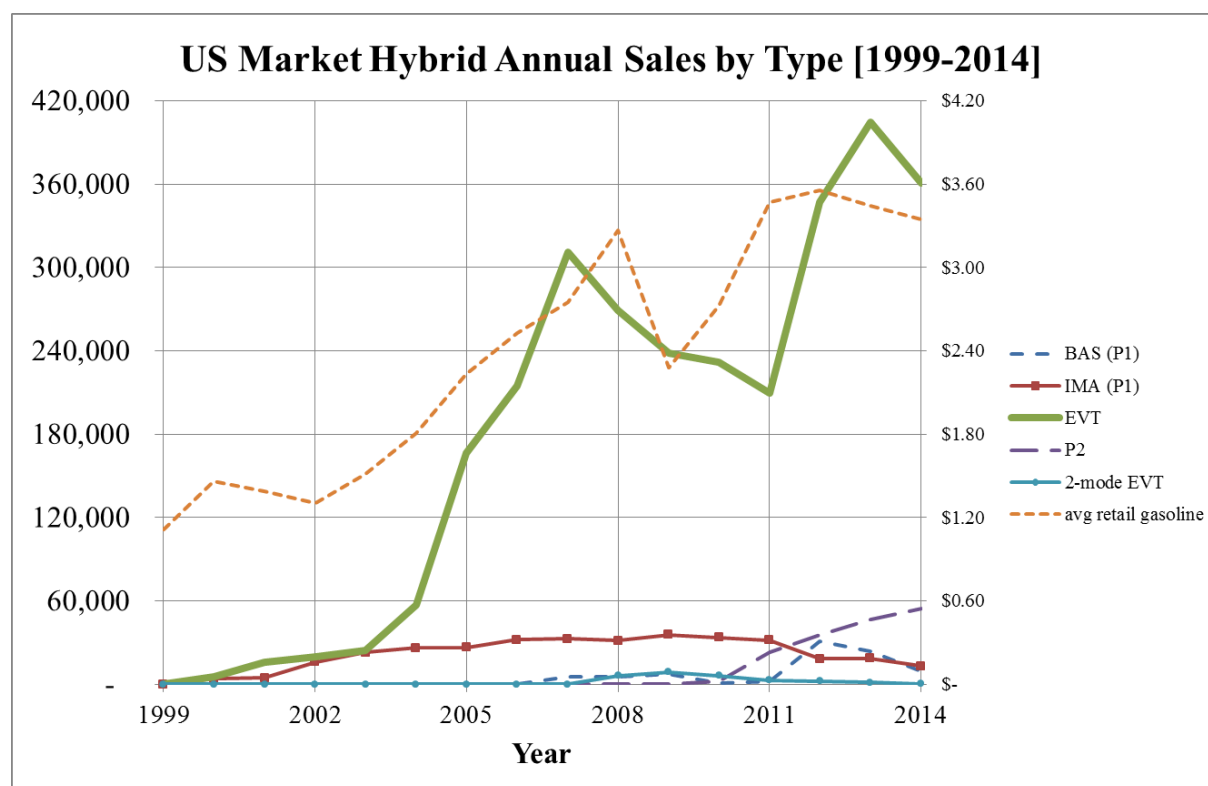


Figure 1: US Hybrid Sales by Hybrid Configuration - with Average Retail Gasoline Price

This report briefly reviews the current state of commercialization for hybrid configurations within the US, analyzing sales growth and trends over the previous decade. We then identify the potential of P3 and P4 architectures to meet the needs of key segments of the future passenger car and light truck fleet. Key performance criteria of launching and towing are discussed and the suitability of each configuration (P1 through P4) to meet these conditions is reviewed. It should be noted that P3 and P4 xEV drives are currently a commercial product of AAM.

Next, the 2016 model year US fleet is reviewed with existing OEM platforms being compared in current CO₂ emissions level to the 2020 US Environmental Protection Agency (EPA) requirements. Gaps are identified for a range of passenger car and light trucks by vehicle type and powertrain. Provisional reduction goals are recorded and projections are made using simulations to determine the effectiveness of P3 configuration to meet both the target CO₂ emissions while maintaining acceleration and performance at current, consumer-validated levels.

This report culminates with the determination of a targeted platform set with strong potential to benefit from implementation of the P3 or P4 hybrid architecture. Specific benefits of these configurations related to energy recuperation, vehicle performance and system reliability are expounded along with vehicle simulation results for fuel economy in an exemplary application. Light Plug-In Hybrid Electric Vehicle (PHEV) operation is also contemplated where needed to mitigate the most severe CO₂ gaps.

The results of this report will be helpful to OEMs and suppliers making hybrid architecture planning and portfolio decisions for both US and global markets. It also serves as a positive voice in the debate as more

industry players are realizing the compelling case for vehicle dynamic performance as a principle attribute to be improved in tomorrow's advanced hybrid configurations.

2. NEW ERA OF CO₂ REDUCTION

A new era of global management of passenger car and light truck CO₂ has begun with OEMs developing future fleets to comply with worldwide targets requiring 4 to 5% annual improvement in fuel economy through 2025. Using the 2016 MY US fleet footprint data and published fuel economy values, the "improvement task" required for average fuel economy is shown in figure 2 for a range of drivelines and vehicle classes.

