2020-01-1286 Published 14 Apr 2020

Benchmarking a 2018 Toyota Camry UB80E Eight-Speed Automatic Transmission

Andrew Moskalik, Mark Stuhldreher, and John Kargul US Environmental Protection Agency

Citation: Moskalik, A., Stuhldreher, M., and Kargul, J., "Benchmarking a 2018 Toyota Camry UB80E Eight-Speed Automatic Transmission," SAE Technical Paper 2020-01-1286, 2020, doi:10.4271/2020-01-1286.

Abstract

As part of the U.S. Environmental Protection Agency's (EPA's) continuing assessment of advanced light-duty automotive technologies in support of regulatory and compliance programs, a 2018 Toyota Camry front wheel drive eight-speed automatic transmission was benchmarked. The benchmarking data were used as inputs to EPA's Advanced Light-duty Powertrain and Hybrid Analysis (ALPHA) vehicle simulation model to estimate GHG emissions from light-duty vehicles.

ALPHA requires both detailed engine fuel consumption maps and transmission torque loss maps. EPA's National Vehicle and Fuels Emissions Laboratory has developed a streamlined, cost-effective in-house method of transmission testing, capable of gathering a dataset sufficient to characterize transmissions within ALPHA. This testing methodology targets the range of transmission operation observed during vehicle testing over EPA's city and highway drive cycles.

With this method, the transmission is tested as a complete system, as opposed to disassembling the transmission components and testing each separately. This paper describes the benchmarking process used to gather transmission data and the test results obtained. A UB80E eight-speed automatic transmission from a 2018 Toyota Camry was installed in an engine dynamometer test cell along with a 4-cylinder 2.5L A25A-FKS engine from the same vehicle. The test dataset collected from the transmission includes gear efficiencies, torque converter slippage and K factors, spin losses, oil temperature and pressure, and CAN bus data.

The transmission data collected with this benchmarking method were used as inputs to the ALPHA full vehicle simulation model. ALPHA simulation results were validated using vehicle chassis dynamometer test data from the 2018 Toyota Camry containing this engine and transmission. The ALPHA simulation also allowed the Toyota UB80E transmission to be compared to other benchmarked transmissions.

Introduction and Background

The National Center for Advanced Technology (NCAT), part of EPA's National Vehicle and Fuel Emissions Laboratory, leads a team that assesses the effectiveness of advanced low emission and low fuel consumption technologies by benchmarking a broad range of key light-duty vehicles, engines and transmissions. The NCAT team benchmarks advanced technologies using laboratory test methods to characterize engine controls, fuel consumption, emissions, and component losses [1, 2, 3, 4, 5, 6, 7, 8, 9].

NCAT leverages in-depth, detailed engineering analyses along with extensive engine and chassis dynamometer laboratory testing to evaluate advanced vehicle, engine and transmission technologies. The test data are used for a variety of purposes, including documenting transmission performance in complete transmission maps, performing technical analyses regarding technology effectiveness, and providing information for full vehicle simulations using EPA's Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool [10, 11, 12]. Both laboratory test data and ALPHA simulation results continue to be used to support evaluation of light-duty vehicle fuel economy, greenhouse gas and criteria pollutant emissions, and the divergence between laboratory test results and actual in-use emissions.

This paper provides an overview of EPA's complete benchmarking work on the 2018 Toyota Camry eight-speed transmission. To perform this work, a streamlined benchmarking method was used to test a UB80E eight-speed transmission from a 2018 Toyota Camry coupled to a 2.5L 4-cylinder A25A-FKS engine from the same vehicle. The engine and transmission were mounted in an engine dynamometer test cell and tethered with a lengthened engine wiring harness to a complete vehicle outside the test cell. This benchmarking process allowed both the engine and transmission mapping to be conducted at EPA's laboratory using the stock ECU and TCU with their factory production calibrations. Additional information on benchmarking of the Toyota Camry A25A-FKS engine can be found in an associated paper [1].

