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Light-Duty Vehicle Transmission Benchmarking – 2021 Toyota RAV4 Prime P810 Transmission and Q610 Rear Axle

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16. Abstract This report benchmarks the 2021 Toyota RAV4 Prime Hybrid P810 electric continuously variable transmission and its Q610 electric rear axle. Benchmarking tasks include component and system level performance of overall transmission efficiency, torque converter performance, in-gear inertia maps, oil pump mapping, ratio determination, and shifting and converter strategies.			
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FOREWORD

The objective of this project was to evaluate and characterize different transmission architectures currently available in North American light-duty vehicles. The National Highway Traffic Safety Administration task order includes the reverse engineering of advanced transmissions offered in MY2019 or newer vehicles produced for the North American market. Southwest Research Institute has worked with NHTSA and project partners to provide NHTSA with empirical data collection, technical support, and data analysis on the transmissions identified for benchmarking consideration. Evaluation of each benchmark transmission consisted of component efficiency mapping, torque converter mapping and engagement strategy, oil pump testing, parasitic loss determination, shift schedule identification, laden and unladen shift algorithm mapping. General ratio spread and packaging envelope of each transmission has also been documented while completing the task order. Throughout the duration of the project, attention has been paid to identify individual components of the transmissions that advance fuel economy and quantify their benefit.

This report follows the specific requirements or SRs outlined by the original NHTSA task order. Each SR section addresses unique objectives of the overall project. SR-1 was the project kick-off meeting held at the award of the program and did not generate any technical content. Therefore, SR-1 has been omitted from the final report. SR-2 deliverables were generated with the fully assembled transmission at the component level. The transmission efficiency, torque converter performance, and in-gear inertia maps were all a part of the SR-2 tasks. Overall component level characterization took place within SR-3. The SR-3 tasks included parasitic measurements of the assembled transmissions, oil pump mapping, ratio determination, and physical dimensioning. SR-4 examined the in-vehicle performance of each transmission. The SR-4 data sets characterized shifting and converter strategies.

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Table of Contents

List of Figures

List of Tables

List of Acronyms

AMT	automatic manual transmission
ATF	automatic transmission fluid
CVT	continuously variable transmission
DCT	dual clutch transmission
e-CVT	electric continuously variable transmission
EV	electric vehicle
EPA	Environmental Protection Agency
FDU	front drive unit
HEV	hybrid electric vehicle
HSD	hybrid synergy drive
RDU	rear drive unit
SoC	state of charge
SwRI	Southwest Research Institute

Project Introduction

This project evaluates and characterizes different transmission architectures available for use in light-duty vehicles produced for the North American market. The transmissions as described in this report (FY2021) consists of a hybrid electric e-CVT. The e-CVT vehicle included an electric drive axle, so additionally, the rear axle was benchmarked for FY2021. The evaluation of each benchmarked transmission consisted of gearbox operational efficiency mapping, and parasitic loss determination.

The transmission benchmarking efforts as part of this project sought to provide NHTSA with powertrain data that improves vehicle modeling and standard writing activities. The report details the technological advancements of each benchmark transmission and the empirical data collected as part of the project.

Introduction to Toyota Rav4 Prime P810 and Q610

NHTSA provided SwRI with a 2021 Toyota RAV4 Prime to quantify the efficiency of the front drive unit transmission and the rear drive unit. The FDU is Toyota's model P810 which is part of the P-series hybrid synergy drive transmission line. The FDU is available in the Toyota's mid-sized SUV line consisting of the Highlander, Sienna, and RAV4 Prime. The FDU produces 134 kW between two motor-generators (MG) that produce drive power and regeneratively charge the vehicle battery. The FDU consists of MG1, MG2, a single planetary gearset, and a differential gearset. The FDU is an electric continuously variable transmission. The ratio between engine speed and output vehicle speed is continuously variable via the MG1 motor-generator. The ratio of the FDU is controlled by the electric motor-generator rather than by the variator of a conventional belt and pulley CVT design. The FDU couples to the RAV4's 2.5 L, 4-cylinder engine creating the power-split configuration that powers the front wheels. The two motors of the power-split are integrated within the power flow which allows seamless transition between hybrid electric vehicle and electric vehicle operation. The modes of operation are determined by driver demands and the battery pack state of charge.

The RDU is independent of the FDU and powers the vehicle's rear wheels. The combination of the FDU and RDU makes the RAV4 AWD capable of improving control of the vehicle during adverse driving scenarios such as wet or icy conditions. The RDU consists of a 40-kW electric motor packaged with a 10.781:1, speed-reducing gearbox and differential to drive each rear wheel.

Inertia mapping, torque converter characterization, pump testing, and shift schedule mapping were not completed for the P810 FDU. The FDU is not equipped with a torque converter and e-CVT ratio is dependent on driver torque demand, vehicle speed, and the EV/HEV operating mode. Additional information regarding the pump in the FDU can be found in Appendix F. Component efficiency mapping for the RDU was completed in-vehicle by using instrumented wheels and an instrumented flywheel.

Vehicle Features

The Toyota RAV4 Prime is an all-wheel-drive vehicle consisting of a hybrid transverse powertrain with an electric transaxle (P810) on the front axle and an electric rear drive axle (Q610). The electric FDU consists of two permanent magnet synchronous motor-generators (MG1 and MG2) that enables varying transmission ratios for the hybrid drive function of the

vehicle and electric drive capability. Both electric motors inside the FDU have a regenerative function so energy recovery to the battery is possible on-road. The two electric motor-generators in the FDU are configured in a parallel axis layout.

The electric motor-generator in the rear axle of the vehicle is not coupled mechanically to the internal combustion engine. The rear powertrain of the Toyota RAV4 is a P4 configuration where the electric motor is connected through a gear mesh and constant velocity half shafts to the rear wheels of the vehicle. The P4 configuration allows for the AWD function of the vehicle, as well as torque split between the front and rear for desirable vehicle dynamics under various conditions. The electric motor-generator in the rear axle is a permanent magnet synchronous motor with parallel axis, helical gear reduction.

Areas of Efficiency Improvement

The hybrid configuration of the Toyota RAV4 Prime allows for decreased fuel consumption compared to the non-hybrid RAV4 vehicles. The e-CVT front drive unit optimizes the engine efficiency in charge sustaining mode versus vehicle speed and torque demand. The variable ratio e-CVT, same as a conventional CVT, allows sustained narrow speed range operation of the engine. Additional tractive effort is available via the motor-generators to shave torque demand spikes and limit engine fuel consumption during transient events. The power-split drive does not achieve the efficiency of an alternative P2 motor position paired with a conventional planetary automatic or dual clutch transmission in charge sustaining mode due to the inefficiencies associated with MG1 controlling gear ratio. The reduction of fuel consumption through optimized engine operation and the fuel saved during charge depleting mode must be balanced in the vehicle calibration against the native inefficiencies of the power-split drive to achieve a net fuel consumption gain against the conventional powertrain vehicles. In comparison to previous Toyota hybrid FDUs, Toyota has reduced the size and mass of the P810 unit compared to the P313 unit it replaces.

Configuring the electric motors into a multi-axis layout has provided a reduction in axial length of the power split transmission. The part content of the assembly has been reduced versus previous power split units and conventional automatic transaxles. The P810 does not have a torque converter, clutches, or a powered oil system. All add parasitic losses to the system if in place. The motor speeds of the motor-generators have been increased over the previous generations. Toyota has reduced motor size and magnetic content but increased motor speed, and as a result, maintained motor power. The torque each motor can produce has been reduced, but due to the increased reduction ratio, equivalent wheel torque is maintained. In the P810, the speed increase has reduced mass and mechanical loss by up to 20 percent.[1] The motors in the transmission use a bar-wound stator, with thick rectangular wires making up the electrical windings. These wires produce a higher fill factor in the stator slots than round wires and reduces overall weight and copper loss versus round wire strands. Details of the internal component dimensions, weights, and integration are found in Appendix F, for the P810 FDU, and Appendix G, for the Q610 RDU.

[1] Taniguchi, M., Yashiro, T., Takizawa, K., Baba, S., Tsuchida, M., Mizutani, T., Endo, H., & Kimura, H. (2016, April 12-14). Development of new hybrid transaxle for compact-class vehicles (SAE Technical Paper 2016-01-1163). SAE 2016 World Congress and Exhibition, https://doi.org/10.4271/2016-01-1163.

The RDU has been upgraded compared to previous units to optimize the efficiency of the component. Toyota has sought to reduce the mass of the unit by using different materials for the electric motor components. The magnet size and configuration of the electric motor has been optimized for MY2021. The Q610 RDU, like the P810 FDU, uses splash lubrication to eliminate the parasitic loss of a lubrication pump. Toyota produces an ultra-fine finish on the RDU gears to minimize noise and reduce the friction at the gear meshes.

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SR-2 Deliverables – Gear Efficiency Maps

Gear Efficiency Mapping – Toyota P810 and Toyota Q610

Component Level Testing Setup

The RAV4 was the first HEV tested on this program, therefore SwRI considered both component level and vehicle level testing to quantify FDU and RDU efficiencies. Efficiency mapping of the FDU and the RDU was undertaken in-vehicle. The inability to interface with the OEM inverters outside of the vehicle introduced potential error in the efficiency data generated. SwRI conducted testing of the RAV4 on an AWD chassis dynamometer. The component level efficiencies were able to be characterized through additional discrete instrumentation at points throughout the vehicle's powertrain.

The vehicle was evaluated on SwRI's AWD chassis dynamometer. The AWD dynamometer has a maximum power rating of 400 hp on the front rollers and 600 hp on the rear rollers, for a combined power rating of 1,000 hp. The dynamometer has a maximum simulated inertia of 14,000 lb. and a maximum speed of 125 mph. A road speed fan was placed at the front of the vehicle to simulate wind speed as the vehicle would experience driving down the road. The dynamometer wheelbase was set to 105.9 inches to accommodate the RAV4 for testing. The ETW (equivalent test weight) was 4,500 lb. and the GVW was 5,530 lb. No emissions were sampled during testing.

Chassis dynamometer testing presented a unique set of challenges relating to power measurements related to the FDU and RDU. Figure 1 shows a diagram of the electrical and mechanical instrumentation used on the vehicle.

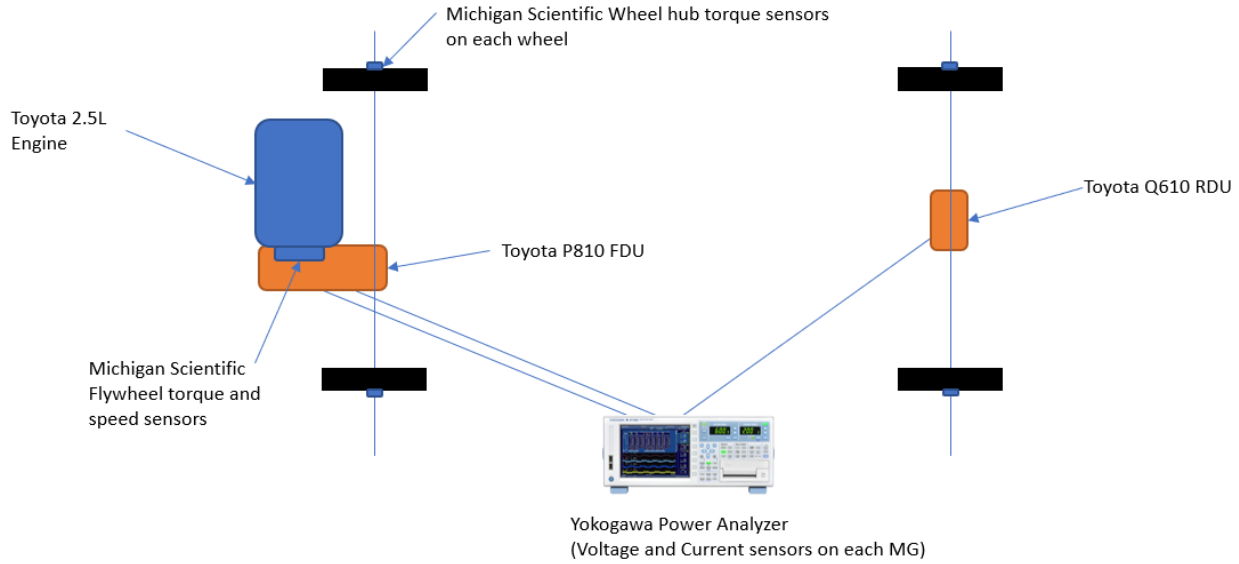

Figure 1. Electrical and mechanical instrumentation for Toyota RAV4 testing

Power was delivered to the FDU in two ways: mechanical power transmitted from the engine and electrical power from the vehicle inverters. The torque transmitted from the engine to the FDU was measured using a Michigan Scientific instrumented flywheel as shown in Figure 2 and Figure 3.The speed measurement was collected from the vehicle's stock crank position sensor. Together, the torque and speed measurements were used to calculate the mechanical power contribution from the engine.

To install the instrumented flywheel, the engine and FDU had to be removed from the vehicle and the engine was separated from the FDU. The custom-built flywheel, instrumented with strain gauges, was installed in place of the stock vehicle flywheel. Figure 4 shows the instrumented flywheel installed on the engine, along with the flywheel torque transmitter that was installed in the engine starter hole. The transmitter was designed so that the transmission mechanical pump could be mounted in its original position (the engine starter hole for conventional powertrain equipped vehicles). The unprocessed torque signal produced by the flywheel includes torsional peaks and valleys from cylinder firing events. A high-speed data acquisition and signal processing program was installed to derive a mean torque from the instrumented flywheel signal by accounting for the firing pulses of the engine. Additional details on the filtering process can be found in SAE Technical Paper 2017-01-1095. Figure 5 shows the filtered, mean torque signal and unfiltered torque signal as measured from the instrumented flywheel.

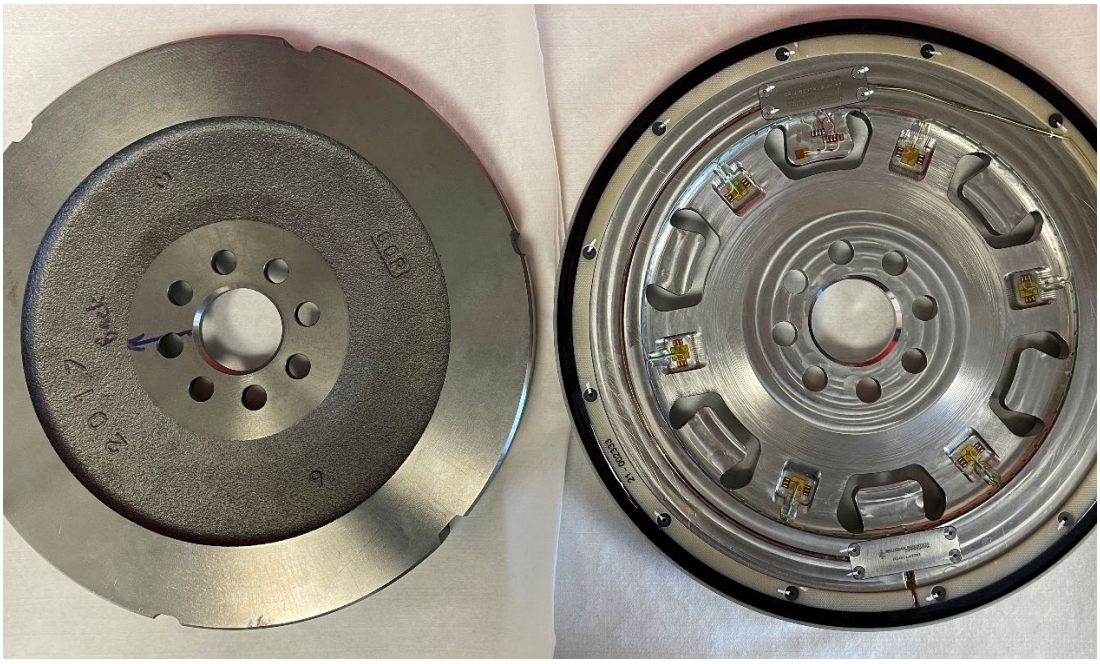

Figure 2. Stock flywheel and instrumented flywheel

Figure 3. Michigan Scientific instrumented flywheel with instrumentation

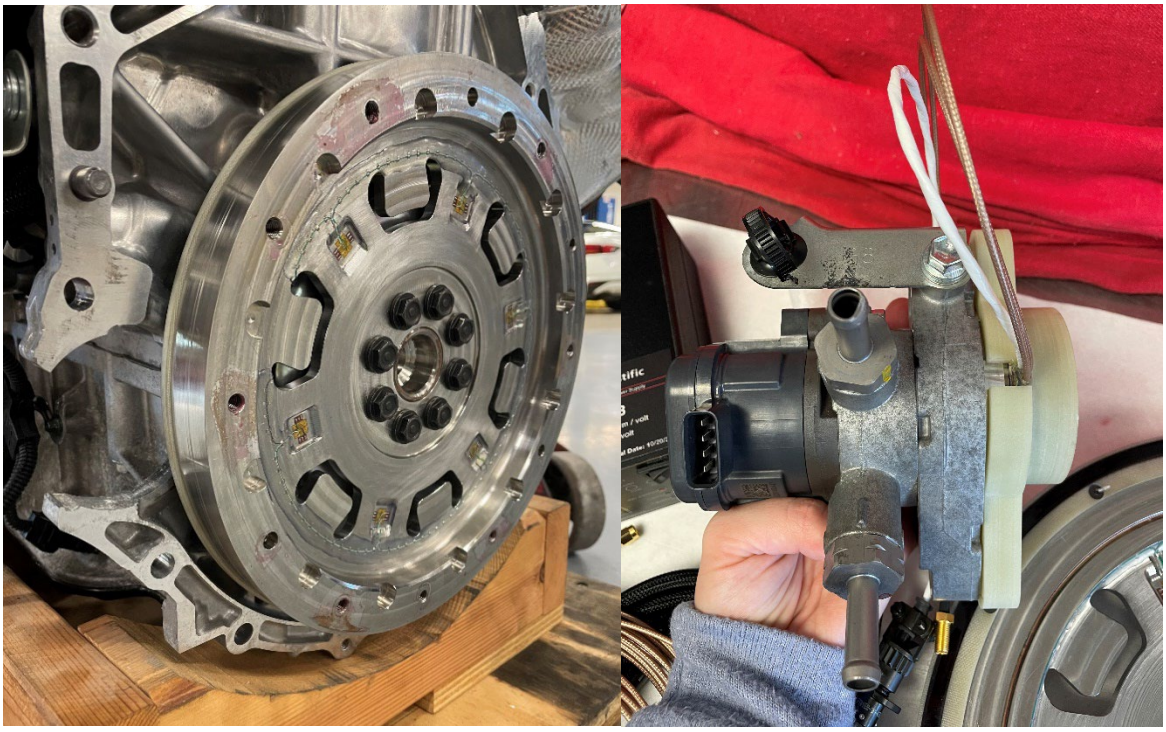

Figure 4. Instrumented flywheel installed on the engine and torque transmitter to be installed in the engine starter hole