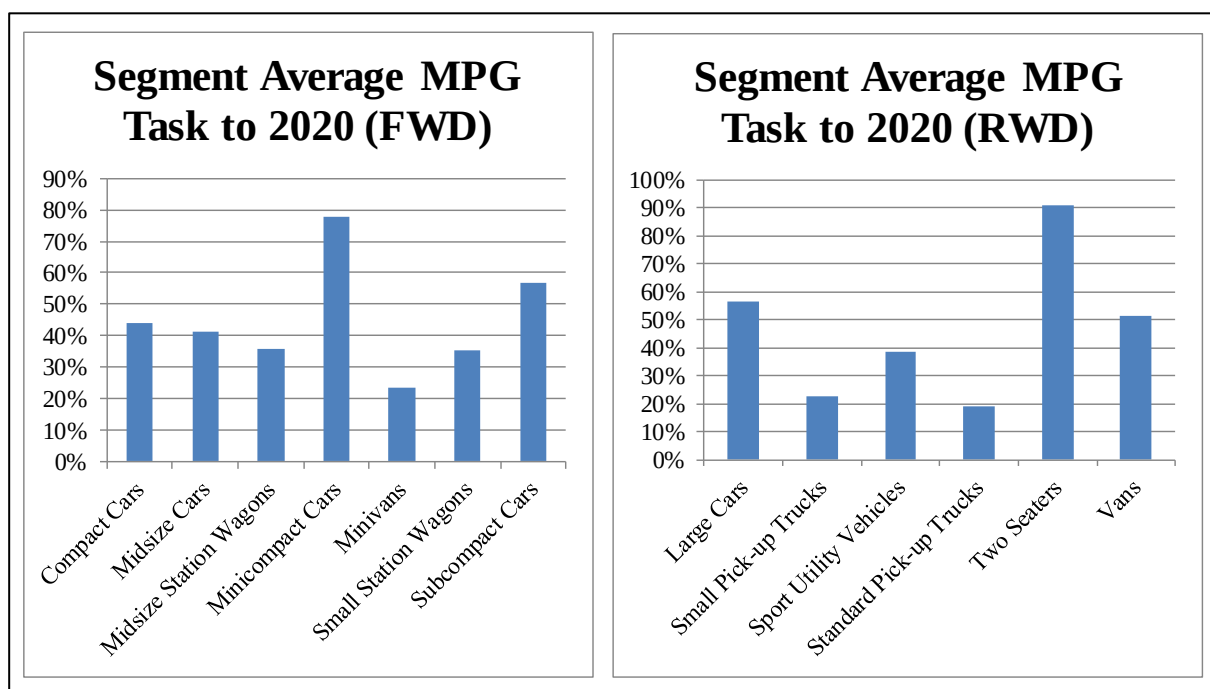


Figure 2: Average US MPG Improvement from 2016 to 2020

Note that the segment MPG improvements above are calculated using a uniform sales distribution and do not include certain non-tailpipe CO₂ credit that amounts to approximately 20 g/mi or about 5 to 10% improvement. Nevertheless, substantial MPG improvement will be needed across all segments of the US fleet. This same general condition exists for world-wide fleets. OEMs have been addressing this impending problem for years as they develop xEV solutions, some of which already meet the most stringent targets. These key models in an OEM portfolio can be instrumental in the coming transformational years. Then, the future strategy is to ensure a favorable sales distribution to maintain overall compliance.

As inferred above, the accounting of CO₂ performance for manufacturer compliance is done in aggregate, so while some models exceed the standard, they are offset by others that fall short. In the end, each manufacturer strives to reach its unique goal based on the footprint size and car/truck mixture they sell. Because of this aggregation, low-volume segments will generally not be targeted for xEV powertrains. In the case of high-sales-volume products, OEMs are developing xEV solutions which will soon be in place. The challenge ahead is to keep the product portfolio exciting and affordable while dramatically increasing the sales of high-relative-efficiency products.

As mentioned at the outset, EVT solutions for FWD platforms are well-established and most likely to see widespread adoption in those segments. Also, two-seater vehicles tend to be low-volume platforms and are

therefore not a focus here. The remaining platforms are RWD pickups, vans, SUVs and large cars. These four segments require significant MPG improvement and thus represent an important focus of this paper.

3. HYBRID CONFIGURATIONS

Hybrid configurations can be classified using the P1 through P4 nomenclature. The letter “P” is used to denote position along the drivetrain where P1 is essentially the engine crankshaft and P3 is downstream of the transmission (See Figure 3). There is also a fifth unique type, the EVT.