Data from both benchmarking tests were subsequently configured as engine and transmission inputs for ALPHA, and a validation of the 2018 Camry was performed in the ALPHA model. Results from the 2018 Camry's chassis dynamometer tests were then used to validate the data from the engine and transmission benchmarking. While a complete analysis of the results of the 2018 Camry model validation is outside the scope of this paper, the ALPHA validation results are provided to inform the discussion. Additional details on ALPHA simulations in general can be found in previously published papers [2, 3, 4, 11, 12, 13].

Finally, the ALPHA tool was used to compare the Camry's UB80E transmission and its losses to previously benchmarked and modeled transmissions to characterize their technical and performance differences over standard regulatory cycles.

Description of Test Article and Setup

The 2018 Toyota Camry engine and transmission used in this project were a 4-cylinder 2.5L A25A-FKS engine and a UB80E eight-speed automatic transmission (AT) [14]. Table 1 summarizes information that describes the vehicle and engine used in this test program.

The UB80E is a front-wheel drive eight-speed automatic transmission, described as a Direct Shift 8-speed ECT-i automatic with sequential shift mode [14]. The transmission, developed by Toyota with Aisin AW [15], has a torque capacity of 280 Nm [16]. A similar transmission (designated UA80) with a higher torque capacity is described in reference [17]. The gear ratios for the UB80E transmission are given in Table 2.

TABLE 1 Summary of vehicle and engine identification information. Regulatory test parameters and test results for this vehicle are given in Tables 8 and 10.

Vehicle (MY, Make, Model)	2018 Toyota Camry
Vehicle Identification Number	JTNB11HKXJ3007695
Engine (displacement, name)	2.5L A25A-FKS four-cylinder
Rated Power	151 kW @ 6600 RPM
Rated Torque	249 Nm @ 4800 RPM
Recommended Fuel	87 octane Anti-Knock Index (AKI)
Transmission	UB80E eight-speed AT

US Environmental Protection Agency.

TABLE 2 Gear ratios for the Toyota Camry UB80E eight speed automatic transmission [14].

Gear	Ratio
First	5.250
Second	3.028
Third	1.950
Fourth	1.456
Fifth	1.220
Sixth	1.000
Seventh	0.808
Eighth	0.673
Reverse	4.014
Differential	2.802

US Environmental Protection Agency.

Test Site and Data Collection

Testing was performed in a light-duty engine dynamometer test cell located at the National Vehicle Fuels and Emissions Laboratory (NVFEL) in Ann Arbor, Michigan. This test cell was equipped with a Meidensha AC dynamometer and dual HBM torque sensors for data collection.

Test cell data acquisition and dynamometer control were performed by iTest, a software package developed by A&D Technology, Inc. Test cell data including temperatures, pressures, speed and torque were logged by iTest at a 10 Hz data rate. Engine and transmission ECU inputs and outputs were measured using RPECS, a hardware and software package for engine control and supplemental data acquisition developed by Southwest Research Institute. The RPECS system was synchronized to the engine speed and samples data in the crank angle domain. RPECS data was logged by iTest via an Ethernet connection and combined with other test cell data into a single output file.

Engine and Transmission System and Tethered Wire Harness

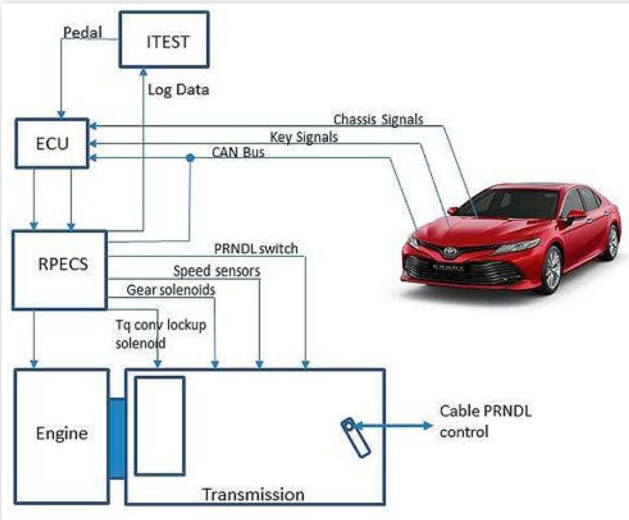
A production Toyota Camry 2.5L A25A-FKS engine was used to support this transmission testing. Specific details for the engine setup and testing are described in reference [1]. The chassis throttle pedal inputs were used to control engine torque during testing by duplicating the production vehicle throttle pedal signals and controlling them with the iTest dyno control.