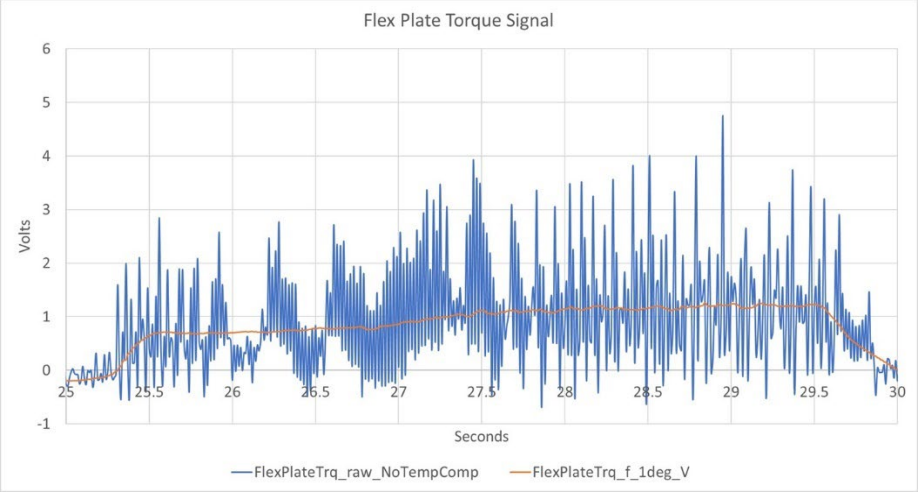

Figure 5. Unfiltered and filtered torque signal from instrumented flywheel

Electrical power was measured between the inverter and MG1 and MG2, both housed in the FDU. As an optional task, the RDU motor-generator characterization was added to the FY2021 effort, so electrical power instrumentation between the inverter and the RDU was included for all testing. A Yokogawa WT1806E power analyzer was used to measure the voltage and current, and therefore power, for the MG1 and MG2 in the FDU and the motor-generator in the RDU. Each motor-generator had three phases; however, since each of the three phases in the motor-generators are balanced, only two phases were needed to calculate the power produced or consumed by each motor. This allowed SwRI to measure the power through each of the three motor-generators simultaneously throughout all vehicle testing. The voltage measurements were taken directly to the Yokogawa via line-to-line leads. A combination of Rogowski and LEM current transducers were used to measure the current within each instrumented AC phase. Measurement accuracy and transducer packaging was balanced in the current transducer type selection and placement.

Speed and torque for each motor-generator was recorded from the vehicle OBD serial communication. These values were used to calculate the mechanical power of the motor-generator at each rotor. The mechanical power of each motor-generator served the drive unit and motor efficiency calculations. It should be noted that the vehicle OBD communicated measurements are low-frequency estimates; during highly transient operation the mechanical power calculated for each rotor lags the discrete wheel torque transducer and AC power instrumentation.

Output power of the FDU was measured using Michigan Scientific wheel torque sensors. The assemblies included a torque transducer and a slip ring to measure the rotational velocity. Custom wheel centers were fabricated by Michigan Scientific. A wheel torque transducer was mounted to each wheel center. Each transducer had a total of 12 strain gage elements, each in a full bridge configuration. The strain gage-to-torque calculations were based on the Wheatstone bridge concept. The stock vehicle tires were mounted on the instrumented wheels and the wheel/tire assemblies were balanced ahead of dyno testing. Once the wheels were mounted on the vehicle, the slip rings were mounted to the transducer with wiring harnesses routed to the conditioning modules inside the vehicle. An amplifier was supplied with each wheel transducer

that allowed direct logging of the analog torque signals. Figure 6 shows a torque wheel transducer and slip ring installed on the front passenger side of the vehicle.

Each wheel torque transducer measured up to 1,085 Nm load with a nonlinearity less than 0.1 percent of full scale. The slip rings used high accuracy encoders with a resolution of 512 pulses per revolution. Two-wheel torque transducers were available for use on this vehicle, therefore initial testing consisted of the transducers placed on the front axle. At the completion of drive cycle and steady-state testing for the FDU, the wheels were swapped to the rear axle for testing of the RDU.

Figure 6. Torque wheel transducer installed on the Toyota RAV4

Additional OBD channels were collected for all testing. Table 1 shows the instrumentation list for the RAV4.

Table 1. RAV4 instrumentation list

Yokogawa		
AC Power MG1	AC Power MG2	AC Power Rear Motor-Generator
Michigan Scientific Equipment		
Wheel Torque Right	Flywheel Torque	Wheel Revolution
Wheel Torque Left	Flywheel Speed	Vehicle Speed
CAN/OBD		
Hybrid/EV Battery SoC	Engine Coolant Temperature	Rear Motor Revolution
Hybrid/EV Battery Voltage	Throttle Position	Rear Motor Torque
Hybrid/EV Battery Current	APP_D	Transaxle Oil Pump Revolution
Transaxle Oil Temperature	MG1 Revolution	Inverter Water Pump Revolution
Rear Axle Temperature	MG1 Torque	EV Mode Status
Engine Speed	MG2 Revolution	Vehicle Speed
Calculated Load Value	MG2 Torque	

Calibrations

The Michigan Scientific equipment (instrumented flywheel, torque wheel transducers, and slip rings rotation sensors) were calibrated prior to testing on the chassis dynamometer according to the factory calibration paperwork provided by Michigan Scientific. Additionally, a shunt calibration was completed on each torque wheel transducer as installed on the vehicle prior to testing.

The Rogowski and LEM current sensors were calibrated by the SwRI Calibration Laboratory prior to installation and testing on the RAV4 using a DC current function generator.

Efficiency calculations were based on the measured input speed, input torque, input electrical power, output wheel torque, and output wheel speed.

Matrix Determinations

Steady-state conditional testing was conducted in addition to drive cycle characterization of the RAV4 for both the FDU and the RDU in EV and HEV modes. The RAV4 was tested at different vehicle speed and grade increments to mimic the SR2 deliverables testing completed for other benchmarked transmissions between FY19 to FY21 at varying speed and torque conditions. Each steady-state vehicle speed and grade condition was held for a minimum of 30 seconds. The data channels were sampled at 20 Hz. Table 2 and

Table 3 outlines the conditions used to evaluate the FDU and RDU for SR-2 component work.

During initial prove-out of vehicle instrumentation and operation, it was discovered that the vehicle would automatically revert to HEV mode at high speed and load conditions, as the engine was needed beyond low road load conditions. Therefore, for testing in EV mode, high speed and load conditions were limited. Vehicle SoC averaged 50 percent for the duration of steady-state testing.

Table 2. Steady-state efficiency testing in HEV mode

Mode: HEV							
		Grade [%]					
		0	2	4	6	8	10
Speed [mph]	20						
	40						
	50						
	65						
	75						

Table 3. Steady-state efficiency testing in EV mode

Mode: EV							
		Grade [%]					
		0	2	4	6	8	10
Speed [mph]	10						
	20						
	40						
	50						
	65						

Efficiency Calculations

The efficiency calculations for the FDU in EV and HEV mode are shown in Equation 1 and Equation 2.

$$\eta_{FDU\ EV\ Mode} = \frac{P_{mechanical\ out}}{P_{electrical\ in}}$$

Equation 1

$$\eta_{FDU\ HEV\ Mode} = \frac{P_{mechanical\ out}}{P_{electrical\ in} + P_{mechanical\ in}}$$

Equation 2

The efficiency calculation for the RDU in EV or HEV mode are shown in Equation 3.

$$\eta_{RDU} = \frac{P_{mechanical\ out}}{P_{electrical\ in}}$$

Equation 3

Toyota P810 Test Results

Full tabular efficiency results are available in Appendix A. Table 4 and Table 5 present the in-vehicle efficiency results for the Toyota P810 in HEV and EV modes of operation. When calculating the total FDU efficiency, the respective sign convention of the power for MG1, MG2, and the engine remained consistent. When the power of MG1 and/or MG2 was positive, the component was acting as a motor, and the power was added to the total AC power deployment summation. When the power of MG1 and/or MG2 was negative, the component was acting as a generator, and the recovered power reduced the total AC power deployment value. During the steady-state testing, MG2 acted as a motor for most of the testing, while MG1 predominantly acted as a generator. MG1 operated in both rotational directions to net the desired e-CVT ratio in HEV operation. The sign convention described above was maintained in both rotational directions.

The FDU oil temperature averaged 62 °C and the battery SoC averaged 80.8 percent for the duration of the HEV mode testing. In HEV mode, the efficiency of the FDU improved with increased speed and load on the vehicle. Since the engine was running during the HEV steady-state testing, the vehicle showed an increased efficiency in highway-style driving conditions.

Table 4. FDU efficiency in HEV mode

FDU Efficiency - HEV Mode		Grade (%)					
		0	2	4	6	8	10
Speed (mph)	20	-	-	82.11%	77.57%	80.62%	89.47%
	40	71.99%	70.69%	83.63%	83.11%	88.15%	92.48%
	50	86.03%	86.77%	89.90%	85.24%	88.83%	93.08%
	65	90.75%	98.93%	92.54%	86.53%	-	-
	75	91.42%	-	92.61%	88.13%	-	-

The FDU oil temperature averaged 72 °C and the battery SoC averaged 73.4 percent for the EV mode testing. In charge-depleting mode, the efficiency of the FDU decreased with an increase in speed and load on the vehicle. Across vehicle modes, MG2 operates at consistent speed and is ratioed to wheel speed. MG2 power contribution reaches similar levels between charge-sustaining and charge-depleting modes at comparable vehicle speed and load. MG1 power differs between operational modes with MG1 torque required to generate FDU ratio between the engine and half shafts. Numerical ratio across the FDU increased with grade during the steady-state mapping in charge-sustaining mode. MG1 speed increased with FDU numerical ratio, and MG1 torque increases proportionally with engine torque to react against the FDU input carrier and maintain ratio. Charge-depleting mode is more efficient when the vehicle is undergoing low-speed and low-load conditions where MG1 torque is not required to net FDU ratio. The FDU in charge-sustaining mode incurred efficiency penalties against charge-depleting mode where the MG1 power reacting against the engine to net ratio is large versus the speed-based losses of the FDU, which are present in both operational modes. The component efficiency for charge-sustaining mode peaks where overall FDU ratio is between 2.8:1 and 3.3:1 with efficiency dropping off with FDU ratio on either side of that window.

Table 5. FDU efficiency in EV mode

FDU Efficiency - EV Mode		Grade (%)					
		0	2	4	6	8	10
Speed (mph)	10	99.36%	89.59%	89.17%	90.20%	89.37%	87.41%
	20	97.57%	93.83%	92.74%	92.39%	91.63%	91.73%
	40	95.74%	95.27%	94.27%	94.16%	-	-
	50	95.20%	94.48%	94.30%	94.20%	-	-
	65	93.21%	95.97%	-	-	-	-
	75	90.43%	-	-	-	-	-

Toyota Q610 Test Results

Full tabular efficiency results are available in Appendix B. Table 6 and Table 7 show the in-vehicle efficiency results for the Toyota Q610 in HEV and EV modes of operation.

Table 6. RDU power measurements in HEV mode

RDU Power Measurements - HEV Mode					
Grade (%)	Speed (mph)	RDU Temperature (°C)	Calculated RDU Power OBD (W)	RDU Power Yokogawa (W)	Calculated Instrumented Wheel Power (W)
0	20	32.00	8.96	-39.10	919.31
0	40	32.00	197.37	64.13	1618.23
0	50	32.00	86.54	34.88	2074.21
0	65	32.00	88.18	34.28	2713.99
0	75	33.00	385.11	458.81	2749.29
2	40	35.00	154.37	70.25	1603.37
2	50	35.00	48.44	34.13	2061.53
2	65	35.00	166.74	27.11	2847.48
2	75	35.00	422.63	459.95	2771.62
4	20	38.00	13.50	-50.80	919.69
4	40	38.00	164.59	65.22	1547.63
4	50	37.67	117.76	34.58	1977.28
4	65	37.00	83.33	26.27	2679.39
4	75	38.00	428.94	438.11	2676.37

RDU Power Measurements - HEV Mode					
Grade (%)	**Speed (mph)**	**RDU Temperature (°C)**	**Calculated RDU Power OBD (W)**	**RDU Power Yokogawa (W)**	**Calculated Instrumented Wheel Power (W)**
6	20	40.00	-5.04	-49.80	951.44
6	40	40.00	190.05	67.51	1528.58
6	50	40.00	82.37	-140.40	2219.60
6	65	40.00	98.81	-31.14	2798.59
6	75	40.00	299.84	260.70	3017.44
8	20	42.00	13.32	-37.26	931.21
8	40	42.00	99.10	4.13	1658.55
8	50	42.00	190.06	-24.08	2074.17
10	20	43.00	31.30	-27.61	1087.44
10	40	43.00	93.36	-31.84	1660.11
10	50	43.00	221.79	-73.73	2006.79

Table 7. RDU power measurements in EV mode

RDU Power Measurements - EV Mode					
Grade (%)	**Speed (mph)**	**RDU Temperature (°C)**	**Calculated RDU Power OBD (W)**	**RDU Power Yokogawa (W)**	**Calculated Instrumented Wheel Power (W)**
0	10	21.85	-10.42	-43.63	653.21
0	20	22.00	8.13	-37.01	1064.17
0	40	22.00	171.11	41.34	1737.20
0	50	22.00	107.90	13.83	2083.31
0	50	30.00	161.45	-70.75	2198.47
0	65	23.00	56.07	20.25	-666.26
0	65	30.00	30.55	-64.33	2789.58
2	10	25.00	9.21	-11.19	648.32
2	20	25.00	7.97	-36.77	1071.65
2	40	25.00	128.27	47.61	1713.44

RDU Power Measurements - EV Mode					
Grade (%)	**Speed (mph)**	**RDU Temperature (°C)**	**Calculated RDU Power OBD (W)**	**RDU Power Yokogawa (W)**	**Calculated Instrumented Wheel Power (W)**
2	50	25.00	126.45	-99.65	2252.70
2	65	25.00	44.84	29.75	2769.54
4	10	27.00	2.45	-10.95	556.47
4	20	28.00	21.62	-35.17	970.19
4	40	28.00	170.27	68.50	1633.82
4	50	28.00	88.21	-82.34	2226.29
6	10	29.62	5.02	-9.60	606.61
6	20	29.00	12.83	-35.47	1066.36
6	40	29.00	95.38	-0.10	1739.51
6	50	29.00	113.48	-54.43	2220.29
8	10	30.16	-0.76	-9.30	573.60
8	20	30.00	9.51	-36.02	1013.96
10	10	31.00	3.78	-9.35	566.72
10	20	31.00	-14.62	-86.57	983.56
-2	20	32.00	-56.21	-77.71	407.49
-6	20	32.00	-1377.80	-1623.79	2565.44
-8	20	32.00	-1493.04	-1740.35	2936.89
-8	40	32.00	-3407.22	-3745.02	5709.93

The RDU provided intermittent tractive power as compared to the front powertrain components (FDU and engine). Steady-state testing was completed at the same speed and load conditions as the FDU. The wheel torque transducer power data presented with an offset versus the RDU motor power. The offset was present as the AWD chassis dynamometer drives the rear wheels to speed match the front wheels driven by the engine and FDU combination. The road load torque applied to rear axle was speed dependent as Table 6 and Table 7 show. The cycle characterization of the RDU confirmed the offset was present throughout testing while the wheel torque transducers were installed on the rear axle. The wheel torque transducer relation to vehicle speed combined with the near zero net RDU rotor power demonstrated that the Q610 RDU motors to match front and rear wheel speed for large portions of the vehicle operation. Figures 7 and 8 illustrate the same steady-state conditional mapping of the RDU in charge-depleting mode. The slight power deployment at the RDU rotor with vehicle speed sensitive wheel torque transducer offset is depicted in Figure 8 without the DC power and pedal position variables. Figures 7 and 8

also demonstrates the rapid deployment and recovery of energy by the RDU. The highly transient nature of the RDU usage reduced the effectiveness of cycle summation energy balances for the RDU characterization. The lower frequency update rates of the rotor power value from the vehicle CAN bus compromised the separation of motor and mechanical efficiency for the RDU. No single rotor power value is sustained for sufficient time to reliably calculate motor and mechanical efficiencies for the RDU. Total efficiency of the RDU was possible through the discrete instrumentation of the AC power into the RDU and the wheel torque transducers out of the RDU. The RDU data supported that the FDU and the engine, are the primary sources of tractive power for the entire vehicle. In most steady-state conditions, the RDU was actively motoring to the point of overcoming its own back EMF curve.