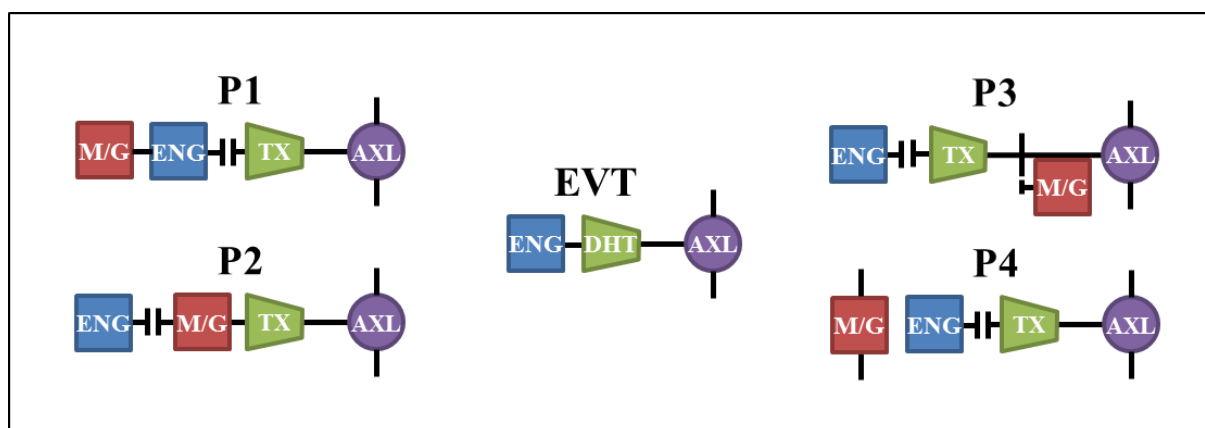


Figure 3: Simplified Hybrid Configurations

In figure 3, “M/G” represents a motor-generator that may include gear or belt reduction (not shown). This motor generator can assist in propulsion and recover energy when retarding the vehicle’s motion. There are two motor-generators within the Dedicated Hybrid Transmission (DHT) of the EVT configuration. A disadvantage of P1 configuration is that M/G speed cannot be decoupled from engine speed. This effectively denies the P1 configuration any EV mode and creates parasitic engine pumping losses during recuperation.

A P2 hybrid includes the benefit that it can be decoupled from engine speed using a strong clutch at the flywheel position. Recuperation can be more efficient than P1 and EV mode is enabled. However, P2 configuration includes a disadvantage in that transmission controls are heavily influenced by engine and NVH requirements. This causes a significant trade-off between customizing transmission controls for hybrid fuel efficiency and controlling the system to maintain expected engine speeds and NVH levels. In short, the transmission controller must satisfy two unique and divergent shift strategies.

P3 and P4 hybrid configurations are similar to one another in that each approach typically places a single M/G at a fixed gear ratio to axle speed (on the order of 10:1). Two-speed gearboxes are sometimes implemented, especially helpful for permanent magnet M/G due to continuous losses at speed. In P3 configuration, the M/G powers the same axle as the engine whereas a P4 M/G unit powers the alternate axle, resulting in an added benefit of electric all-wheel-drive (eAWD). P3 is commonly understood to indicate a “post-transmission” hybrid. Figure 3 shows simplified longitudinal configurations but each can also exist in a transverse powertrain.

EVT configuration is quite efficient due to the use of two motor-generators within the DHT. Using various unique arrangements of planetary gear set(s) and two independently-controlled electric machines, the EVT system allows an EV mode and infinitely variable engine speed control to operate along the minimum specific fuel consumption line. A common approach for EVT hybrids, first employed by Toyota, is to leverage the high efficiency thermodynamic cycle first patented by James Atkinson in 1887. The Atkinson

cycle is instrumental in allowing some spark ignition engines to achieve up to 40% thermal efficiency [4]. Almost any hybrid configuration could benefit from this inherently synergistic Atkinson cycle whereby its only disadvantage is a reduction in specific power output.

The hybrid configurations presented in figure 3 are not intended as an exhaustive listing – many other combinations and layouts exist. However, these five prevalent configurations represent the focal point of this investigation.

4. P3 AND P4 STRENGTHS

Best-in-class energy saving hybrids for mainstream FWD passenger cars are well understood and have received significant optimization, employing two electric machines in a dedicated hybrid transmission. However, very few rear-wheel-drive powertrains have succeeded in providing future-compliant MPG relative to footprint size. The 2015 EPA database lists only two RWD (non-plug-in) vehicles with tailpipe “compliant” CO₂ performance relative to 2020 targets: F-150 Ecoboost LWB and RAM 1500 Diesel LWB. Note that both of these cases leverage a “stretched” wheelbase to achieve the enviable position. By contrast, there are dozens of 2020-compliant FWD (non-plug-in) vehicles in the same EPA database. Effective hybrid solutions are currently lacking for traditional RWD platforms like pickups, vans, large SUVs and large cars.

Figure 4 illustrates the natural relationship between platform efficiency and MPG rating. Reduced road load power requirement generally results in increased MPG as shown. The family of curves illustrates the impact of engine power rating whereby platforms with low relative power may achieve significantly higher MPG than platforms with high output engines.