In modern vehicles the engine control unit (ECU) is no longer the main computer. The ECU now requires communication with the body control module (BCM), the transmission control unit (TCU) and other various modules to monitor the entire vehicle operation (security, entry, key on, dash board signals, etc.). Because the ECU needs signals from these other modules to operate as calibrated by the manufacturer, these signals need to be extended to the test cell. The wiring harnesses connecting the ECU to the rest of the vehicle were lengthened to allow the engine and transmission in the dynamometer cell to be tethered to its vehicle chassis located outside the cell, as illustrated in Figure 1. Signal wires from the ECU to the engine and transmission were tapped to allow the signals to be monitored and utilized as needed. This ensured engine dynamometer testing could be performed without setting ECU/TCU fault codes and in a manner consistent with expected transmission operation in the vehicle.

Transmission Setup in the Test Cell

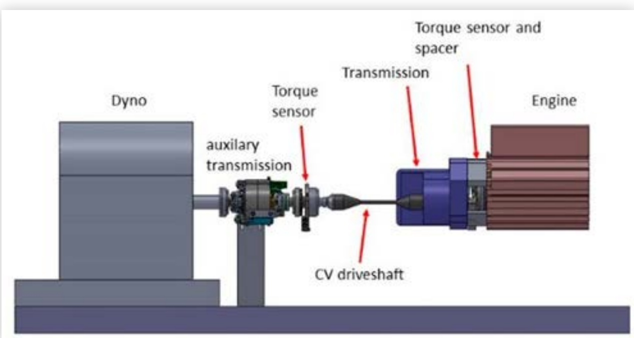
To incorporate the transmission into the test cell, a system was designed to instrument and record the output speed and torque from both the engine and transmission. This setup was similar to that used earlier by the EPA for transmission testing [4]. Figure 2 shows a model of the engine and transmission setup connection used in the test cell.

FIGURE 1 Schematic of the engine and transmission tethered to the vehicle with an extended wire harness.



US Environmental Protection Agency.

FIGURE 2 Test cell model with engine, transmission, and driveline main components.



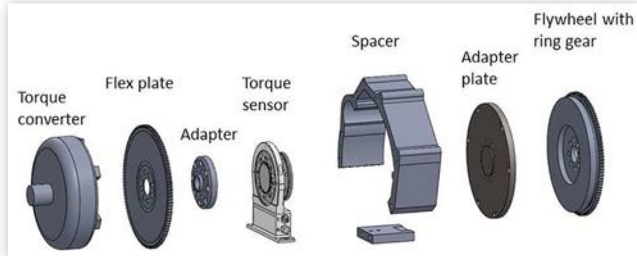
US Environmental Protection Agency.

As a part of the setup, a transmission input inline torque sensor was installed between the engine and transmission. This sensor needed to be placed in a way which maintained the concentricity and axial spacing of the transmission torque converter and engine flywheel. For this purpose, a custom flywheel was designed and built, incorporating the stock ring gear which allowed the engine to be started with the stock starter. Adapters were fabricated to connect the inline torque sensor to the engine flywheel and transmission flex-plate. The final design of this assembly is illustrated with an exploded view in Figure 3. Figure 4 shows the final engine and transmission assembly, along with the torque sensors, after installation into the test cell.