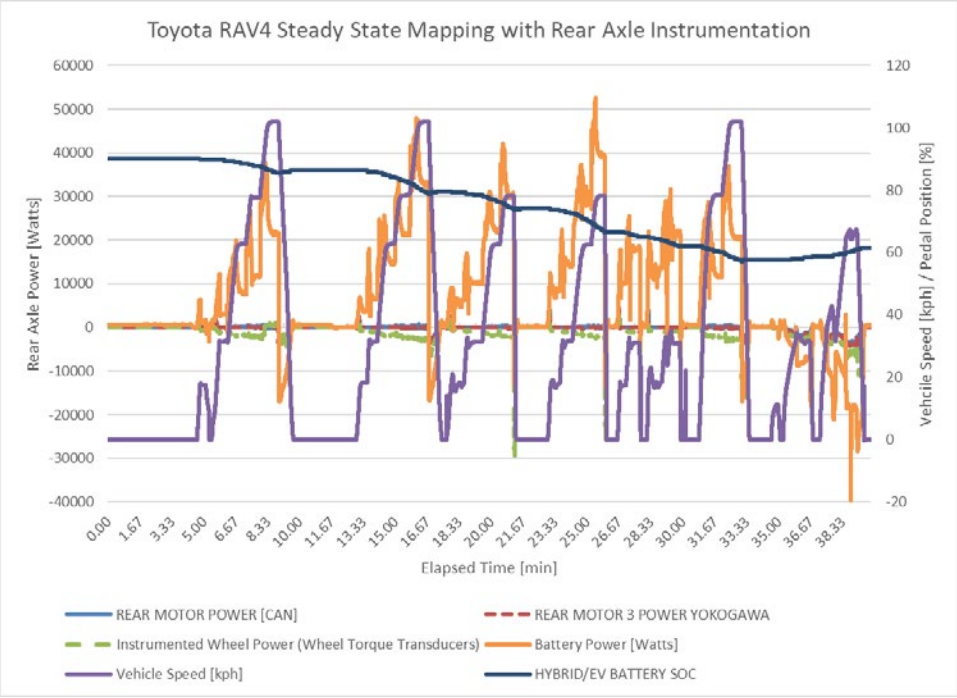

Figure 7. RDU steady-state mapping – Battery SoC, vehicle speed, and DC power deployment

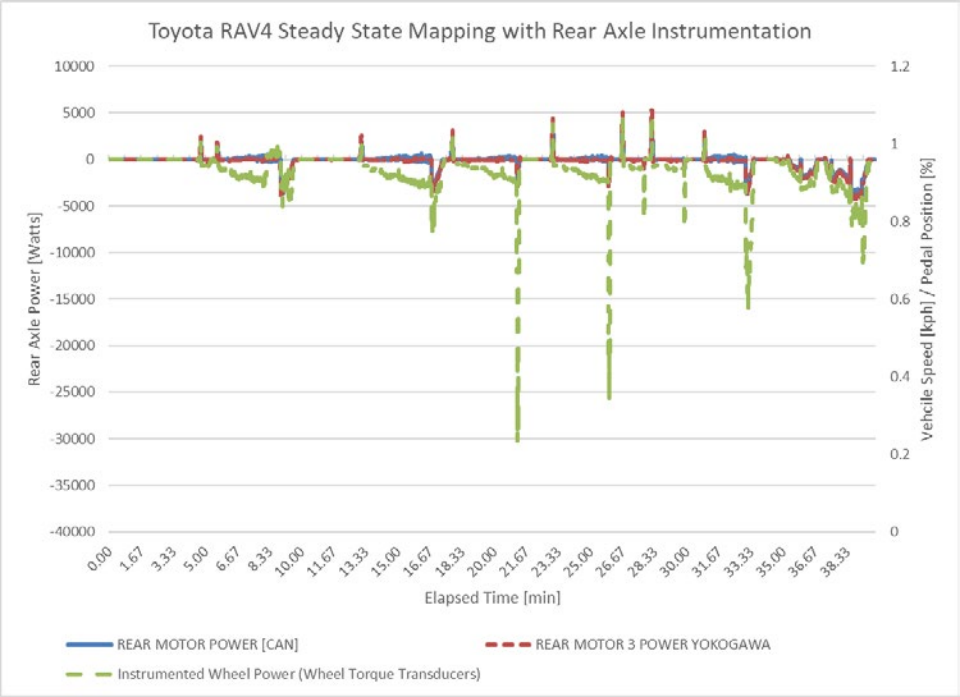

Figure 8. RDU Steady-state mapping – Rear axle power comparison

Equivalent steady-state mapping was completed for both charge depleting and sustaining modes. Minimal difference in RDU function was observed during the steady-state mapping of both vehicle modes. Sustained RDU regeneration was achieved during negative graded testing in charge-depleting mode shown at 34 minutes and later in Figure 8.

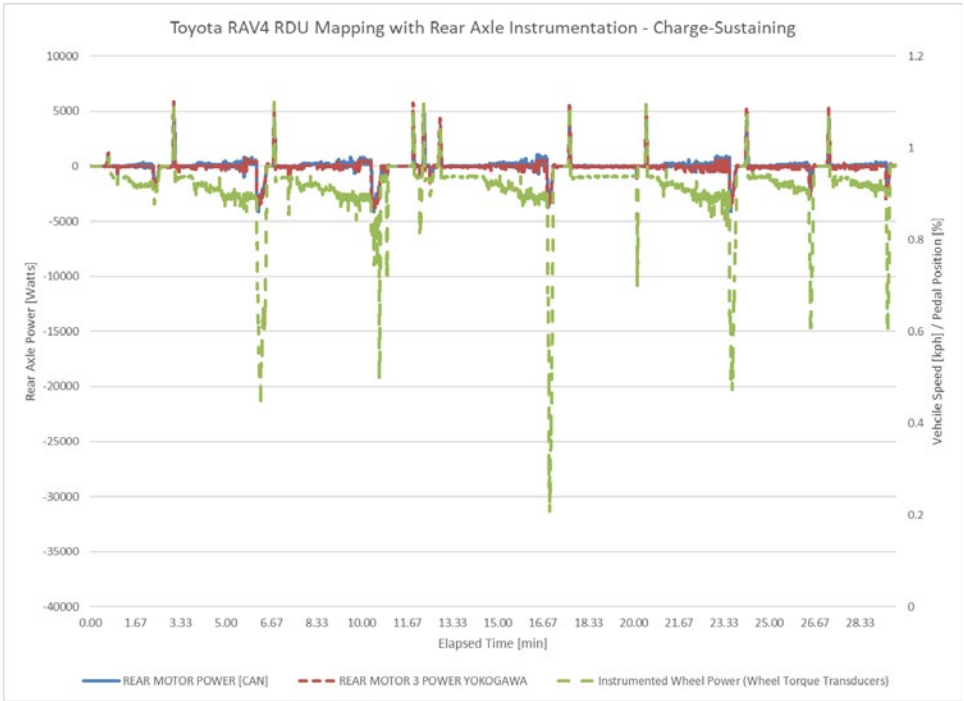

Figure 9. RDU steady-state mapping – Charge-sustaining mode

Figure 9 illustrates the RDU operated at < 1 kW of power deployment or regeneration independent of vehicle mode. The RDU contributed power during the highly transient accelerations and decelerations; thus, the RDU was observed to support the vehicle operation, but never functioned as a prime mover or contributed a sustained, large percentage of the road load power. The maximum tractive power contribution from the RDU during testing approached 6 kW where the regenerative power peaked at 31 kW intermittently. In charge-depleting mode and negative grade conditions, the RDU sustained regeneration of up to 3.8 kW at very steep grades (-8%). The sustained negative grade condition provided portions of operation where rotor power via the CAN communication was suitable for motor and mechanical efficiency calculations for the RDU.

SR-3 Deliverables – Overall Transmission Characterization

The SR-3 task focused on overall drive unit characterization for the chosen benchmark units. This task objective was to provide additional information on each benchmark transmission to compare available technologies and highlight features of the benchmark transmissions that contribute to fuel efficiency. Figure 10 summarizes the Toyota RAV4.

Ratio Determination and Physical Packaging Dimensions

E-CVT	
Model	P810
Oil Pump	Splash Lubricated
Gear Ratios	CVT
Rear Axle Ratio	10.781
Tire Size	235/55R19
Fluid Type	Toyota Genuine ATF WS

Vehicle	2021 Toyota RAV4 Prime
VIN	JTMFB3FV0MD010258
Engine	2.5L Four-Cylinder
Drive Type	AWD
Transmission	P810 E-CVT

Figure 10. Test vehicle summary – Toyota Rav4 Prime – P810 e-cvt

Toyota P810 and Q610 Ratio and Packaging Information

The Toyota RAV4 Prime houses two motor-generators (MG1 and MG2) in the FDU, and a third motor-generator in the rear axle of the vehicle. The Toyota P810 is a fully electric transaxle that operates as a e-CVT. The FDU does not have an overall set gear ratio. The speed of the planetary carrier and MG1 housed in the FDU determine the ratio of the engine speed to the ring gear. This allows for the engine to operate in optimal conditions while the vehicle is in HEV mode. Also housed inside the FDU, the reduction gears connected to MG2 do have set ratios. The FDU is physically coupled to the engine via the flywheel and FDU input carrier.

The Toyota Q610 is a fully electric rear-drive axle. The axle has a double reduction in gears with ratios of 15:41 and 18:71, for a 10.781 combined overall gear ratio.

Toyota P810 and Q610 Efficiency Improvement Features

The hybrid functionality of the Toyota RAV4 Prime allows for an increase in overall fuel efficiency of the vehicle. The vehicle consists of three motor-generators. Each of the motor-generators can produce electrical power but can also regenerate power when the vehicle is slowing. This allows the DC battery to be recharged when the vehicle decelerates. The hybrid functionality allows for the internal combustion to operate at its optimal speeds. In general, the engine operates when the vehicle is at a low SoC or when the vehicle is experiencing high-speed

and high-load conditions. As shown in the steady-state testing of charge-depleting and charge-sustaining mode, MG1 contributes to FDU losses, to generate e-CVT ratio. The FDU as a product is more efficient in charge-depleting mode.

The rear axle is a passive component in the vehicle powertrain for the bulk operational points tested. The rear axle is used when the vehicle is experiencing a more severe acceleration/deceleration or when the vehicle experiences wheel slip. The RDU provided regenerative power back to the battery when the vehicle is decelerating.

Both the FDU and RDU have received a reduction in size, mass, and rotational elements, as compared to previous versions Toyota has developed. Since there are no clutch elements housed within the FDU or RDU, there is no need for a high-speed hydraulic system to produce pressure for the clutches. This reduces the number of losses in both systems by reducing the friction, heat losses, and pumping losses. Also, the FDU uses a flywheel to couple to the internal combustion engine, therefore eliminating any losses associated with using a torque converter in the system.

Parasitic Loss Mapping

The loss testing for the Toyota P810 transmission and Q610 rear axle was conducted in-vehicle by performing coast downs of the vehicle on the chassis dynamometer. The vehicle was placed in a "neutral" mode to conduct vehicle coast down testing.

Toyota RAV4 Prime Parasitic Results

For the coast down testing of the Toyota RAV4, two Highway drive cycles were completed to warm up the vehicle. Next, the vehicle was placed in a "neutral" mode and completed four coast downs. For each coast down repeat, the dynamometer was ramped up to 70 mph, and the vehicle was allowed to coast down to 10 mph. Based on the coast down times and forces, vehicle coefficients were calculated. Table 8 shows the vehicle coefficients generated from each vehicle coast down. The target coefficients were set based on the EPA coefficients for the Toyota RAV4. The set and rolling resistance coefficients were calculated from the coast downs. The loss coefficients were calculated based on the equation "Loss Coefficients = Rolling Resistance Coefficients – Set Coefficients". Figure 11 shows the graphical representation of the vehicle losses over speeds ranging from 0 to 100 mph.

Table 8. Toyota RAV4 vehicle coastdown coefficients

	Target Coefficients			**Set Coefficients**			**Rolling Resistance Coefficients**			**Loss Coefficients**		
Run	F0	F1	F2	A	B	C	R0	R1	R2	L0	L1	L2
1	28.089	0.14349	0.02558	0	0	0.02558	33.314	0.22973	0.02576	33.3140	0.22973	0.00018
2	28.089	0.14349	0.02558	-5.22504	-0.08624	0.0254	28.0396	0.11234	0.02589	33.2646	0.19858	0.00049
3	28.089	0.14349	0.02558	-5.22504	-0.08624	0.0254	28.0803	0.07168	0.02649	33.3054	0.15792	0.00109
4	28.089	0.14349	0.02558	-5.22504	-0.08624	0.0254	27.7255	0.06244	0.02655	32.9505	0.14868	0.00115

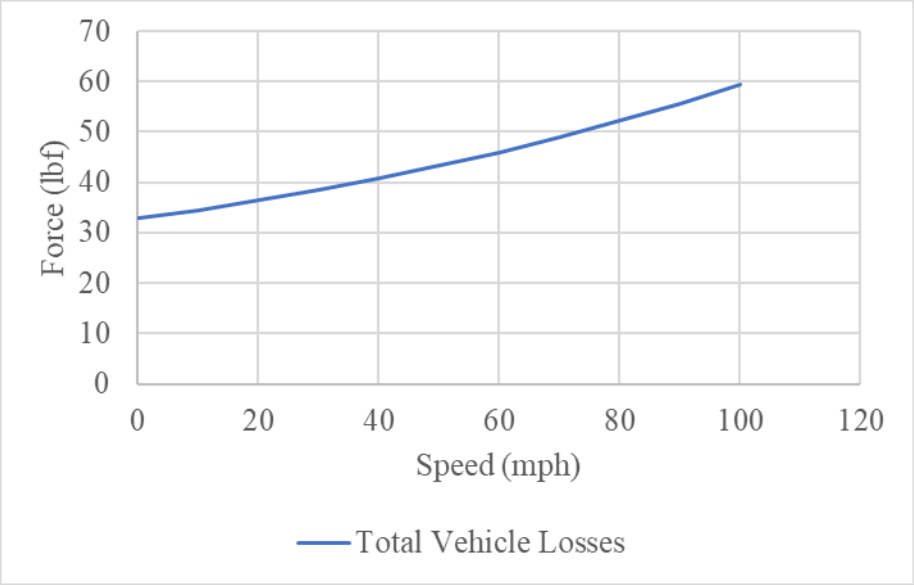

Figure 11. Toyota RAV4 total vehicle losses

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SR-4 Deliverables – In-Use Performance Testing

SR-4 deliverables were centered around establishing an understanding of drive unit behavior in the vehicle. The following sections explain the methods used to complete the vehicle in-use testing with the goal of establishing a baseline of drive unit operation and understanding the transmission control and shifting behavior. The Toyota P810 transaxle and Q610 e-axle were tested in-vehicle on an AWD chassis dynamometer. Additional information regarding vehicle level instrumentation and setup can be found in the Gear Efficiency Mapping section.

Drive Cycle Characterization

The RAV4 vehicle underwent in-use testing on a SwRI AWD chassis dynamometer. All testing was completed in a temperature-controlled environment with a target ambient temperature of 73 °F. A variable speed fan was used to recreate on-road air flow across the front of the vehicle. Vehicle tests began with determination of dyno coefficients. Vehicle coast downs generated the rolling and frictional coefficients for the RAV4 benchmark vehicle. EPA aerodynamic coefficients were used for the cycle and mapping work. All in-use testing was conducted at vehicle curb weight. The maximum tractive effort in each drive cycle was less than 2,000 lbf.

Toyota RAV4 Drive Cycle Characterization

The in-use testing for the Toyota RAV4 Prime began with drive cycle characterizations following the SAE J1711 test method for hybrid-electric vehicles. The vehicle started each test sequence with a full SoC (state-of-charge) with the vehicle in Automatic mode (reverts to EV mode unless the vehicle experiences heavy accelerations/decelerations). Each drive cycle (UDDS, Highway, US06) was repeated until the vehicle went from a charge-depleting mode to a charge-sustaining mode of operation (occurred at approximately 12% SoC). With an estimated 42-mile range in charge-depleting mode for the Toyota RAV4, the vehicle completed 10 UDDS cycles, 8 Highway cycles, and 7 US06 cycles to reach the criteria of the J1711 test method. A summary of the test sequence can be found in Figure 12.