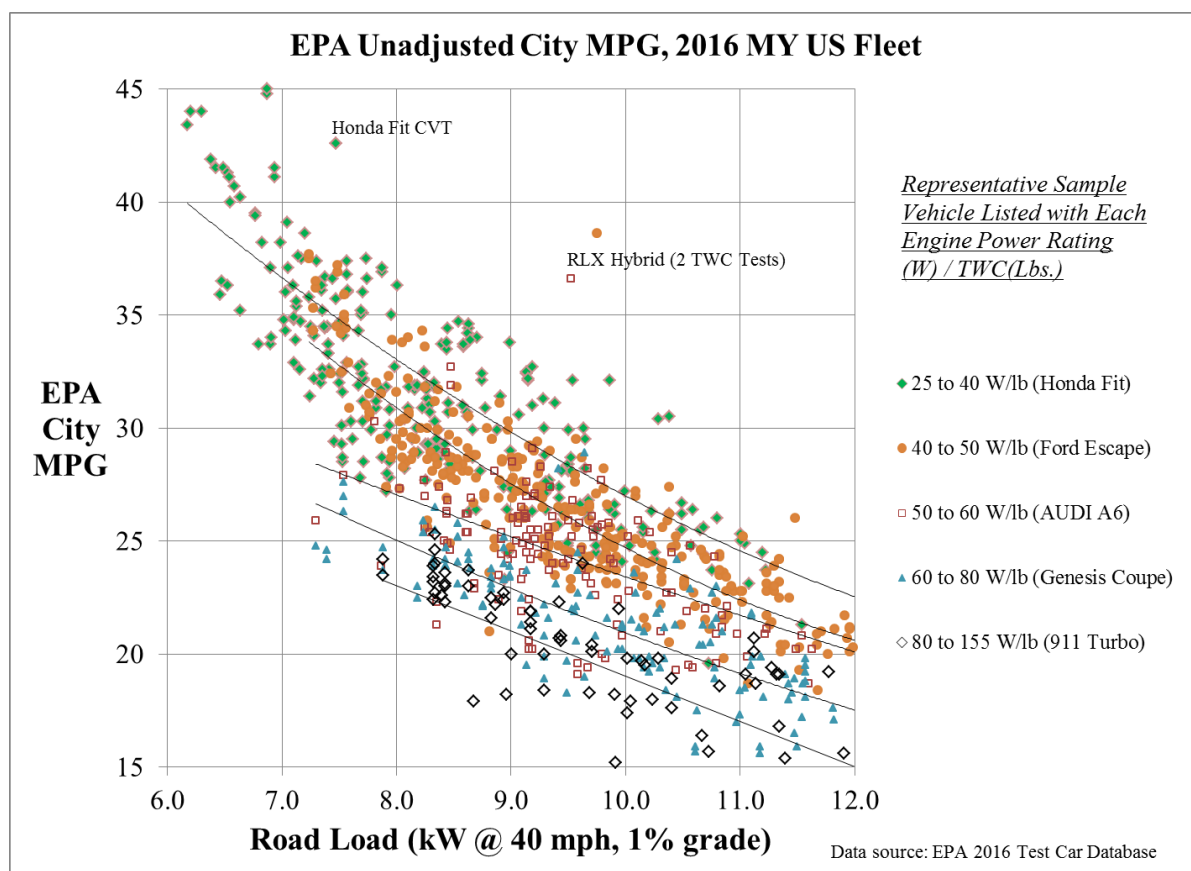


Figure 4: City MPG vs. Road Load and Vehicle ICE Specific Power Index

Hybrid powertrains can escape the bounds of this relationship as illustrated by the Acura RLX Hybrid data points. A powerful engine is less detrimental to fuel economy when hybrid systems operate frequently near peak efficiency and rarely idle. Future hybrid platforms will provide appealing peak power capacity with a strong contribution from electric propulsion. These same solutions will operate near optimum specific fuel consumption in real-world driving conditions. Next, we describe why P3 and P4 configurations are an excellent choice for platforms with sport driving capability or physical utility as required in the light truck segment.

- Efficient** – Wheel-P3/P4-Wheel recuperation energy path is short and efficient
- Consistent driving feel** – Transmission shifts not required for recuperation – P1, P2 often in the wrong gear
- Helps launch performance** – P3/P4 weight distributed at rear axle
- Excellent grade towing and smooth, aggressive launch** – Torque converter is maintained
- Avoids addition of K0 clutch** – Eliminates cost and maintains system reliability
- Maintains drivetrain position** – No change required in engine or transmission position
- eTV integration** – P1 and P2 hybrids cannot do this. Mode-switch e-vectoring is an economical design
- Maintains or shrinks ATX requirements** – No input torque increases for ATX (may go down)

Figure 5: Eight Advantages of P3 and P4 Configuration

Figure 5 shows eight advantages of P3 and P4 which in many cases cannot be achieved with P1, P2, or EVT configuration. P3 and P4 are similar in that they both place the M/G near the wheel, often using a single-speed reduction on the order of 10:1. The main difference is that P3 accommodates an input shaft from the ICE drive system. The round-trip recuperation energy path is very short and efficient for P3 and P4 configurations. Before an energy recuperation phase while driving, the first notable action is accelerator pedal lift causing transmission upshifting and a resultant low engine speed. In this condition, both P1 and P2 hybrids are not prepared to recover as much energy as a P3 or P4 hybrid which will exhibit M/G speeds similar to maintaining 2nd gear at all times – This is an inherent advantage for P3 and P4 configuration.