Transmission System and Control

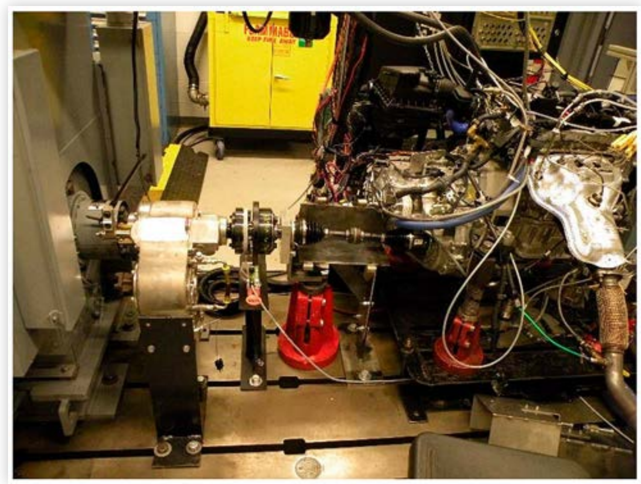
To properly control the transmission, maintain consistent operating temperatures, and record the appropriate data, a series of modifications and procedural steps were required.

FIGURE 3 Transmission inline torque sensor and spacers assembly.



US Environmental Protection Agency.

FIGURE 4 Final engine and transmission test cell installation.



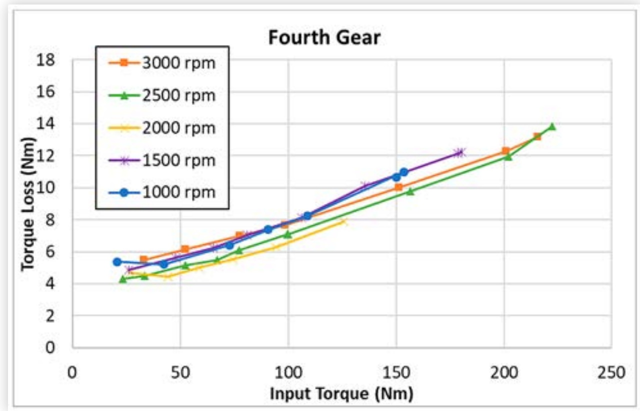
US Environmental Protection Agency.

1. **PRNDL Shift Controls**: The transmission shifting is controlled by the PRNDL shift lever, normally mounted in the vehicle. For the test cell setup, a second PRNDL lever was mounted in the test cell and tethered to the iTest console. This PRNDL was used in manual mode to select and hold the transmission in a specific gear.
2. **Transmission Fluid Cooling**: The transmission fluid cooling circuit was kept in the stock configuration, which consisted of an external liquid-to-liquid cooler with transmission fluid and engine coolant flowing through it. This configuration allowed the engine coolant to both heat and cool the transmission fluid to maintain a constant temperature.
3. **Torque converter clutch lockup**: The torque converter clutch is normally controlled by the transmission control unit (TCU). For this testing, the torque converter clutch was controlled directly by tapping into the wires connecting the clutch solenoid and the TCU. The signal coming out of the TCU was read by RPECS and a new signal was passed to the clutch solenoid that would allow either a locked or an unlocked clutch position as desired.
4. **Transmission gear solenoids*:*** To hold the transmission in a specific gear, the transmission gear

solenoids were controlled directly by the RPECS, which emulated the stock control signals.

5. **Auxiliary transmission**: The transmission was tested as a complete unit, including the differential gear assembly. With the differential in place, the transmission output torque is much higher than the test cell dynamometer can absorb, so an auxiliary transmission was installed between the transmission under test and the dynamometer. The auxiliary transmission had a 3.8:1 ratio to transform the speed and torque to a range that the dynamometer could absorb (see Figure 2).
6. **Driveshaft**: The test transmission was connected to the auxiliary transmission with the stock CV shaft (see Figure 2). The transmission differential was modified to lock the spider gears, so a single output shaft could be used.

FIGURE 5 Transmission torque losses in fourth gear, from points as measured.



US Environmental Protection Agency.