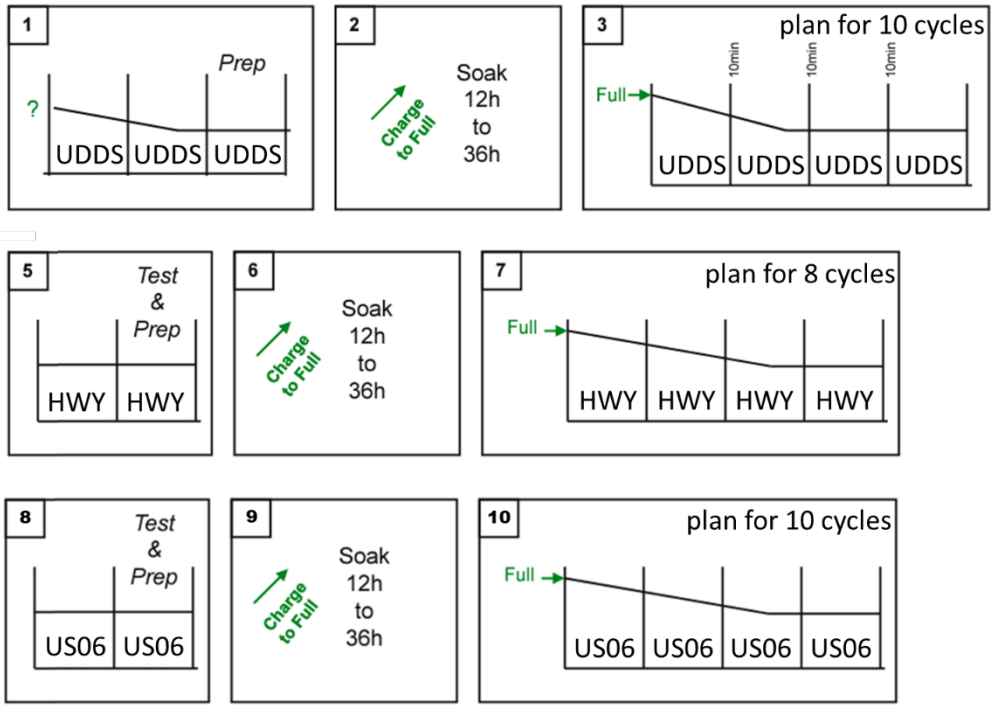

Figure 12. Toyota RAV4 J1711 drive cycle test sequence

For the drive cycle testing using the SAE J1711 procedure, the wheel torque sensors were placed on the front axle of the vehicle to measure output torque of the FDU. Additional drive cycle testing was completed with the torque wheel sensors placed on the rear axle of the vehicle, though only two runs of each drive cycle (UDDS, Highway, US06) were completed—one run with the vehicle in charge-depleting mode and one run with the vehicle in charge-sustaining mode.

Figures 13 through 15 show the results from the J1711 drive cycle testing. As evidenced in each figure, the DC battery SoC slowly decreases over each drive cycle, until the vehicle reaches a low enough SoC threshold (approximately 12% SoC) where the internal combustion engine starts operating. When in charge-depleting mode, the ratios of AC power-to-motor mechanical power and motor mechanical power-to-instrument wheel power yielded the motor efficiency and FDU mechanical efficiency. Once the vehicle enters a charge-sustaining mode of operation (the internal combustion engine is producing power), the DC power consumption from the battery and AC power to the motor-generators drop significantly. The delta in motor mechanical power contribution between cycles illustrates the power replacement required by the engine for the later cycles. The cycle summations reveal electric motor contribution in all cycles independent of battery SoC, cycle count, or operational mode.

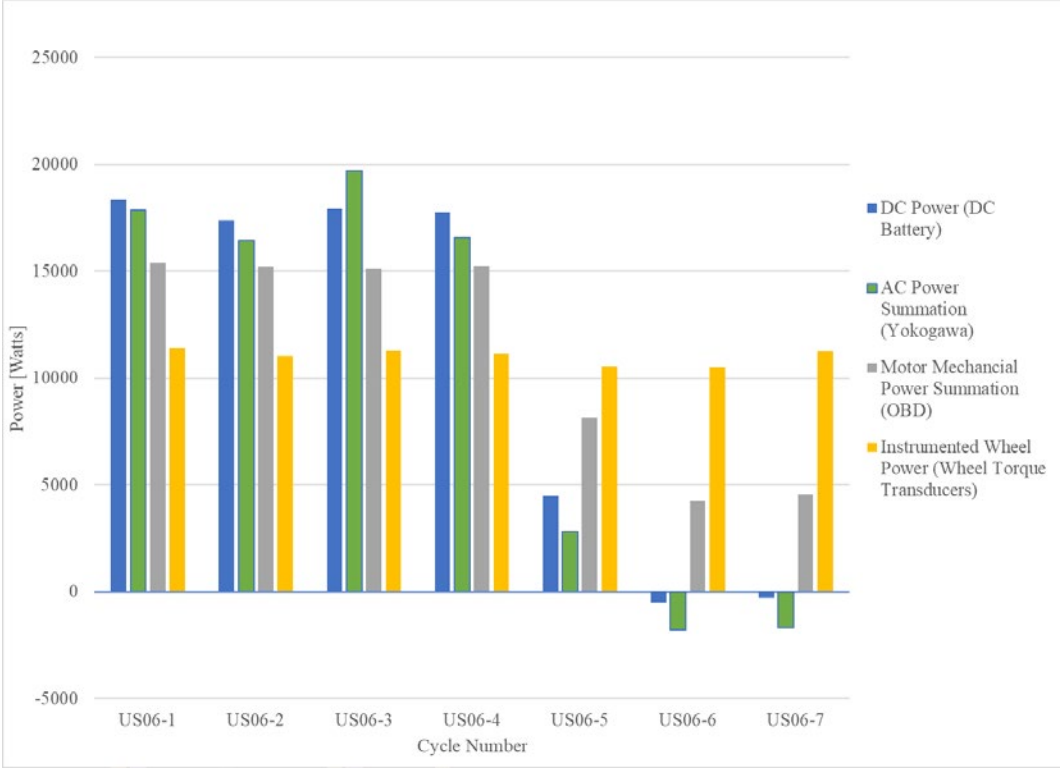

Figure 13. FDU power summary for J1711 US06 drive cycle testing

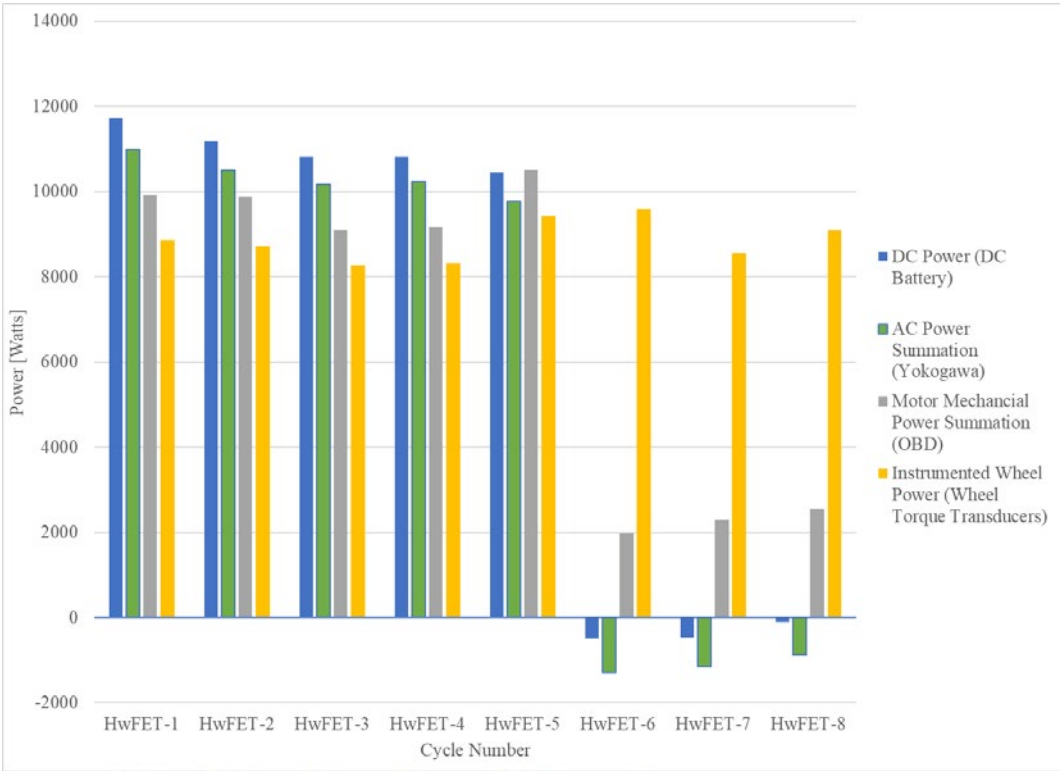

Figure 14. FDU power summary for J1711 HWFET drive cycle testing

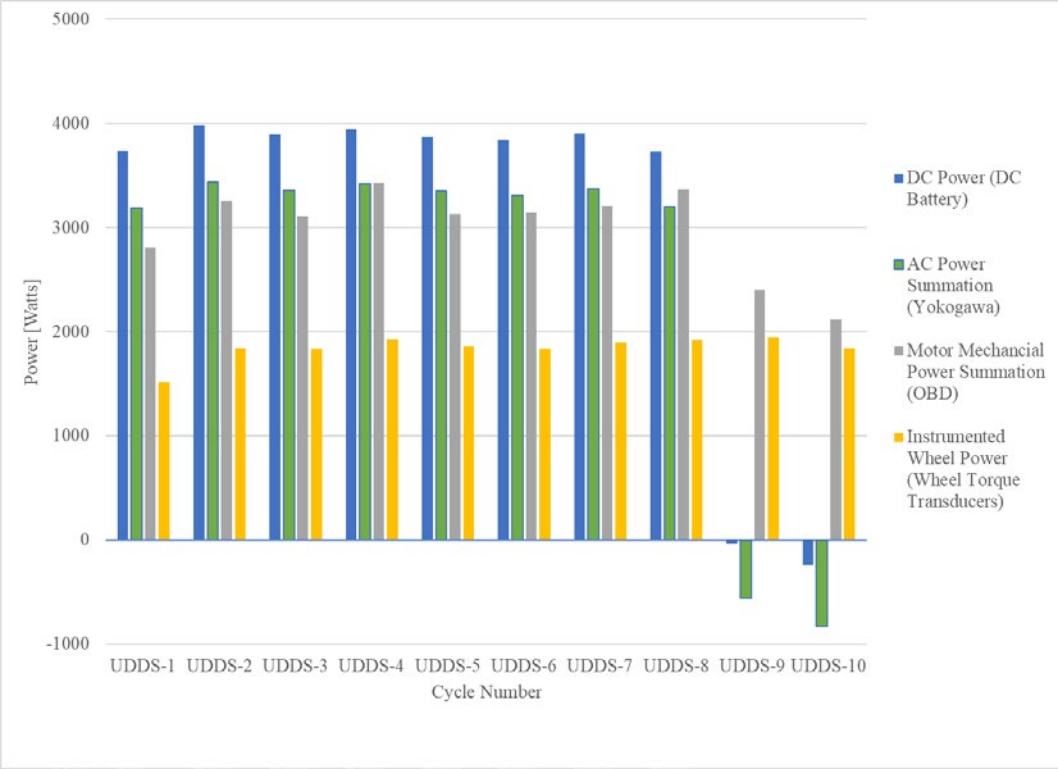

Figure 15. FDU power summary for J1711 UDDS drive cycle testing

Figure 16 shows the results from the RDU drive cycle testing, with the vehicle operating in charge-depleting and charge-sustaining mode over the three drive cycles (US06, HwFET, and UDDS). The wheel torque sensors were placed on the two rear wheels of the vehicle for this testing. The disparity between the motor mechanical power summation and the rear wheel instrumented power figures graphically presents the FDU versus the RDU usage for the charge-depleting cycles. The RDU tractive power contribution is consistent across operating modes using the cycle summation data. Figure 17 depicts the wheel torque offset on the rear axle due to the chassis dynamometer motoring the rear wheels to speed and the near zero RDU power for the majority of the HWFET drive cycle. The RDU power deployment and recovery occurred around the transient demands of the drive cycle.

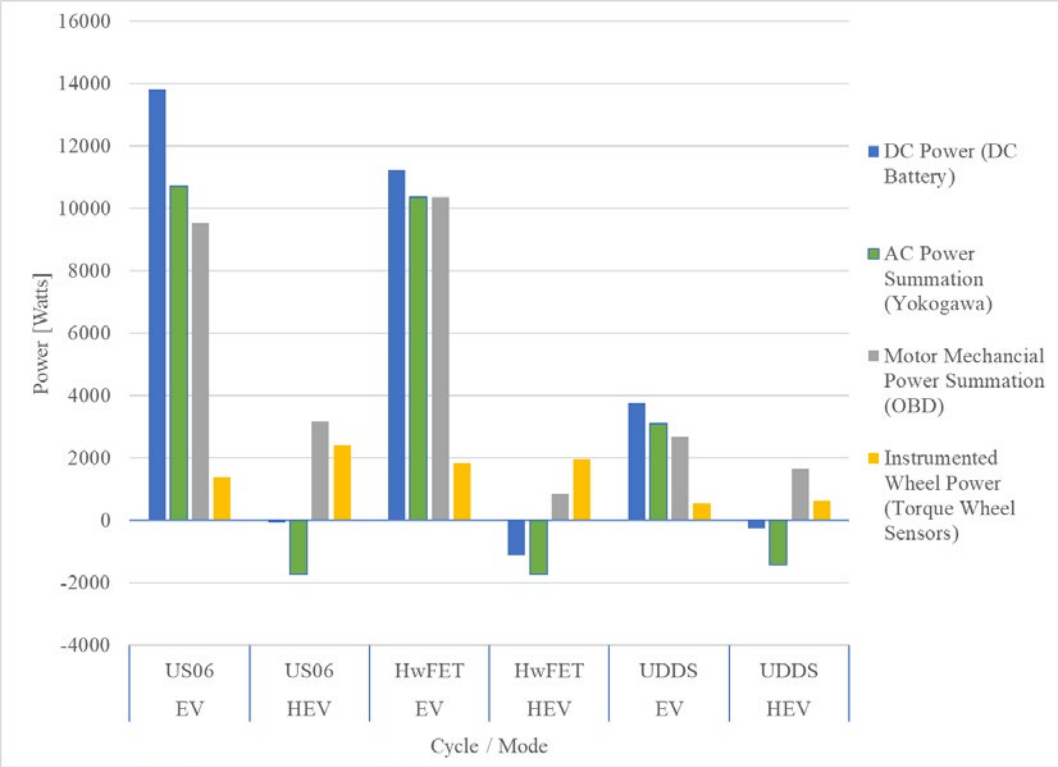

Figure 16. RDU power summary for drive cycle testing

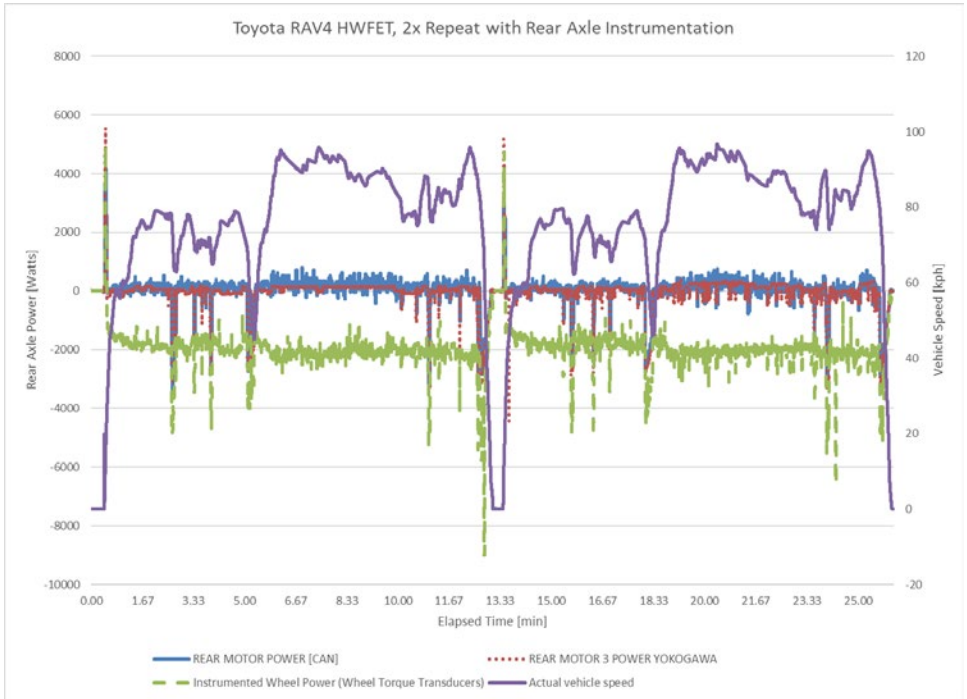

Figure 17. RDU rear axle instrumentation results for HWFET drive cycle

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Appendix A: Toyota P810 Loaded Efficiency