Rear-wheel-drive platforms typically benefit in launch performance when components are situated toward the rear of the vehicle. This is due to weight transfer during acceleration and is a slight disadvantage of P1 and P2 configurations. Another important factor in trucks and performance cars is the role that a torque converter plays in smoothing a launch and amplifying engine torque. Some commercial P2 implementations eliminate the torque converter to allocate room for the M/G. However, this approach causes discontinuous and diminished launch torque and compromises low-speed grade towing, especially in any cold ambient where battery power is compromised.

The P2 configuration includes a K0 clutch to decouple the engine. This clutch can be either wet or dry and represents added cost, engineering development and reliability concerns. These aspects are not required in a P3 or P4 hybrid which makes use of neutral gear to disengage engine. In the case of certain P1 and P2 hybrids, additional space must be allocated for the M/G placed between engine and transmission. P3 and P4 hybrid configuration does not require a change to engine or transmission position but may change the required prop shaft length.

Torque vectoring is an important function that is propagating in the industry due to its improved sport driving capability and for its low-mu active safety benefits. Drivers experience a dramatic increase in steering authority in slippery conditions. Electric torque vectoring (eTV) is often integrated with P3 or P4 drive units. One low-cost strategy is to implement a mode-shift type of eTV that automatically or manually shifts between hybrid and vectoring mode. This type of design uses a single M/G which will alternately couple between propulsion and a L/R vectoring function. The majority of time, this system remains in hybrid mode, providing a substantial gain in fuel economy, because the fraction of time that driving conditions dictate a change to vectoring mode is low. eTV cannot be integrated at a P1 or P2 motor-generator.

Finally, there is a benefit of P3 and P4 configuration simply because their torque is not passing through the transmission to power the wheels or when receiving recuperative energy. Transmissions need not be increased in capacity to implement P3 or P4 configuration whereas upsizing is sometimes required for P1 and P2 designs, especially in high performance applications.

5. P3 AND P4 CHALLENGES

RWD passenger car platforms are often limited in packaging space at the rear axle. In order to effectively package a P3 hybrid solution with a rear drive module, creative electric drive packaging solutions must be identified. In truck and van applications, space to package a P3 rear axle system is usually not an issue, but added un-sprung mass is highly undesirable. Therefore, creative designs are needed to save weight in the rear beam axle assembly so that net axle weight is not increased.

Another challenge for P3 and P4 configuration is in the area of engine operating point modulation. EVT configuration is able to modulate both speed and load effectively with an infinite degree of variation. All of the parallel hybrid configurations (P1-P4) can only modulate engine load (torque) and transmission ratio is selected as usual. However, if a CVT is employed with a parallel hybrid (akin to Honda IMA) then both engine speed and load can be modulated freely.

P3 and P4 hybrids experience a certain limitation in that they are not able to generate electricity unless the vehicle is in motion. For this reason, hybrid system controls must employ algorithms that anticipate energy needs to compensate for this limitation. P4 hybrids have a unique requirement of providing AWD functionality during extended travel in low-mu conditions. Often a combination of (P1, P2 or P3) and P4 are used whereby the first machine generates power to continuously supply P4 energy for AWD.

The challenges identified for P3 and P4 are non-trivial but nevertheless solutions are currently being developed to overcome or compensate for their limitations.

6. LIGHT TRUCK CASE STUDY

Key longitudinal platforms identified for P3 and P4 hybridization include pickups, vans, large cars and large SUVs. Transverse powertrain vehicles also benefit substantially from P4 configuration but are not the focus of this research. For this study, a full-sized pickup was analyzed as both a P3 HEV and a P3 light-PHEV. The three main manufacturers were reviewed and the regular wheelbase truck that fell in the middle based on its footprint size of 57 square feet. This vehicle is the 2016 RAM 1500 with 5.7 liter V8 and eight-speed automatic transmission. Complete vehicle parameters were retrieved from the EPA test car database as shown in Table 1.

Table 1: Base Vehicle Input Parameters and Base Simulation Results

<u>Base Vehicle Parameters: 2016 RAM V8, 8-Spd AT</u>						
A	=	49.39 lbs	g1 = 4.71	EPA City	=	18.5 MPG, unadjusted
B	=	-0.2126 lbs/mph	g2 = 3.14	EPA Hwy	=	29.9 MPG, unadjusted
C	=	0.03811 lbs/mph/mph	g3 = 2.11	EPA Comb	=	22.3 MPG, unadjusted
TWC	=	5500 lbs	g4 = 1.67	Compliance	=	398 g/mi, CO2
revs	=	655 rev/mi	g5 = 1.285	SIM City	=	18.2 MPG, unadjusted
FDR	=	3.21 final drive ratio	g6 = 1.000	SIM Hwy	=	30.1 MPG, unadjusted
Disp	=	5.7 liters	g7 = 0.839	SIM Comb	=	22.1 MPG, unadjusted
Eng	=	295 kW	g8 = 0.667	Compliance	=	401 g/mi, CO2

SIMULINK vehicle simulation models are used by AAM to research and identify efficiency opportunities in both hybrid and conventional powertrain systems. Standard models are first set up with all known input data for the baseline vehicle and results are checked to ensure they agree with published EPA test results.

This procedure allows researchers to better understand the behavior of the base vehicle and provides a solid foundation for exploring powertrain enhancements. The results of the simulation were very close to the actual test values with overall CO₂ within 1% of actual values. This is as close as can be expected for this level of simulation where the engine fuel map is generic or scaled, for example.

While the actual compliance CO₂ level of the vehicle (the emission level that EPA considers this truck to produce in their official tabulations) is 398 g/mi, based on the 57 ft² footprint, the target for 2017 is 311 g/mi and for 2025 it is a very challenging 217 g/mi (45% below the current value). Powertrain enhancements are needed in both the near term and the longer term to reach these goals while maintaining the important functional capabilities that customers require, like hauling at GCW on a 12% grade – P3 and P4 solutions are a good option for this kind of application.

In order to provide production-level proven hybrid fuel economy, complex system control algorithms with load-shifting strategies and calibrations to maintain smooth drivability are developed. There are myriad approaches which are too lengthy for discussion here. For this paper, a simple hybrid system control strategy based on load-shifting at a fixed, marginal generation of 4000 W during ICE ON conditions was analyzed. It is well-known in the art that the marginal efficiency is normally quite high for producing one additional unit of energy from an internal combustion engine that is already operating at a low to intermediate load point. For example, Figure 6 illustrates this relationship for a four-cylinder engine.

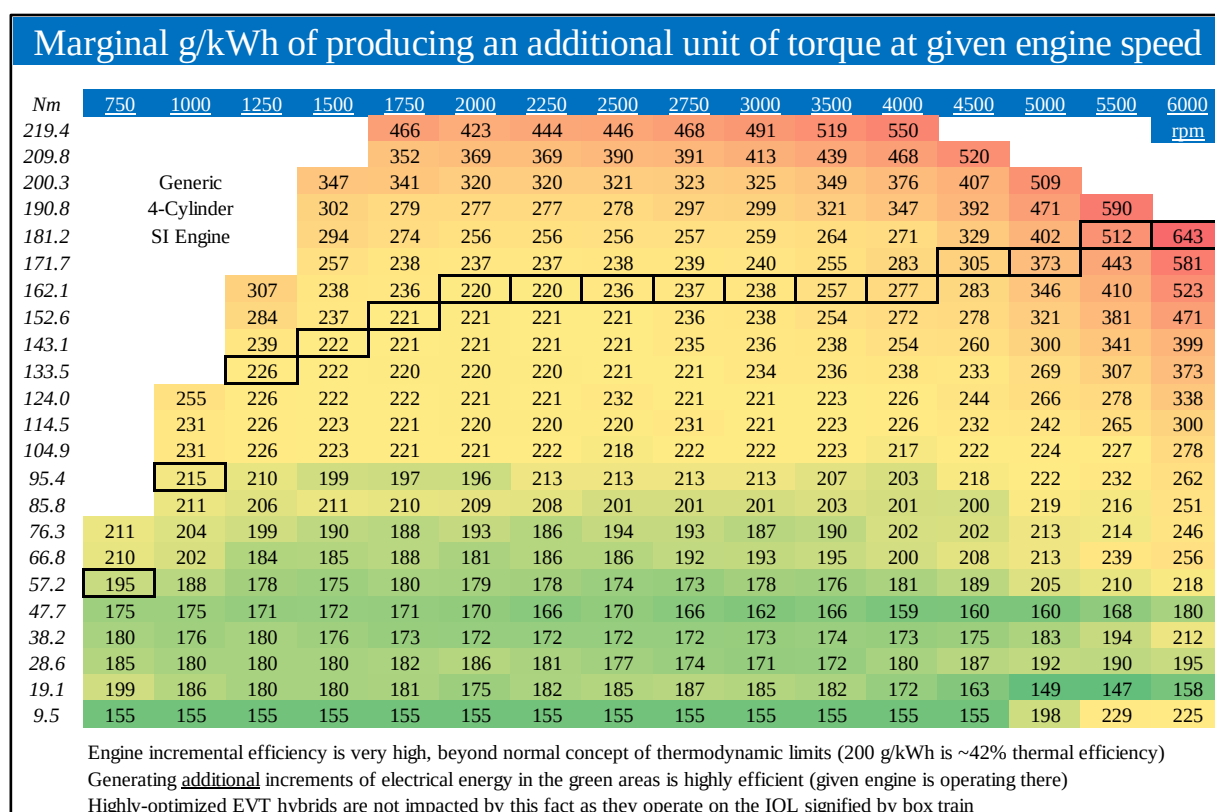


Figure 6: Favorable Load Zones for Generating Power (Generic Four-Cylinder Example)

Given an existing operating point at say, 50 Nm and 2000 RPM, it would be highly desirable to generate incremental hybrid power for storage and thus raise the crankshaft torque. In this case, 4000 W mechanical power of generation would raise the crank torque to 69 Nm. This incremental energy transaction occurs at a cost of only about 180 g/kWh (mechanical). Parallel hybrids with EV modes can benefit from an ability to

generate efficient marginal energy if they are not already mechanized for continuous Ideal Operating Line (IOL) strategy.

As mentioned above, the goal in this study was to analyze a basic hybrid strategy – one possible approach of many – to discover what city and highway fuel economy could be achieved with a P3 hybrid given the system characteristics of Table 2.