Steady-State Efficiency Testing – HEV Mode

Grade (%)	Speed (mph)	Dyno Force (N)	Engine Speed OBD (rpm)	Engine Coolant Temperature OBD (°C)	Calculated Load Value OBD (%)	Battery SOC (%)	Throttle Position OBD (%)	FDU Oil Temperature (°C)	Vehicle Speed (km/hr)	Battery Current (A)	Battery Voltage (V)	MGU1 Speed OBD (rpm)	MGU1 Torque OBD (Nm)	MGU2 Speed OBD (rpm)	MGU2 Torque OBD (Nm)
0	40	140.23	1280.00	42.35	21.13	89.02	16.86	28.99	61.00	13.72	385.00	541.13	-4.04	5249.88	8.74
0	40	146.10	1376.00	92.75	66.52	79.22	27.38	86.46	61.00	-26.84	380.44	870.49	-36.83	5259.64	-16.98
0	50	253.08	1450.67	91.69	70.89	79.61	29.12	87.00	76.00	-22.45	380.96	112.75	-40.06	6558.00	-15.07
0	50	218.36	1459.26	91.83	70.50	79.61	28.67	87.00	76.00	-25.25	380.00	115.38	-39.96	6587.98	-16.59
0	65	411.95	1600.00	91.94	61.33	80.00	26.85	87.00	99.00	-0.43	378.64	-927.48	-36.54	8544.89	-6.74
0	65	400.23	1472.96	91.80	67.60	79.61	28.29	87.00	99.16	-0.03	377.00	-1423.72	-39.24	8562.80	-8.93
0	75	573.27	1860.30	92.55	73.31	79.61	32.16	87.00	114.31	-1.14	378.00	-1052.44	-45.12	9853.25	-8.20
2	40	544.22	1634.39	91.46	66.45	78.82	29.05	86.00	61.00	-22.11	379.38	1804.02	-38.40	5260.37	-6.98
2	50	645.51	1621.97	92.00	63.83	79.22	28.16	86.00	76.00	-4.02	378.42	704.97	-37.49	6570.56	-1.34
2	50	645.40	1555.94	72.47	59.62	83.53	24.92	36.00	76.00	1.08	380.00	480.55	-33.00	6564.58	1.55
2	65	820.77	1907.90	89.69	74.23	83.92	32.49	39.00	99.00	-0.51	381.00	190.27	-43.89	8545.91	-0.33
4	20	1038.18	1838.97	92.70	73.00	79.22	32.13	86.84	77.00	0.59	378.00	1445.79	-43.17	6635.99	6.42
4	40	921.89	1655.88	92.27	67.61	79.61	29.80	87.00	61.00	-5.91	379.00	1833.25	-38.43	5276.57	4.30
4	40	932.92	1472.00	90.19	72.20	80.39	29.58	45.00	61.00	-5.00	377.11	1169.89	-39.55	5263.07	3.81
4	40	902.81	1632.32	92.18	64.85	80.39	28.92	55.99	61.26	-8.11	378.06	1745.49	-35.92	5297.37	4.70
4	50	1024.38	1730.71	90.82	73.76	80.39	31.76	47.00	76.00	-0.14	377.16	1095.78	-42.26	6572.60	5.73
4	50	1000.98	1634.87	92.00	64.54	80.39	28.76	55.00	76.21	11.38	376.00	735.50	-36.77	6590.34	9.00
4	65	1242.16	2472.92	91.00	75.26	80.39	36.94	49.79	100.87	-0.03	377.08	2112.93	-46.48	8668.23	9.72
4	65	1195.29	2382.65	92.00	74.23	80.39	36.39	54.00	99.00	-0.14	377.38	1902.65	-45.98	8557.48	8.83
4	75	1362.50	2917.25	90.99	79.04	80.39	40.33	51.76	114.36	0.17	377.08	2779.80	-48.27	9851.68	11.61
6	20	1200.58	1421.37	93.00	67.72	80.39	28.41	70.00	30.00	-13.38	380.00	3075.47	-35.26	2638.41	14.17

Grade (%)	Speed (mph)	Dyno Force (N)	Engine Speed OBD (rpm)	Engine Coolant Temperature OBD (°C)	Calculated Load Value OBD (%)	Battery SOC (%)	Throttle Position OBD (%)	FDU Oil Temperature (°C)	Vehicle Speed (km/hr)	Battery Current (A)	Battery Voltage (V)	MGU1 Speed OBD (rpm)	MGU1 Torque OBD (Nm)	MGU2 Speed OBD (rpm)	MGU2 Torque OBD (Nm)
6	40	1351.91	1884.02	92.04	73.02	80.00	32.52	60.00	60.89	-0.04	377.85	2665.83	-40.58	5250.73	16.05
6	40	1312.64	1847.56	92.51	72.38	80.00	32.50	69.00	61.00	0.23	377.38	2583.21	-40.28	5270.52	14.87
6	50	1459.19	2299.22	92.00	73.85	80.00	35.69	61.00	76.00	0.08	377.30	3161.99	-43.39	6554.06	17.25
6	50	1421.70	2286.33	92.46	73.06	80.00	35.53	68.00	76.00	-1.02	377.46	3104.75	-43.32	6584.31	15.88
6	65	1628.31	3029.49	92.18	82.05	80.00	41.36	63.00	99.00	-2.21	377.37	4219.55	-47.85	8525.79	19.72
6	65	1588.18	2959.92	92.00	80.52	80.00	40.75	66.58	99.20	-0.36	377.16	3961.19	-46.70	8558.43	18.84
6	75	1778.78	3321.95	90.75	96.69	80.00	45.15	65.00	114.08	-2.21	377.05	4226.97	-53.87	9837.61	18.97
8	20	1612.50	1536.00	94.00	71.16	80.00	30.89	72.00	30.00	-12.44	379.00	3520.00	-38.46	2623.70	25.45
8	20	1607.22	1632.96	92.91	70.91	80.36	31.36	77.91	32.78	-12.34	379.82	3669.75	-38.88	2871.36	25.50
8	40	1735.74	2222.17	93.00	73.50	80.00	35.03	74.00	61.00	0.00	378.00	3907.47	-42.15	5255.12	27.70
8	40	1711.58	2222.65	92.31	72.91	80.00	34.90	77.00	61.00	-0.05	378.00	3911.73	-42.31	5269.89	26.74
8	50	1825.46	2781.45	93.00	75.65	80.00	38.76	76.00	76.00	-0.02	378.00	4855.34	-44.28	6571.63	29.74
10	20	2036.55	1712.24	94.00	72.47	79.61	31.75	80.18	37.96	-0.64	377.00	3628.04	-39.74	3272.03	39.44
10	20	2015.39	1701.25	94.00	71.85	79.61	31.76	86.00	38.00	-0.70	378.00	3607.46	-40.01	3300.25	39.08
10	40	2135.80	2491.22	93.00	74.76	79.61	36.86	82.00	61.00	0.51	377.61	4867.57	-44.07	5245.11	40.45
10	40	2109.66	2482.31	92.64	74.19	79.61	36.86	85.00	61.00	0.30	378.00	4830.64	-43.77	5276.98	38.30
10	50	2241.74	3045.41	92.84	82.56	79.61	41.45	84.00	76.00	-1.41	377.69	5827.65	-47.81	6561.59	40.67

Grade (%)	Speed (mph)	MGU1 Power Yokogawa (W)	MGU2 Power Yokogawa (W)	Flywheel Torque (Nm)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Calculated Engine Power (W)	Total Wheel Torque (Nm)
0	40	-258.76	5060.30	39.79	66.68	-71.56	463.31	5283.67	5332.91	138.24
0	40	-2928.51	-9534.18	142.29	58.48	-70.23	464.08	-10211.34	20503.56	128.71

Grade (%)	Speed (mph)	MGU1 Power Yokogawa (W)	MGU2 Power Yokogawa (W)	Flywheel Torque (Nm)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Calculated Engine Power (W)	Total Wheel Torque (Nm)
0	50	-61.09	-11008.11	152.47	80.53	-91.96	579.24	-8553.56	23161.74	172.49
0	50	-76.32	-11703.23	150.27	73.09	-84.09	581.22	-9593.92	22963.04	157.18
0	65	3790.15	-6370.95	133.79	109.84	-120.54	754.37	-162.00	22417.40	230.38
0	65	6209.95	-8532.34	143.15	105.19	-118.89	755.76	-10.50	22080.11	224.08
0	75	5323.93	-8219.80	162.26	137.49	-150.55	870.25	-431.97	31610.59	288.04
2	40	-6579.50	-3966.17	169.92	129.66	-139.95	464.10	-8388.29	29081.74	269.61
2	50	-2336.77	-1333.03	161.69	148.79	-159.67	579.94	-1521.95	27463.77	308.45
2	50	-1441.99	996.81	126.74	153.80	-161.73	579.73	408.65	20650.05	315.52
2	65	-372.94	-811.14	158.86	188.04	-194.66	754.27	-195.05	31738.76	382.69
4	20	-5939.60	4072.69	183.74	214.37	-234.39	585.60	221.53	35383.59	448.77
4	40	-6814.68	2272.04	169.90	195.22	-210.31	465.71	-2239.86	29460.72	405.53
4	40	-4642.34	2186.57	180.01	201.28	-210.45	464.57	-1885.35	27747.93	411.73
4	40	-6257.06	2736.57	143.44	191.86	-204.31	467.28	-3065.09	24519.70	396.17
4	50	-4518.66	3855.17	180.61	217.60	-229.70	580.50	-53.10	32733.51	447.31
4	50	-2633.58	6096.57	144.14	213.29	-225.66	581.69	4279.09	24676.87	438.95
4	65	-9808.66	8792.09	186.01	258.41	-270.83	765.60	-12.94	48168.68	529.24
4	65	-8707.01	7767.86	175.05	250.05	-263.75	755.38	-53.70	43677.94	513.80
4	75	-13706.12	12522.64	187.51	277.40	-293.16	869.56	64.72	57281.81	570.56
6	20	-11184.53	4116.12	153.21	243.18	-257.54	232.80	-5083.28	22804.74	500.72
6	40	-10992.54	8724.18	187.57	272.83	-289.92	463.70	-14.29	37006.19	562.76
6	40	-10462.89	8303.98	168.36	264.07	-282.72	465.13	87.30	32574.57	546.79
6	50	-13893.78	11758.01	193.77	290.16	-311.37	578.76	31.72	46655.44	601.53
6	50	-13450.75	11097.46	178.16	284.53	-302.28	581.05	-386.66	42655.42	586.81

Grade (%)	Speed (mph)	MGU1 Power Yokogawa (W)	MGU2 Power Yokogawa (W)	Flywheel Torque (Nm)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Calculated Engine Power (W)	Total Wheel Torque (Nm)
6	65	-20479.30	17413.28	205.76	325.83	-341.99	753.30	-834.91	65275.85	667.83
6	65	-19028.86	16783.58	195.74	318.32	-334.50	755.33	-136.79	60671.16	652.81
6	75	-22965.12	19809.90	223.97	353.02	-370.89	869.11	-832.13	77914.39	723.91
8	20	-13950.20	7344.88	169.20	312.70	-334.56	231.65	-4715.61	27214.94	647.26
8	20	-14488.06	7961.49	156.50	313.36	-335.17	253.42	-4688.78	26762.60	648.53
8	40	-16865.17	15059.65	177.43	337.76	-359.56	464.12	-1.32	41288.35	697.31
8	40	-16855.32	14577.86	169.33	333.73	-355.74	465.22	-19.18	39411.68	689.48
8	50	-22045.62	19792.54	179.92	356.45	-376.97	580.02	-7.15	52404.80	733.42
10	20	-14701.64	13769.75	162.78	390.34	-413.24	288.89	-241.58	29187.32	803.58
10	20	-14436.62	13664.93	149.81	382.00	-408.39	290.89	-266.10	26688.66	790.39
10	40	-22040.95	21563.28	175.30	407.41	-435.13	463.15	192.56	45731.03	842.53
10	40	-21681.44	21182.14	166.91	403.68	-429.65	465.21	112.84	43388.21	833.33
10	50	-28493.33	27155.47	185.34	429.56	-457.35	579.00	-531.21	59108.73	886.91

Grade (%)	Speed (mph)	Calculated Instrumented Wheel Power (W)	Calculated MGU1 Power OBD (W)	Calculated MGU2 Power OBD (W)	MGU1 Efficiency (%)	MGU2 Efficiency (%)	AC Power Summation Yokogawa (W)	Drivetrain Power Summation (W)	Front Powertrain Efficiency (%)
0	40	6707.00	-228.91	4805.91	1.13	0.95	4840.70	10134.45	66.18%
0	40	6254.99	-3357.48	-9352.76	0.87	0.98	-12427.66	8040.87	77.79%
0	50	10462.80	-472.92	-10346.51	0.13	0.94	-11063.93	12092.53	86.52%
0	50	9566.93	-482.84	-11444.95	0.16	0.98	-11773.63	11183.49	85.55%
0	65	18199.42	3549.14	-6031.49	0.94	0.95	-2287.21	19836.61	91.75%
0	65	17734.26	5850.67	-8007.08	0.94	0.94	-2345.97	19757.72	89.76%

Grade (%)	Speed (mph)	Calculated Instrumented Wheel Power (W)	Calculated MGU1 Power OBD (W)	Calculated MGU2 Power OBD (W)	MGU1 Efficiency (%)	MGU2 Efficiency (%)	AC Power Summation Yokogawa (W)	Drivetrain Power Summation (W)	Front Powertrain Efficiency (%)
0	75	26250.13	4972.38	-8461.71	0.93	1.03	-2404.28	28714.72	91.42%
2	40	13103.38	-7253.50	-3843.95	0.91	0.97	-10510.35	18536.07	70.69%
2	50	18732.67	-2767.70	-921.93	0.84	0.69	-3662.69	23793.97	78.73%
2	50	19155.05	-1660.56	1062.90	0.87	1.07	-434.24	20204.87	94.80%
2	65	30228.07	-874.56	-294.14	0.43	0.36	-1197.96	30554.68	98.93%
4	20	27520.19	-6535.78	4460.65	0.91	1.10	-1857.41	33516.67	82.11%
4	40	19777.55	-7378.29	2375.40	0.92	1.05	-4506.72	24918.09	79.37%
4	40	20030.76	-4845.66	2097.17	0.96	0.96	-2414.48	25292.16	79.20%
4	40	19385.66	-6566.07	2604.87	0.95	0.95	-3481.24	20999.21	92.32%
4	50	27191.86	-4848.91	3941.20	0.93	1.02	-650.90	32070.02	84.79%
4	50	26738.25	-2831.84	6210.27	0.93	1.02	3476.07	28139.86	95.02%
4	65	42431.38	-10285.20	8823.17	0.95	1.00	-1019.30	47152.12	89.99%
4	65	40643.48	-9161.25	7914.05	0.95	1.02	-957.16	42738.78	95.10%
4	75	51955.20	-14050.02	11975.65	0.98	0.96	-785.27	56098.33	92.61%
6	20	12207.01	-11354.37	3916.36	0.99	0.95	-7107.16	15736.33	77.57%
6	40	27326.36	-11329.69	8822.94	0.97	1.01	-2260.00	34737.83	78.66%
6	40	26633.18	-10895.63	8207.48	0.96	0.99	-2147.06	30415.66	87.56%
6	50	36457.04	-14367.08	11839.33	0.97	1.01	-2163.53	44519.67	81.89%
6	50	35706.00	-14085.39	10951.03	0.95	0.99	-2363.53	40302.14	88.60%
6	65	52681.66	-21143.44	17602.06	0.97	1.01	-3180.90	62209.83	84.68%
6	65	51636.23	-19373.69	16881.34	0.98	1.01	-2388.91	58425.88	88.38%
6	75	65885.24	-23845.07	19544.80	0.96	0.99	-2977.01	74759.17	88.13%
8	20	15701.16	-14177.99	6991.87	0.98	0.95	-6649.85	20609.62	76.18%

Grade (%)	Speed (mph)	Calculated Instrumented Wheel Power (W)	Calculated MGU1 Power OBD (W)	Calculated MGU2 Power OBD (W)	MGU1 Efficiency (%)	MGU2 Efficiency (%)	AC Power Summation Yokogawa (W)	Drivetrain Power Summation (W)	Front Powertrain Efficiency (%)
8	20	17210.88	-14941.51	7666.83	0.97	0.96	-6566.32	20236.03	85.05%
8	40	33890.97	-17247.43	15241.18	0.98	1.01	-1811.19	39482.83	85.84%
8	40	33589.58	-17329.91	14755.15	0.97	1.01	-2239.05	37134.22	90.45%
8	50	44547.65	-22514.61	20464.03	0.98	1.03	-2334.83	50151.72	88.83%
10	20	24310.38	-15099.65	13512.68	0.97	0.98	-937.81	28255.43	86.04%
10	20	24076.61	-15112.90	13506.51	0.96	0.99	-777.66	25916.97	92.90%
10	40	40863.60	-22466.07	22217.48	0.98	1.03	-533.68	45253.37	90.30%
10	40	40596.68	-22139.87	21162.32	0.98	1.00	-461.94	42888.91	94.66%
10	50	53775.73	-29174.44	27946.85	0.98	1.03	-1354.88	57770.87	93.08%