Table 2: P3 HEV and PHEV Parameters and CO₂ Projections

Hybrid System Parameters: P3 HEV and PHEV Concept							
P3	=	146	kW	<u>PHEV Pack</u>	SIM HEV City	=	37.7 MPG, unadjusted
P3	=	350	Nm	8 kWh, 15 mi AER	SIM HEV Hwy	=	31.1 MPG, unadjusted
P3 eta	=	50%	min		SIM HEV Comb	=	34.4 MPG, unadjusted
P3 eta	=	96%	max		SIM HEV Compliance (meets 2021)	=	258 g/mi, CO ₂
reduction	=	10:01	ratio		SIM PHEV City	=	62.8 MPG, unadjusted
P3 delta	=	44	kg	UF = 0.37	SIM PHEV Hwy	=	47.8 MPG, unadjusted
inverter	=	10	kg		SIM PHEV Comb	=	55.0 MPG, unadjusted
pack	=	60	kg		SIM PHEV Compliance (meets 2025)	=	161 g/mi, CO ₂

The SIMULINK model was run in ICE mode over the drive cycles with weight set at HEV level and with 4000 W DC of continual marginal generation. All data were recorded and specifically instantaneous gal/mi values were stored along with time and speed trace data. Then the same model was run in EV mode over the cycles and the 4000 W generation was turned off. Weight was kept at hybrid level. Instantaneous Wh/mi data was stored and those traces were used in comparison with the gal/mi data from the same cycle ICE runs.

Then the data are combined into Wh/gal at each moment (using Wh/mi ÷ gal/mi = instantaneous Wh/gal). This resultant data series is highly instructive, showing at each moment how much DC Wh in EV mode are required to offset a gallon of fuel. The series varies dramatically - when the engine is running efficiently the value approaches about 11,500 Wh/gal. On the other hand, during inefficient light loads the engine may only be capable of a few thousand Watt-hours equating to a gallon consumed. The next step in the analysis is to set up a variable Wh/gal threshold to balance the energy recoverable in ICE mode due to the power generation. This threshold is adjusted higher or lower which changes the incremental energy sums generated during ICE operation and required during EV phases. When the energy generated matches the amount required, the total fuel and cycle MPG is known based on a hybrid mode that switches between ICE and electric propulsion when it is most efficient for each power source. Figure 7 illustrates the arbitration that helps determine the most appropriate engine operation periods.

An advanced hybrid control system will evaluate more elegant engine load management strategies, incorporate rules to minimize spurious engine starts/stops and provide an expected degree of drivability resulting from extensive calibration. The goal of this analysis is to show the potential of P3 configuration to dramatically reduce fuel consumption, especially as demonstrated here on the city cycle. While the hybrid city cycle result is double the non-HEV MPG, it is not unprecedented. EVT hybrids commonly provide more than twice the city MPG as is the case with 2016 Fusion 2.0 HEV (60.6 mpg) vs 2.0 ICE (28.6 mpg). A portion of the benefit in the case of Fusion HEV results from the Atkinson cycle engine.

In highway cycle fuel economy, the results are a 4% increase from 29.9 mpg base to 31.1 mpg. This result shows the challenging frontier of raising highway fuel economy of trucks using hybrid technology. There is a relatively small amount of recuperation energy available on the EPA highway cycle. The 2013 Silverado 2-mode achieved 32.8 mpg on the highway cycle, showing that more optimization is required in the current

control strategy employed in this study. Also, implementation of a large displacement Atkinson V8 would likely prove beneficial in the truck segments, exceeding the efficiency levels achieved through cylinder deactivation.