Steady-State Efficiency Testing – EV Mode

Grade (%)	Speed (mph)	Dyno Force (N)	Engine Speed OBD (rpm)	Engine Coolant Temperature OBD (°C)	Calculated Load Value OBD (%)	Battery SOC (%)	Throttle Position OBD (%)	FDU Oil Temperature (°C)	Vehicle Speed (km/hr)	Battery Current (A)	Battery Voltage (V)	MGU1 Speed OBD (rpm)	MGU1 Torque OBD (Nm)	MGU2 Speed OBD (rpm)	MGU2 Torque OBD (Nm)
0	10	-78.46	0.00	82.00	0.00	85.49	19.22	74.00	16.34	1.80	383.00	-1132.64	-0.03	1432.32	3.17
0	20	11.29	0.00	76.00	0.00	90.59	19.22	74.00	31.00	6.57	389.00	-2114.97	-0.03	2678.30	7.95
0	40	161.32	0.00	75.00	0.00	89.80	19.22	74.00	60.99	20.19	386.00	-4149.48	0.03	5247.92	13.45
0	50	263.63	0.00	74.00	0.00	89.02	19.22	74.00	76.00	31.69	383.87	-5173.94	0.04	6546.54	17.45
0	65	444.23	0.00	73.00	0.00	87.54	19.22	74.00	99.00	57.94	378.00	-6724.86	0.03	8520.81	23.99
0	65	339.39	0.00	70.00	0.00	85.18	19.22	74.00	100.00	46.58	376.20	-6790.72	0.02	8600.07	19.78
0	75	578.80	0.00	71.00	0.00	85.88	19.22	74.00	114.22	79.89	372.00	-7778.31	-1.20	9852.53	26.33
2	10	281.33	0.00	81.16	0.00	85.49	19.22	74.00	17.12	7.49	382.16	-1170.82	-0.03	1480.58	14.11
2	10	434.56	0.00	72.00	0.00	77.25	19.22	71.00	17.00	13.60	371.52	-1196.47	0.02	1513.92	21.71
2	20	416.00	0.00	81.00	0.00	85.10	19.22	73.00	30.00	16.48	380.00	-2061.08	0.02	2610.80	20.66
2	20	397.29	0.00	73.00	0.00	77.25	19.22	71.00	30.00	18.35	371.00	-2086.60	0.02	2643.12	19.64
2	40	544.32	0.00	79.00	0.00	83.82	19.22	73.00	61.00	38.36	375.00	-4148.51	0.00	5255.76	26.43
2	40	485.39	0.00	74.00	0.00	77.65	19.22	71.00	61.02	37.69	368.18	-4181.31	0.03	5291.33	23.97
2	50	647.68	0.00	78.00	0.00	82.35	19.22	72.00	76.00	57.00	371.00	-5172.78	-0.04	6549.49	31.42
2	50	600.82	0.00	74.49	0.00	78.35	19.22	72.00	76.49	54.22	366.48	-5211.18	0.01	6598.37	28.83
2	65	834.34	0.00	76.00	0.00	79.62	19.22	72.00	99.00	90.62	363.00	-6735.21	0.02	8530.98	36.68
4	10	820.84	0.00	70.00	0.00	76.86	19.22	71.00	17.10	16.02	371.00	-1199.88	0.03	1517.93	32.45
4	10	705.05	0.00	64.00	0.00	67.45	19.22	70.00	16.86	14.82	360.00	-1165.73	-0.01	1477.43	29.69
4	20	818.01	0.00	69.00	0.00	76.08	19.22	70.16	30.00	29.96	368.00	-2083.07	-0.02	2639.99	34.70
4	20	788.43	0.00	65.00	0.00	68.22	19.22	70.00	30.19	28.49	358.03	-2089.94	-0.04	2650.79	32.74
4	40	951.84	0.00	68.00	0.00	73.73	19.22	70.46	61.00	62.86	360.00	-4142.71	-0.03	5248.34	38.72

Grade (%)	Speed (mph)	Dyno Force (N)	Engine Speed OBD (rpm)	Engine Coolant Temperature OBD (°C)	Calculated Load Value OBD (%)	Battery SOC (%)	Throttle Position OBD (%)	FDU Oil Temperature (°C)	Vehicle Speed (km/hr)	Battery Current (A)	Battery Voltage (V)	MGU1 Speed OBD (rpm)	MGU1 Torque OBD (Nm)	MGU2 Speed OBD (rpm)	MGU2 Torque OBD (Nm)
4	40	892.45	0.00	66.00	0.00	68.81	19.22	70.00	61.17	62.05	354.46	-4175.86	-0.02	5288.89	38.48
4	50	1040.23	0.00	67.00	0.00	70.22	19.22	70.00	76.00	85.05	353.00	-5180.34	0.00	6560.51	43.18
6	10	1242.46	0.00	63.00	0.00	67.06	19.22	70.00	17.31	24.58	359.16	-1217.19	0.04	1538.74	46.38
6	10	1180.84	0.00	60.00	0.00	58.04	19.22	70.00	16.92	27.79	349.15	-1189.99	-0.01	1503.26	47.18
6	20	1238.21	0.00	62.91	0.00	66.27	19.22	70.00	30.00	40.27	356.00	-2087.17	0.04	2646.60	48.58
6	20	1154.51	0.00	60.00	0.00	58.43	19.22	70.00	30.65	38.24	348.00	-2103.78	0.04	2666.47	44.92
6	40	1341.08	0.00	62.00	0.00	63.53	19.22	71.00	61.00	86.14	347.00	-4141.89	0.04	5249.00	52.85
6	40	1404.36	0.00	61.00	0.00	59.34	19.22	70.00	60.67	92.41	342.22	-4142.14	-0.01	5246.65	55.96
6	50	1469.94	0.00	61.00	0.00	60.91	19.22	71.00	75.98	118.59	340.16	-5166.21	0.09	6543.79	56.34
8	10	1646.09	0.00	59.84	0.00	57.65	19.22	71.00	17.86	34.75	349.86	-1250.59	0.03	1584.03	61.76
8	20	1650.07	0.00	59.00	0.00	56.47	19.22	71.00	29.88	52.20	346.00	-2055.13	0.10	2599.25	62.18
10	10	2011.12	0.00	58.00	0.00	55.30	19.22	71.00	17.00	38.87	347.46	-1206.15	-0.02	1527.15	71.78
10	20	2001.23	0.00	58.00	0.00	53.52	19.22	72.00	31.66	67.31	342.00	-2168.25	-0.04	2748.11	73.24

Grade (%)	Speed (mph)	MGU1 Power Yokogawa (W)	MGU2 Power Yokogawa (W)	Flywheel Torque (Nm)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Calculated Engine Power (W)	Total Wheel Torque (Nm)
0	10	-0.20	565.74	-108.90	16.49	-26.09	126.04	690.16	0.00	42.57
0	20	-0.10	2290.50	-127.10	41.30	-49.04	236.21	2556.61	0.00	90.35
0	40	6.73	7267.72	-127.10	66.94	-76.57	463.42	7791.82	0.00	143.51
0	50	10.69	11583.96	-127.10	87.31	-94.78	578.84	12165.25	0.00	182.10
0	65	19.01	20992.57	-127.10	122.40	-127.59	752.20	21901.83	0.00	249.99
0	65	18.71	17583.56	-127.10	96.66	-108.76	758.46	17524.05	0.00	205.43

Grade (%)	Speed (mph)	MGU1 Power Yokogawa (W)	MGU2 Power Yokogawa (W)	Flywheel Torque (Nm)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Calculated Engine Power (W)	Total Wheel Torque (Nm)
0	75	604.26	29132.38	-127.10	145.01	-150.23	869.71	29719.36	0.00	295.24
2	10	-0.30	2588.42	-108.90	77.43	-85.44	129.76	2862.39	0.00	162.87
2	10	-0.30	3485.35	-108.90	112.14	-119.99	134.29	5051.98	0.00	232.12
2	20	-0.30	5846.04	-108.90	109.98	-118.92	230.69	6263.95	0.00	228.90
2	20	-0.10	5542.38	-108.90	100.95	-110.33	233.14	6808.37	0.00	211.28
2	40	5.64	14039.60	-108.90	133.82	-141.78	463.70	14385.46	0.00	275.60
2	40	6.14	12735.64	-108.90	122.10	-126.04	467.06	13876.25	0.00	248.14
2	50	9.60	20291.09	-108.90	154.32	-161.99	578.68	21145.81	0.00	316.31
2	50	10.89	19222.87	-108.90	146.38	-151.75	582.49	19870.30	0.00	298.13
2	65	21.49	32008.91	-108.90	188.19	-201.39	753.46	32895.20	0.00	389.57
4	10	-0.40	5797.13	-108.90	177.75	-183.66	134.37	5942.95	0.00	361.41
4	10	-0.20	4880.59	-108.90	158.04	-166.76	130.00	5335.46	0.00	324.80
4	20	-0.20	9707.92	-108.90	179.39	-190.18	232.71	11024.65	0.00	369.57
4	20	0.10	9372.18	-108.90	174.10	-180.96	233.66	10200.61	0.00	355.06
4	40	6.14	21505.05	-108.90	204.63	-215.60	463.39	22629.65	0.00	420.23
4	40	5.74	20575.74	-108.90	192.93	-201.96	466.53	21993.96	0.00	394.89
4	50	11.68	29313.86	-108.90	222.97	-232.85	579.32	30021.65	0.00	455.82
6	10	-0.10	8397.92	-108.90	254.93	-271.90	136.40	8829.21	0.00	526.83
6	10	-0.30	7735.25	-108.90	245.09	-258.97	133.05	9701.10	0.00	504.06
6	20	-0.50	13848.32	-108.90	251.45	-268.59	233.68	14335.46	0.00	520.04
6	20	0.00	12986.04	-108.90	238.50	-252.13	234.78	13307.32	0.00	490.63
6	40	5.35	28966.73	-108.90	272.24	-288.40	463.66	29888.94	0.00	560.64
6	40	6.73	30056.44	-108.90	282.99	-300.80	464.03	31625.53	0.00	583.79

Grade (%)	Speed (mph)	MGU1 Power Yokogawa (W)	MGU2 Power Yokogawa (W)	Flywheel Torque (Nm)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Calculated Engine Power (W)	Total Wheel Torque (Nm)
6	50	13.37	39148.91	-108.90	296.61	-313.12	577.74	40340.59	0.00	609.74
8	10	-0.10	11030.40	-108.90	323.97	-345.92	140.53	12156.77	0.00	669.90
8	20	0.20	17608.42	-108.90	324.56	-345.47	229.95	18061.12	0.00	670.03
10	10	-0.50	12880.89	-108.90	386.48	-409.84	135.02	13504.65	0.00	796.32
10	20	0.40	22108.91	-108.90	386.43	-411.68	242.67	23018.53	0.00	798.11

Grade (%)	Speed (mph)	Calculated Instrumented Wheel Power (W)	Calculated MGU1 Power OBD (W)	Calculated MGU2 Power OBD (W)	MGU1 Efficiency (%)	MGU2 Efficiency (%)	AC Power Summation Yokogawa (W)	Drivetrain Power Summation (W)	Front Powertrain Efficiency (%)
0	10	561.90	3.30	475.69	-16.68	0.84	555.35	565.54	99.36%
0	20	2234.75	7.54	2229.39	-76.13	0.97	2249.90	2290.40	97.57%
0	40	6964.31	-11.02	7393.00	-0.61	1.02	7308.71	7274.46	95.74%
0	50	11038.06	-23.13	11960.45	-0.46	1.03	11601.49	11594.65	95.20%
0	65	19691.41	-18.74	21408.28	-1.01	1.02	20986.93	21011.58	93.72%
0	65	16316.10	-11.88	17811.03	-1.57	1.01	17556.53	17602.28	92.69%
0	75	26889.58	978.37	27168.90	1.62	0.93	30211.09	29736.63	90.43%
2	10	2213.20	4.02	2188.43	-13.54	0.85	2574.65	2588.12	85.51%
2	10	3264.32	-2.25	3441.08	0.13	0.99	3473.96	3485.05	93.67%
2	20	5529.70	-3.87	5647.30	0.08	0.97	5809.21	5845.74	94.59%
2	20	5158.13	-5.27	5436.65	0.02	0.98	5505.74	5542.28	93.07%
2	40	13382.78	-1.88	14546.18	-3.00	1.04	14085.35	14045.25	95.28%
2	40	12136.61	-14.36	13279.90	-0.43	1.04	12790.40	12741.78	95.25%
2	50	19168.02	21.79	21548.49	2.27	1.06	20191.09	20300.69	94.42%
2	50	18185.14	-6.42	19919.41	-1.70	1.04	19125.94	19233.76	94.55%

Grade (%)	Speed (mph)	Calculated Instrumented Wheel Power (W)	Calculated MGU1 Power OBD (W)	Calculated MGU2 Power OBD (W)	MGU1 Efficiency (%)	MGU2 Efficiency (%)	AC Power Summation Yokogawa (W)	Drivetrain Power Summation (W)	Front Powertrain Efficiency (%)
2	65	30738.30	-10.91	32764.67	-1.97	1.02	32054.06	32030.40	95.97%
4	10	5085.35	-3.50	5157.83	0.11	0.89	5786.14	5796.73	87.73%
4	10	4421.83	1.59	4593.19	-8.01	0.94	4869.90	4880.40	90.60%
4	20	9006.39	3.37	9594.27	-17.04	0.99	9671.68	9707.72	92.78%
4	20	8687.95	7.99	9088.30	80.71	0.97	9335.84	9372.28	92.70%
4	40	20392.34	14.23	21282.20	2.32	0.99	21558.12	21511.19	94.80%
4	40	19292.21	9.47	21310.24	1.65	1.04	20615.54	20581.49	93.74%
4	50	27652.94	-1.01	29667.53	-11.60	1.01	29230.40	29325.54	94.30%
6	10	7525.39	-5.44	7474.13	0.02	0.89	8387.62	8397.82	89.61%
6	10	7022.95	1.47	7427.04	-4.93	0.96	7724.46	7734.95	90.80%
6	20	12725.88	-9.33	13464.87	0.05	0.97	13811.68	13847.82	91.90%
6	20	12062.79	-9.41	12543.32	0.00	0.97	12949.11	12986.04	92.89%
6	40	27221.95	-16.37	29051.87	-0.33	1.00	29006.73	28972.08	93.96%
6	40	28368.19	2.95	30747.03	0.44	1.02	30097.33	30063.17	94.36%
6	50	36889.34	-49.88	38610.74	-0.27	0.99	39096.44	39162.28	94.20%
8	10	9858.06	-3.65	10243.92	0.03	0.93	11019.31	11030.30	89.37%
8	20	16134.60	-20.91	16924.54	-0.01	0.96	17573.07	17608.61	91.63%
10	10	11259.22	2.27	11479.67	-4.58	0.89	12870.50	12880.40	87.41%
10	20	20281.86	8.01	21075.85	20.22	0.95	22070.10	22109.31	91.73%

Appendix B: Toyota Q610 Loaded Efficiency

Steady-State Efficiency Testing – HEV Mode

Grade (%)	Speed (mph)	Dyno Force (N)	Engine Speed OBD (rpm)	Engine Coolant Temperature OBD (°C)	Calculated Load Value OBD (%)	Battery SOC (%)	Throttle Position OBD (%)	Vehicle Speed (km/hr)	Battery Current (A)	Battery Voltage (V)	RDU Speed OBD (rpm)	RDU Torque OBD (rpm)	RDU Temperature (°C)
0	20	3.82	1566.57	40.76	38.31	58.82	19.68	30.00	-18.23	356.00	2524.34	0.03	32.00
0	40	126.39	1308.98	51.25	65.48	59.08	22.78	61.00	-23.63	357.79	5013.56	0.38	32.00
0	50	239.09	1316.94	59.65	65.55	59.22	23.15	77.00	-13.07	357.00	6312.94	0.13	32.00
0	65	411.74	1574.69	70.05	62.12	58.82	24.53	99.23	1.68	354.10	8180.90	0.10	32.00
0	75	564.25	1917.61	83.11	74.28	58.82	32.47	115.00	-6.63	355.87	9468.93	0.39	33.00
2	40	543.07	1462.13	84.15	72.88	58.82	29.35	61.16	-21.79	357.00	5070.18	0.29	35.00
2	50	619.42	1462.93	84.98	71.52	59.22	29.15	76.00	-6.38	356.00	6276.97	0.07	35.00
2	65	816.34	1951.20	85.49	73.85	59.22	32.55	100.00	-0.41	356.00	8192.94	0.19	35.00
2	75	966.83	2348.42	85.19	74.99	59.22	36.02	115.00	0.24	355.84	9439.29	0.43	35.00
4	20	819.27	950.93	85.69	31.06	58.43	21.64	31.00	2.23	353.05	2575.52	0.05	38.00
4	40	930.03	1632.00	88.23	66.84	58.82	29.32	61.00	-7.27	356.00	5029.47	0.31	38.00
4	50	1031.90	1814.45	88.47	73.49	58.82	32.16	77.00	-0.38	355.00	6311.46	0.18	37.67
4	65	1211.78	2517.97	88.81	75.04	58.82	37.03	100.00	-3.01	355.69	8176.21	0.10	37.00
4	75	1358.50	2963.58	89.01	80.84	58.43	40.84	115.00	-1.16	355.00	9415.95	0.44	38.00
6	20	1327.77	1466.91	90.32	72.19	57.65	29.75	30.72	-18.60	356.07	2536.40	-0.02	40.00
6	40	1328.55	1817.95	90.97	73.33	57.65	32.05	61.00	0.50	354.00	5026.97	0.36	40.00
6	50	1431.39	2301.29	91.54	74.12	57.65	35.54	77.00	0.40	354.00	6307.92	0.12	40.00
6	65	1608.21	2971.22	92.00	81.33	57.25	40.91	99.00	-0.19	354.00	8135.14	0.12	40.00
6	75	1753.03	3266.87	89.44	95.22	57.25	44.41	114.93	0.29	354.11	9367.27	0.31	40.00
8	20	1615.02	1541.09	93.00	70.73	57.65	30.89	30.00	-13.85	356.00	2479.43	0.05	42.00
8	40	1728.11	2227.74	93.00	73.07	57.65	34.90	61.00	-0.17	355.00	4997.56	0.19	42.00