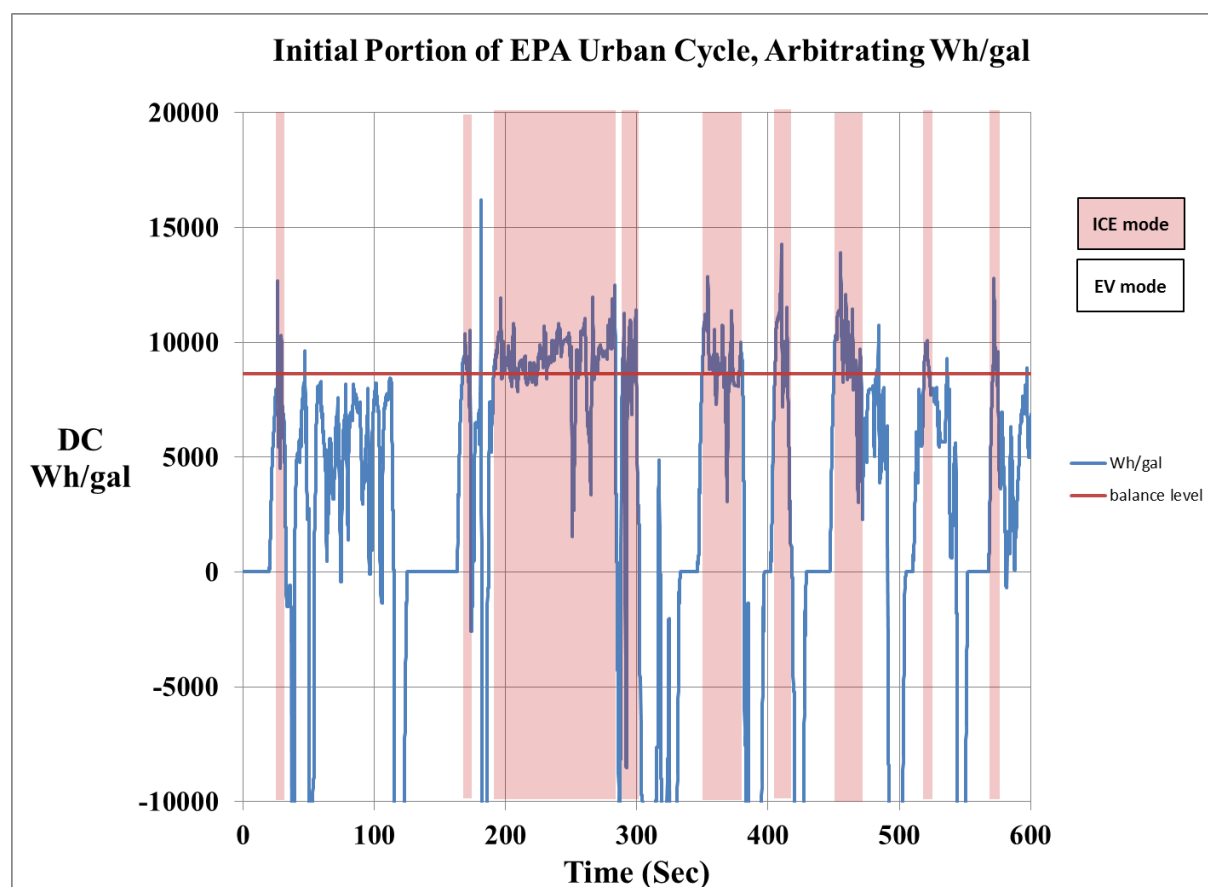


Figure 7: Cycle Arbitration Strategy to Determine Efficient Engine Operation Periods

Overall, the HEV fuel economy and CO₂ results of this study show that P3 hybrid configuration represents an opportunity for significant improvement in overall values to 34.4 mpg combined, unadjusted and 258 g/mi, CO₂. These results would achieve EPA compliance to 2021. It is estimated that the addition of Atkinson V8 and other minor fuel saving technologies would extend compliance possibly to 2023. It should be noted again that these compliance projections are given a regular wheelbase – a non-trivial challenge that avoids stretching wheelbase to lower the MPG target.

In order to meet CO₂ targets beyond 2023, further technologies are likely to be introduced. PHEV results for the P3 configuration show that substantial further reduction of CO₂ is possible. A gross battery pack energy of 8 kWh was selected and combined all electric range of 15 miles was projected for the vehicle. This resulted in utility factors of approximately 37% and CO₂ of 161 g/mi, well below the 2025 requirement. In this case, the modest usable pack energy of 5 kWh might motivate vehicle system developers to integrate on-board hands-free charging for the home and other sites to improve convenience of recharging.

Summary and Conclusions

The proliferation of US hybrid configurations over the past decade has been analyzed to show the leading approaches and trends. A review of recent EPA fuel economy and CO₂ emissions data was produced to show that many vehicle classes will require dramatic improvement to meet the coming requirements with the sample year of 2020 being used in this review. While there are already several effective hybrid solutions for lowering CO₂ among front-wheel-drive passenger cars, there was shown to be a notable lack of vehicle technologies in place to address CO₂ in larger, traditionally rear-wheel-drive platforms.

Next, the range of popular hybrid configurations were presented and explained mechanically while elaborating the strengths and challenges of each approach. Specific, customer expected functional capabilities were considered and the ability of each configuration to address them was presented. P3 and P4 configuration were then further explored with more details regarding inherent strengths and challenges. An important emerging technology of integrated, electric torque vectoring was also presented.

Finally, system simulations were performed for a technology candidate, full-sized pickup truck to first demonstrate integrity of the model on the baseline vehicle and then apply P3 hybrid system effects to determine potential for CO₂ reduction. Results were compliance to 2021 as an HEV, to 2023 with addition of Atkinson cycle V8 and minor fuel-saving technologies, and beyond 2025 as a light (15 mile AER) PHEV.

In conclusion, P3 and P4 hybrid architecture for larger platforms and longitudinal powertrains with demanding customer performance expectations is understood to be both inherently capable of maintaining the required performance and has the potential for dramatic hybrid fuel economy that will comply with EPA requirements to 2025 and beyond. Maintaining a standard of excellence in customer-expected functional performance in these segments will be a major factor for consumer uptake of these new technologies in the coming decade. This winning combination of desirability and efficiency represents a powerful CO₂ compliance tool in US and global OEMs.

Acknowledgments

The authors wish to thank AAM for supporting the research included here and for the company's steadfast pursuit of technology leadership, operational excellence and quality in manufacturing. A further thanks to our supporting teams at the AAM Advanced Technology Development Center in Detroit and at Trollhattan Technical Center in Sweden.

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