Grade (%)	Speed (mph)	Dyno Force (N)	Engine Speed OBD (rpm)	Engine Coolant Temperature OBD (°C)	Calculated Load Value OBD (%)	Battery SOC (%)	Throttle Position OBD (%)	Vehicle Speed (km/hr)	Battery Current (A)	Battery Voltage (V)	RDU Speed OBD (rpm)	RDU Torque OBD (rpm)	RDU Temperature (°C)
8	50	1826.07	2778.91	93.00	75.42	57.65	38.70	76.00	0.62	354.69	6242.37	0.29	42.00
10	20	2102.18	1774.65	95.46	72.58	57.25	32.13	38.00	-3.44	354.32	3131.27	0.10	43.00
10	40	2127.73	2518.29	93.00	74.21	57.25	36.99	61.00	-1.62	354.41	4986.11	0.18	43.00
10	50	2126.56	3057.51	92.00	82.28	57.25	41.53	76.00	-3.31	355.00	6231.57	0.34	43.00

Grade (%)	Speed (mph)	RDU Power Yokogawa (W)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Total Wheel Torque (Nm)	Calculated Instrumented Wheel Power (W)	Calculated RDU Power OBD (W)	RDU Efficiency (%)	Drivetrain Power Summation (W)	Rear Powertrain Efficiency (%)
0	20	-39.10	-17.73	20.12	231.97	-6488.21	37.84	919.31	8.96	-0.23	-39.10	-2351%
0	40	64.13	-13.60	19.90	461.24	-8454.10	33.50	1618.23	197.37	3.08	64.13	2523%
0	50	34.88	-14.28	19.82	580.87	-4665.14	34.10	2074.21	86.54	2.48	34.88	5947%
0	65	34.28	-15.19	19.24	752.76	594.93	34.43	2713.99	88.18	2.57	34.28	7917%
0	75	458.81	-11.92	18.21	871.27	-2359.36	30.13	2749.29	385.11	0.84	458.81	599%
2	40	70.25	-14.52	18.31	466.41	-7779.55	32.83	1603.37	154.37	2.20	70.25	2282%
2	50	34.13	-14.94	19.14	577.50	-2271.31	34.09	2061.53	48.44	1.42	34.13	6040%
2	65	27.11	-15.25	20.82	753.90	-145.94	36.07	2847.48	166.74	6.15	27.11	10502%
2	75	459.95	-11.82	18.65	868.48	85.51	30.48	2771.62	422.63	0.92	459.95	603%
4	20	-50.80	-16.67	20.38	237.03	786.89	37.05	919.69	13.50	-0.27	-50.80	-1811%
4	40	65.22	-13.25	18.69	462.68	-2588.87	31.94	1547.63	164.59	2.52	65.22	2373%
4	50	34.58	-13.21	19.30	580.76	-133.35	32.51	1977.28	117.76	3.41	34.58	5718%
4	65	26.27	-16.09	17.92	752.34	-1070.77	34.01	2679.39	83.33	3.17	26.27	10200%
4	75	438.11	-12.39	17.11	866.40	-411.69	29.50	2676.37	428.94	0.98	438.11	611%
6	20	-49.80	-17.68	21.12	234.18	-6623.04	38.80	951.44	-5.04	0.10	-49.80	-1910%

Grade (%)	Speed (mph)	RDU Power Yokogawa (W)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Total Wheel Torque (Nm)	Calculated Instrumented Wheel Power (W)	Calculated RDU Power OBD (W)	RDU Efficiency (%)	Drivetrain Power Summation (W)	Rear Powertrain Efficiency (%)
6	40	67.51	-13.20	18.37	462.47	177.70	31.56	1528.58	190.05	2.81	67.51	2264%
6	50	-140.40	-16.38	20.14	580.41	143.36	36.52	2219.60	82.37	-0.59	-140.40	-1581%
6	65	-31.14	-16.54	19.16	748.49	-66.93	35.70	2798.59	98.81	-3.17	-31.14	-8986%
6	75	260.70	-15.17	18.26	861.96	101.30	33.43	3017.44	299.84	1.15	260.70	1157%
8	20	-37.26	-17.65	21.38	227.84	-4930.14	39.03	931.21	13.32	-0.36	-37.26	-2499%
8	40	4.13	-15.44	19.00	459.86	-60.76	34.44	1658.55	99.10	24.00	4.13	40165%
8	50	-24.08	-14.43	20.04	574.51	220.05	34.48	2074.17	190.06	-7.89	-24.08	-8614%
10	20	-27.61	-15.76	20.23	288.56	-1219.48	35.99	1087.44	31.30	-1.13	-27.61	-3938%
10	40	-31.84	-14.98	19.58	458.74	-572.52	34.56	1660.11	93.36	-2.93	-31.84	-5214%
10	50	-73.73	-14.30	19.14	573.00	-1173.61	33.44	2006.79	221.79	-3.01	-73.73	-2722%

Steady-State Efficiency Testing – EV Mode

Grade (%)	Speed (mph)	Dyno Force (N)	Engine Speed OBD (rpm)	Engine Coolant Temperature OBD (°C)	Calculated Load Value OBD (%)	Battery SOC (%)	Throttle Position OBD (%)	Vehicle Speed (km/hr)	Battery Current (A)	Battery Voltage (V)	RDU Speed OBD (rpm)	RDU Torque OBD (rpm)	RDU Temperature (°C)
0	10	-104.41	0.00	24.00	0.00	89.80	19.22	16.78	3.41	389.00	1397.56	-0.07	21.85
0	20	18.33	0.00	24.00	0.00	89.75	19.22	30.00	7.59	387.93	2522.06	0.03	22.00
0	40	137.31	0.00	24.00	0.00	88.63	19.22	61.00	20.73	384.00	5028.51	0.32	22.00
0	50	221.60	0.00	24.00	0.00	87.84	19.22	75.00	30.38	381.00	6216.81	0.17	22.00
0	50	231.05	0.00	25.00	0.00	60.13	19.22	76.00	33.27	349.00	6283.94	0.25	30.00
0	65	409.87	0.00	24.00	0.00	85.89	19.22	99.00	58.08	373.57	8160.25	0.07	23.00
0	65	410.52	0.00	25.00	0.00	58.04	19.22	99.00	59.88	344.00	8157.30	0.04	30.00
2	10	363.96	0.00	24.00	0.00	86.27	19.22	17.22	9.41	382.00	1464.84	0.06	25.00
2	20	421.35	0.00	24.00	0.00	85.88	19.22	30.00	17.24	380.00	2521.75	0.03	25.00
2	40	537.68	0.00	24.00	0.00	84.36	19.22	61.00	40.12	374.43	5017.97	0.24	25.00
2	50	628.41	0.00	24.00	0.00	82.69	19.22	76.00	57.96	369.00	6273.42	0.19	25.00
2	65	812.16	0.00	24.00	0.00	79.91	19.22	99.00	92.04	360.00	8147.98	0.05	25.00
4	10	874.10	0.00	24.00	0.00	79.22	19.22	16.73	16.97	373.00	1421.95	0.02	27.00
4	20	817.49	0.00	24.00	0.00	78.59	19.22	30.00	27.48	370.00	2505.23	0.08	28.00
4	40	939.33	0.00	24.00	0.00	76.62	19.22	61.00	61.12	362.00	5012.37	0.32	28.00
4	50	1034.55	0.00	24.00	0.00	74.59	19.22	76.00	85.07	355.43	6256.42	0.13	28.00
6	10	1259.83	0.00	24.00	0.00	73.73	19.22	16.56	22.60	365.75	1389.72	0.03	29.62
6	20	1216.59	0.00	24.00	0.00	72.80	19.22	31.00	39.47	361.57	2542.73	0.05	29.00
6	40	1331.19	0.00	24.00	0.00	70.11	19.22	61.00	82.65	351.62	5007.31	0.18	29.00
6	50	1426.37	0.00	24.00	0.00	67.34	19.22	76.00	114.57	344.00	6256.43	0.17	29.00
8	10	1584.29	0.00	25.00	0.00	66.66	19.22	16.04	28.12	356.00	1378.67	-0.01	30.16

Grade (%)	Speed (mph)	Dyno Force (N)	Engine Speed OBD (rpm)	Engine Coolant Temperature OBD (°C)	Calculated Load Value OBD (%)	Battery SOC (%)	Throttle Position OBD (%)	Vehicle Speed (km/hr)	Battery Current (A)	Battery Voltage (V)	RDU Speed OBD (rpm)	RDU Torque OBD (rpm)	RDU Temperature (°C)
8	20	1607.18	0.00	25.00	0.00	65.40	19.22	30.00	50.59	352.00	2496.14	0.04	30.00
10	10	2056.92	0.00	25.00	0.00	64.22	19.22	16.46	36.63	353.00	1399.07	0.03	31.00
10	20	1865.50	0.00	25.00	0.00	62.14	19.22	30.00	62.32	347.14	2481.39	-0.06	31.00
-2	20	-697.24	0.00	25.00	0.00	57.65	19.22	9.90	-2.03	353.40	840.89	-0.64	32.00
-6	20	-1175.76	0.00	25.00	0.00	58.43	19.22	30.00	-20.84	357.00	2533.98	-5.19	32.00
-8	20	-1965.07	0.00	25.00	0.00	59.03	19.22	39.14	-46.50	360.20	3243.36	-4.40	32.00
-8	40	-1434.24	0.00	25.00	0.00	60.76	19.22	64.25	-53.36	363.26	5328.52	-6.11	32.00

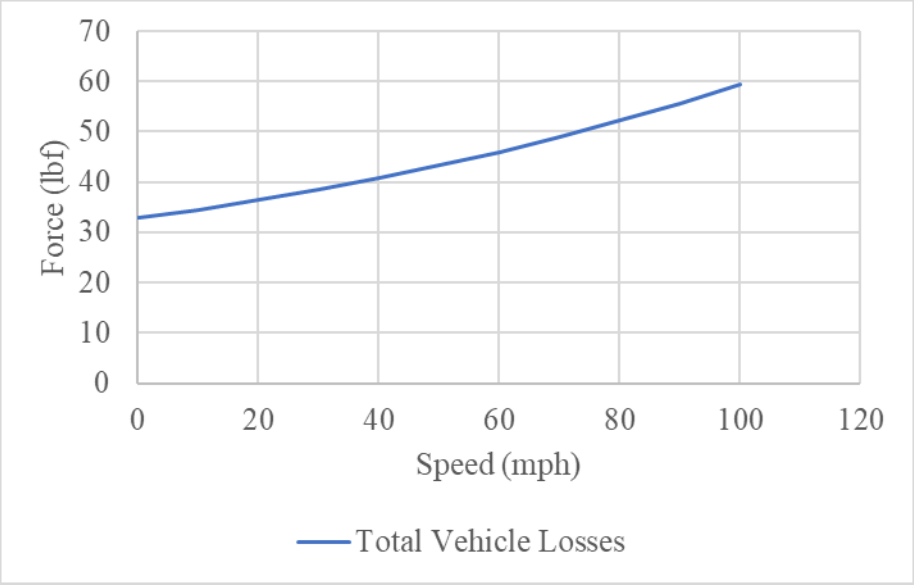
Grade (%)	Speed (mph)	RDU Power Yokogawa (W)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Total Wheel Torque (Nm)	Calculated Instrumented Wheel Power (W)	Calculated RDU Power OBD (W)	RDU Efficiency (%)	Drivetrain Power Summation (W)	Rear Powertrain Efficiency (%)
0	10	-43.63	-22.35	26.32	128.15	1327.82	48.68	653.21	-10.42	0.24	-43.63	-14.97
0	20	-37.01	-18.23	25.51	232.29	2944.40	43.75	1064.17	8.13	-0.22	-37.01	-28.75
0	40	41.34	-14.90	20.96	462.65	7959.85	35.86	1737.20	171.11	4.14	41.34	42.02
0	50	13.83	-15.19	19.59	571.98	11574.01	34.78	2083.31	107.90	7.80	13.83	150.63
0	50	-70.75	-14.80	21.51	578.22	11611.75	36.31	2198.47	161.45	-2.28	-70.75	-31.08
0	65	20.25	0.00	-8.48	750.79	21695.24	-8.47	-666.26	56.07	2.77	20.25	-32.90
0	65	-64.33	-14.94	20.54	750.71	20598.66	35.48	2789.58	30.55	-0.47	-64.33	-43.36
2	10	-11.19	-19.05	26.93	134.64	3595.73	45.98	648.32	9.21	-0.82	-11.19	-57.92
2	20	-36.77	-20.51	23.58	232.14	6552.61	44.08	1071.65	7.97	-0.22	-36.77	-29.15
2	40	47.61	-14.56	20.87	461.84	15023.45	35.43	1713.44	128.27	2.69	47.61	35.99
2	50	-99.65	-16.19	21.07	577.31	21388.69	37.26	2252.70	126.45	-1.27	-99.65	-22.61
2	65	29.75	-15.16	20.12	749.70	33134.73	35.28	2769.54	44.84	1.51	29.75	93.09

Grade (%)	Speed (mph)	RDU Power Yokogawa (W)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Total Wheel Torque (Nm)	Calculated Instrumented Wheel Power (W)	Calculated RDU Power OBD (W)	RDU Efficiency (%)	Drivetrain Power Summation (W)	Rear Powertrain Efficiency (%)
4	10	-10.95	-17.95	22.46	131.49	6330.77	40.41	556.47	2.45	-0.22	-10.95	-50.84
4	20	-35.17	-16.93	23.28	230.42	10167.59	40.21	970.19	21.62	-0.61	-35.17	-27.58
4	40	68.50	-14.73	19.10	461.21	22124.44	33.83	1633.82	170.27	2.49	68.50	23.85
4	50	-82.34	-16.19	20.74	575.71	30235.64	36.93	2226.29	88.21	-1.07	-82.34	-27.04
6	10	-9.60	-19.88	25.24	128.37	8267.33	45.13	606.61	5.02	-0.52	-9.60	-63.18
6	20	-35.47	-18.97	24.56	233.90	14269.61	43.54	1066.36	12.83	-0.36	-35.47	-30.06
6	40	-0.10	-15.16	20.89	460.78	29060.46	36.05	1739.51	95.38	-958.62	-0.10	-17482.06
6	50	-54.43	-15.90	20.93	575.70	39410.42	36.83	2220.29	113.48	-2.08	-54.43	-40.79
8	10	-9.30	-19.32	23.87	126.81	10010.64	43.19	573.60	-0.76	0.08	-9.30	-61.65
8	20	-36.02	-16.63	25.50	229.81	17807.62	42.13	1013.96	9.51	-0.26	-36.02	-28.15
10	10	-9.35	-17.93	23.91	129.35	12929.23	41.84	566.72	3.78	-0.40	-9.35	-60.59
10	20	-86.57	-17.13	24.03	228.16	21633.25	41.17	983.56	-14.62	0.17	-86.57	-11.36
-2	20	-77.71	-23.24	28.24	75.58	-716.46	51.48	407.49	-56.21	0.72	-77.71	-5.24
-6	20	-1623.79	-47.91	57.20	233.08	-7438.87	105.10	2565.44	-1377.80	0.85	-1623.79	-1.58
-8	20	-1740.35	-42.51	52.33	295.71	-16748.11	94.84	2936.89	-1493.04	0.86	-1740.35	-1.69
-8	40	-3745.02	-51.43	59.77	490.34	-19384.01	111.20	5709.93	-3407.22	0.91	-3745.02	-1.52

Appendix C: Toyota RAV4 Spinloss Result

Toyota Rav4 Vehicle Loss Results

	Target Coefficients			Set Coefficients			Rolling Resistance Coefficients			Loss Coefficients		
Run	F0	F1	F2	A	B	C	R0	R1	R2	L0	L1	L2
1	28.089	0.14349	0.02558	0	0	0.02558	33.314	0.22973	0.02576	33.3140	0.22973	0.00018
2	28.089	0.14349	0.02558	-5.22504	-0.08624	0.0254	28.0396	0.11234	0.02589	33.2646	0.19858	0.00049
3	28.089	0.14349	0.02558	-5.22504	-0.08624	0.0254	28.0803	0.07168	0.02649	33.3054	0.15792	0.00109
4	28.089	0.14349	0.02558	-5.22504	-0.08624	0.0254	27.7255	0.06244	0.02655	32.9505	0.14868	0.00115



Appendix D: Toyota P810 In-Use Test Results

FDU Drive Cycle Testing Summary

	Dyno Force (N)	Engine Speed OBD (rpm)	Engine Coolant Temperature OBD (°C)	Calculated Load Value OBD (%)	Battery SOC (%)	Throttle Position OBD (%)	FDU Oil Temperature (°C)	Vehicle Speed (km/hr)	Battery Current (A)	Battery Voltage (V)	MGU1 Speed OBD (rpm)	MGU1 Torque OBD (rpm)	MGU2 Speed OBD (rpm)	MGU2 Torque OBD (Nm)
US06-1	290.79	0.00	23.54	0.00	81.49	19.22	27.62	74.64	49.55	370.66	-5079.56	-0.31	6434.04	21.48
US06-2	291.28	0.00	24.68	0.00	64.80	19.22	39.46	75.24	49.23	353.14	-5118.67	-0.34	6484.24	21.18
US06-3	291.05	0.00	26.43	0.00	46.71	19.22	50.45	75.11	52.68	340.68	-5109.91	-0.50	6473.44	20.91
US06-4	291.31	0.00	27.96	0.00	27.52	19.22	59.17	75.36	53.58	331.48	-5126.34	-0.53	6493.76	21.01
US06-5	289.02	990.57	61.04	39.04	13.80	22.84	66.32	74.91	13.62	329.71	-1496.93	-18.88	6457.14	6.65
US06-6	288.73	1122.25	89.76	45.51	13.28	25.18	71.78	74.85	-1.53	332.05	-1012.62	-25.07	6452.05	1.35
US06-7	290.55	1145.52	91.24	46.36	13.21	25.09	76.96	74.89	-0.87	332.03	-937.26	-24.74	6453.94	2.19
HwFET-1	213.46	0.00	22.71	0.00	83.69	19.22	26.72	69.57	31.23	375.35	-4739.42	-0.03	6003.56	15.58
HwFET-2	215.79	0.00	24.08	0.00	68.47	19.22	38.19	69.55	31.25	357.81	-4736.15	-0.05	5999.62	15.49
HwFET-3	211.37	0.00	25.06	0.00	53.04	19.22	45.97	67.94	31.29	345.84	-4628.05	-0.04	5862.71	14.67
HwFET-4	210.97	0.00	27.14	0.00	37.43	19.22	49.23	67.85	31.95	338.81	-4621.07	-0.03	5853.73	14.79
HwFET-5	226.87	140.68	29.23	5.72	20.42	19.38	52.46	73.02	31.65	330.15	-4460.56	-1.97	6300.43	14.33
HwFET-6	228.68	1009.79	80.95	43.57	14.12	22.06	58.76	73.82	-1.48	332.15	-1353.18	-21.49	6368.14	-1.72
HwFET-7	215.21	919.27	89.55	39.70	14.14	22.25	61.45	69.43	-1.43	332.35	-1380.23	-19.91	5990.00	-1.11
HwFET-8	222.56	953.89	90.95	39.45	14.04	22.19	65.73	71.84	-0.29	332.38	-1422.67	-19.91	6198.03	-0.75
UDDS-1	39.16	0.00	25.29	0.00	84.56	19.22	29.25	27.05	9.82	380.57	-1851.74	-0.12	2345.14	9.88
UDDS-2	42.40	0.00	26.90	0.00	74.41	19.22	38.34	30.01	10.76	370.05	-2054.78	-0.11	2602.61	10.32
UDDS-3	43.11	0.00	28.08	0.00	65.57	19.22	43.82	29.60	10.80	360.33	-2024.64	-0.13	2564.18	9.93
UDDS-4	43.56	0.00	29.33	0.05	56.21	19.26	47.32	30.41	11.19	352.20	-2081.37	-0.12	2636.02	10.82
UDDS-5	41.56	0.00	30.54	0.00	46.69	19.22	49.77	29.88	11.15	347.16	-2043.60	-0.13	2588.29	9.95

	Dyno Force (N)	Engine Speed OBD (rpm)	Engine Coolant Temperature OBD (°C)	Calculated Load Value OBD (%)	Battery SOC (%)	Throttle Position OBD (%)	FDU Oil Temperature (°C)	Vehicle Speed (km/hr)	Battery Current (A)	Battery Voltage (V)	MGU1 Speed OBD (rpm)	MGU1 Torque OBD (rpm)	MGU2 Speed OBD (rpm)	MGU2 Torque OBD (Nm)
UDDS-6	42.28	0.00	31.25	0.00	36.97	19.22	51.49	29.69	11.16	343.68	-2031.54	-0.12	2572.67	10.09
UDDS-7	41.65	0.00	32.03	0.00	27.10	19.22	52.57	30.05	11.49	339.74	-2057.17	-0.11	2605.32	10.24
UDDS-8	41.81	71.56	32.97	2.09	17.31	19.16	53.17	30.47	11.20	333.20	-1823.69	-0.48	2640.24	10.28
UDDS-9	42.39	383.90	79.41	16.27	14.05	19.97	57.08	30.21	-0.11	332.81	-667.91	-6.38	2619.36	5.65
UDDS-10	41.24	379.43	87.18	15.88	14.04	20.10	60.96	29.71	-0.72	333.33	-652.61	-6.71	2577.12	4.74

	Rear Motor Torque OBD (Nm)	Rear Motor Temperature (°C)	MGU1 Power Yokogawa (W)	MGU2 Power Yokogawa (W)	Rear Motor Power Yokogawa (W)	Flywheel Torque (Nm)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Calculated Engine Power (W)	Total Wheel Torque (Nm)	Calculated Instrumented Wheel Power (W)	Calculated MGU1 Power OBD (W)	Calculated MGU2 Power OBD (W)	Calculated Rear Motor Power OBD (W)
US06-1	1.17	25.62	141.15	17903.63	-160.52	-0.10	92.37	-99.73	568.12	18366.98	0.00	192.10	11428.65	163.84	14472.33	755.47
US06-2	1.00	33.75	163.97	16426.48	-161.61	-0.10	89.41	-94.88	572.56	17385.33	0.00	184.28	11049.34	181.66	14382.30	648.30
US06-3	1.06	39.10	243.15	19639.28	-161.81	-0.10	89.04	-99.55	571.55	17946.99	0.00	188.58	11287.28	267.07	14176.28	687.57
US06-4	1.07	42.78	260.48	16501.10	-182.47	-0.10	89.26	-96.61	573.27	17760.96	0.00	185.87	11158.56	284.18	14284.43	698.55
US06-5	1.10	45.28	491.95	2505.58	-164.98	94.20	87.60	-88.92	570.13	4489.59	9771.13	176.52	10538.74	2959.60	4496.11	709.04
US06-6	1.05	47.95	-536.82	-1038.45	-197.94	86.45	86.51	-89.54	569.64	-506.66	10159.72	176.06	10502.19	2658.82	911.04	677.52
US06-7	1.02	50.21	-653.11	-794.91	-220.62	74.36	86.93	-101.77	569.80	-289.26	8920.67	188.69	11259.30	2427.98	1482.93	658.56
HwFET-1	0.21	24.25	13.52	11039.54	-62.05	0.00	78.04	-82.42	527.04	11721.20	0.00	160.46	8855.88	15.52	9793.64	124.59
HwFET-2	0.20	33.17	29.10	10540.88	-62.81	0.00	74.63	-82.69	529.66	11182.19	0.00	157.32	8726.21	24.04	9730.40	121.50
HwFET-3	0.11	38.36	27.86	10234.48	-85.43	0.00	72.05	-80.47	517.59	10822.39	0.00	152.53	8267.25	21.39	9004.53	65.20
HwFET-4	0.17	38.25	21.66	10281.48	-64.33	0.00	73.01	-80.79	516.77	10825.35	0.00	153.80	8323.14	12.93	9068.82	101.29
HwFET-5	0.19	42.34	185.73	9647.84	-71.36	3.73	76.45	-85.19	556.20	10450.02	54.94	161.64	9414.72	919.16	9456.68	119.22
HwFET-6	0.13	44.50	426.69	-1669.41	-54.45	77.81	77.17	-85.95	562.17	-493.18	8227.88	163.13	9603.33	3045.11	-1147.06	81.24

	Rear Motor Torque OBD (Nm)	Rear Motor Temperature (°C)	MGU1 Power Yokogawa (W)	MGU2 Power Yokogawa (W)	Rear Motor Power Yokogawa (W)	Flywheel Torque (Nm)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Calculated Engine Power (W)	Total Wheel Torque (Nm)	Calculated Instrumented Wheel Power (W)	Calculated MGU1 Power OBD (W)	Calculated MGU2 Power OBD (W)	Calculated Rear Motor Power OBD (W)
HwFET-7	0.18	44.38	344.39	-1450.00	-54.72	83.61	72.33	-81.97	528.78	-475.80	8048.51	154.30	8544.27	2877.67	-697.02	110.04
HwFET-8	0.11	47.13	292.59	-1082.85	-84.82	80.97	73.43	-85.16	546.93	-97.28	8087.95	158.59	9083.06	2966.72	-483.97	66.36
UDDS-1	1.52	27.03	2.85	3211.83	-25.35	0.00	30.10	-40.39	205.26	3736.96	0.00	70.49	1515.13	23.04	2425.41	357.52
UDDS-2	1.61	32.87	-1.08	3460.40	-19.70	0.00	32.71	-43.98	229.74	3982.55	0.00	76.69	1844.88	23.03	2813.36	421.19
UDDS-3	1.63	36.19	6.99	3368.59	-19.58	0.00	32.88	-44.40	226.45	3890.58	0.00	77.28	1832.62	27.98	2665.13	418.14
UDDS-4	1.58	38.22	-0.80	3463.70	-42.29	0.00	33.55	-45.51	232.77	3942.11	0.00	79.06	1927.16	25.22	2985.72	418.06
UDDS-5	1.57	39.44	1.72	3380.11	-27.95	0.00	32.77	-44.80	228.55	3870.84	0.00	77.57	1856.60	27.76	2697.29	406.39
UDDS-6	1.54	40.33	1.05	3336.19	-32.02	0.00	32.36	-44.68	227.20	3834.07	0.00	77.04	1833.01	25.77	2719.10	396.63
UDDS-7	1.48	40.73	4.09	3412.12	-40.33	0.00	33.03	-45.40	230.07	3902.10	0.00	78.43	1889.47	22.66	2795.03	387.68
UDDS-8	1.63	41.13	-126.23	3362.19	-34.36	-1.03	32.66	-45.92	233.15	3732.36	-7.70	78.57	1918.36	92.51	2842.74	431.42
UDDS-9	1.53	41.53	-1470.10	958.44	-46.79	2.77	33.98	-46.42	231.16	-37.27	111.51	80.40	1946.19	446.30	1550.55	402.43
UDDS-10	1.46	42.06	-1527.80	745.14	-44.74	32.25	32.61	-44.90	227.43	-238.74	1281.54	77.51	1846.04	458.73	1279.29	378.22

	MGU1 Efficiency (%)	MGU2 Efficiency (%)	Rear Motor Efficiency (%)	AC Power Summation Yokogawa (W)	Drivetrain Power Summation (W)	Front Powertrain Efficiency (%)	Inverter Efficiency (%)
US06-1	1.16	0.81	-4.71	17884.26	18044.78	63.33%	0.97
US06-2	1.11	0.88	-4.01	16428.84	16590.45	66.60%	0.94
US06-3	1.10	0.72	-4.25	19720.63	19882.43	56.77%	1.10
US06-4	1.09	0.87	-3.83	16579.11	16761.58	66.57%	0.93
US06-5	6.02	1.79	-4.30	2832.56	12768.66	82.54%	0.63
US06-6	-4.95	-0.88	-3.42	-1773.20	11734.99	89.49%	3.50

	MGU1 Efficiency (%)	MGU2 Efficiency (%)	Rear Motor Efficiency (%)	AC Power Summation Yokogawa (W)	Drivetrain Power Summation (W)	Front Powertrain Efficiency (%)	Inverter Efficiency (%)
US06-7	-3.72	-1.87	-2.99	-1668.64	10368.69	108.59%	5.77
HwFET-1	1.15	0.89	-2.01	10991.01	11053.06	80.12%	0.94
HwFET-2	0.83	0.92	-1.93	10507.17	10569.99	82.56%	0.94
HwFET-3	0.77	0.88	-0.76	10176.91	10262.34	80.56%	0.94
HwFET-4	0.60	0.88	-1.57	10238.81	10303.14	80.78%	0.95
HwFET-5	4.95	0.98	-1.67	9762.21	9888.50	95.21%	0.93
HwFET-6	7.14	0.69	-1.49	-1297.17	6985.16	137.48%	2.63
HwFET-7	8.36	0.48	-2.01	-1160.33	6942.89	123.07%	2.44
HwFET-8	10.14	0.45	-0.78	-875.07	7297.69	124.46%	9.00
UDDS-1	8.09	0.76	-14.10	3189.33	3214.68	47.13%	0.85
UDDS-2	-21.31	0.81	-21.38	3439.62	3459.32	53.33%	0.86
UDDS-3	4.01	0.79	-21.36	3356.00	3375.57	54.29%	0.86
UDDS-4	-31.42	0.86	-9.88	3420.61	3462.90	55.65%	0.87
UDDS-5	16.10	0.80	-14.54	3353.88	3381.83	54.90%	0.87
UDDS-6	24.54	0.82	-12.39	3305.23	3337.24	54.93%	0.86
UDDS-7	5.54	0.82	-9.61	3375.88	3416.21	55.31%	0.87
UDDS-8	-0.73	0.85	-12.56	3201.60	3228.26	59.42%	0.86
UDDS-9	-0.30	1.62	-8.60	-558.45	-400.14	-486.37%	14.98
UDDS-10	-0.30	1.72	-8.45	-827.41	498.88	370.04%	3.47

Appendix E: Toyota Q610 In-Use Test Results

RDU Drive Cycle Testing Summary

Mode	Cycle	Dyno Force (N)	Engine Speed OBD (rpm)	Engine Coolant Temperature OBD (°C)	Calculated Load Value OBD (%)	Battery SOC (%)	Throttle Position OBD (%)	FDU Oil Temperature (°C)	Vehicle Speed (km/hr)	Battery Current (A)	Battery Voltage (V)
EV	US06	194.11	0.00	69.94	0.00	37.83	19.22	62.77	76.35	51.87	337.85
HEV	US06	279.86	1273.89	86.36	48.17	28.81	24.60	71.46	74.18	-0.19	343.23
EV	HwFET	218.80	0.00	66.99	0.00	35.02	19.22	67.53	72.30	32.98	340.81
HEV	HwFET	226.82	1095.09	86.97	45.83	27.81	22.39	69.70	74.43	-3.23	343.32
EV	UDDS	36.87	0.00	53.22	0.00	49.46	19.22	56.94	27.98	10.74	349.24
HEV	UDDS	40.66	422.95	81.83	18.35	45.56	20.30	61.42	29.58	-0.76	349.63

Mode	Cycle	MGU1 Speed OBD (rpm)	MGU1 Torque OBD (rpm)	MGU2 Speed OBD (rpm)	MGU2 Torque OBD (Nm)	Rear Motor Speed OBD (rpm)	Rear Motor Torque OBD (Nm)	Rear Motor Temperature (°C)
EV	US06	-5193.52	-0.52	6579.54	21.61	6279.52	0.96	41.10
HEV	US06	-416.53	-24.61	6389.68	2.03	6097.62	1.13	45.47
EV	HwFET	-4924.03	-0.07	6237.60	15.64	5957.02	0.17	44.23
HEV	HwFET	-1074.08	-22.82	6420.40	-2.60	6131.18	0.05	47.39
EV	UDDS	-1914.31	-0.10	2424.58	9.22	2317.11	1.28	36.76
HEV	UDDS	-484.30	-7.79	2562.32	3.47	2448.69	1.27	39.19

Mode	Cycle	MGU1 Power Yokogawa (W)	MGU2 Power Yokogawa (W)	Rear Motor Power Yokogawa (W)	Flywheel Torque (Nm)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Calculated Engine Power (W)	Total Wheel Torque (Nm)
EV	US06	221.32	14188.17	-160.89	0.00	-17.84	21.79	508.34	17525.11	0.00	39.63
HEV	US06	-811.41	-667.89	-248.28	100.66	-18.99	22.79	548.68	-63.62	13427.67	41.78
EV	HwFET	34.46	10392.28	-82.16	0.00	-14.95	18.02	534.60	11240.03	0.00	32.96

Mode	Cycle	MGU1 Power Yokogawa (W)	MGU2 Power Yokogawa (W)	Rear Motor Power Yokogawa (W)	Flywheel Torque (Nm)	Wheel Torque Left (Nm)	Wheel Torque Right (Nm)	Wheel Speed OBD (rpm)	Calculated Battery Power (W)	Calculated Engine Power (W)	Total Wheel Torque (Nm)
HEV	HwFET	592.09	-2263.39	-71.83	96.34	-15.22	18.21	558.14	-1107.52	11048.54	33.43
EV	UDDS	2.44	3124.32	-41.93	0.00	-11.49	14.86	202.56	3751.29	0.00	26.35
HEV	UDDS	-1741.70	393.00	-75.82	25.42	-11.26	15.51	219.11	-265.52	1125.80	26.77

Mode	Cycle	Calculated Instrumented Wheel Power (W)	Calculated MGU1 Power OBD (W)	Calculated MGU2 Power OBD (W)	Calculated Rear Motor Power OBD (W)	MGU1 Efficiency (%)	MGU2 Efficiency (%)	Rear Motor Efficiency (%)	AC Power Summation Yokogawa FDU (W)	Drivetrain Power Summation RDU (W)	Rear Powertrain Efficiency (%)	Inverter Efficiency (%)
EV	US06	2109.67	284.08	14887.95	629.99	1.28	1.05	-3.92	14248.60	-160.89	-1311.24%	0.81
HEV	US06	2400.44	1073.51	1360.28	721.95	-1.32	-2.04	-2.91	-1727.59	-248.28	-966.81%	27.16
EV	HwFET	1845.36	36.30	10215.94	104.88	1.05	0.98	-1.28	10344.58	-82.16	-2246.06%	0.92
HEV	HwFET	1954.08	2566.31	-1745.74	33.19	4.33	0.77	-0.46	-1743.13	-71.83	-2720.31%	1.57
EV	UDDS	558.96	19.38	2341.17	310.22	7.93	0.75	-7.40	3084.83	-41.93	-1333.03%	0.82
HEV	UDDS	614.22	395.31	931.87	324.68	-0.23	2.37	-4.28	-1424.52	-75.82	-810.09%	5.37

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