Transmission Testing Procedure

A series of tests were performed to determine the losses and operational characteristics of the transmission. The testing process was generally similar to that followed earlier by the EPA for transmission testing [4]. The test data collected included:

- total efficiency in each gear at a constant temperature
- estimation of the effect of temperature on torque losses
- torque converter K factor
- required idle torque
- transmission coastdown losses

The following subsections cover each test procedure and data set individually.

Transmission Torque Loss/Efficiency Testing

The transmission gearbox efficiency test was performed after the transmission was heated to a constant temperature between 85 °C and 90 °C. While at temperature, the transmission was held in a selected gear and the torque converter was locked up. The transmission input speed and load were controlled to a fixed value, and the speed and load of both the transmission input shaft and output shaft were logged at a 10 Hz sampling frequency for 10 seconds, then averaged to create a single average data point. From the collected data, the input torque loss was calculated according to Equation (1).

$$\text{Torque Loss} = \left(1 - \frac{\text{Torque Out} \times \text{Speed Out}}{\text{Torque In} \times \text{Speed In}}\right) \times \text{Torque In} \quad (1)$$

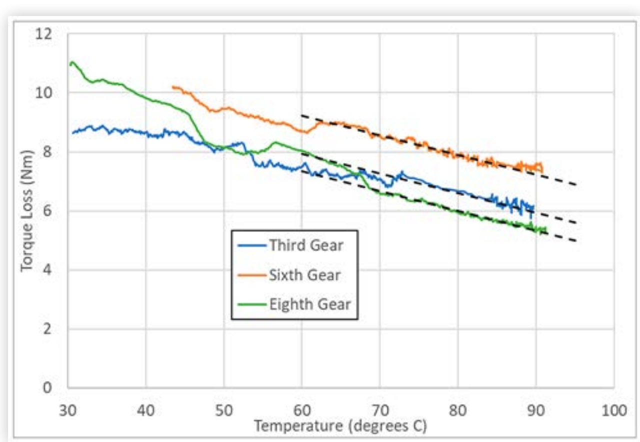
Each gear was tested over a range of transmission speeds and loads. An example of the data collected, in this case for fourth gear, is given in Figure 5. The remaining data collected, for gears one through eight, are shown in Appendix A.

Effect of Temperature on Transmission Torque Loss

To determine the effect of transmission fluid temperature changes on transmission torque loss, the transmission was operated at a constant speed, load, and gear over a period of time. Testing began at room temperature, and the transmission was warmed up; temperature, speed, and torque data were continuously recorded until a temperature of 90 °C was reached. The transmission was allowed to cool overnight and the test process was repeated using a total of three different transmission gears.

The resulting data are shown in Figure 6. Although the data shown in Figure 6 are somewhat irregular, over the range of 70 °C to 90 °C all three gears exhibit a torque loss reduction of about one Newton per fifteen degrees temperature increase.

FIGURE 6 Transmission torque losses as a function of temperature. Dashed lines indicate a reduction in torque loss of one Newton per 15 °C temperature increase.



US Environmental Protection Agency.

Torque Converter Stall Speed/K Factor Testing

A stall speed test was conducted by holding the transmission in a selected gear (sixth), with the torque converter unlocked and the transmission output speed held to zero. The transmission temperature was held constant near 90 °C. The pedal input signal to the engine was increased, increasing both engine speed and load, until the maximum signal was reached. At this point, the engine speed (the "stall speed") and shaft load were recorded. The data were used to determine the K factor (Equation 2), a semi-dimensionless parameter commonly used in industry to compare torque converters with the same diameter and fluid properties.

$$\text{K Factor} = \frac{\text{Input Speed}}{\sqrt{\text{Torque In}}} \quad (2)$$

Two tests were completed, with the resulting measurements shown in Table 4.

Idle Torque Testing

The engine torque required at idle to overcome transmission drag was also tested. This test was conducted by idling the engine, holding the transmission output speed to zero, unlocking the torque converter, and placing the transmission either in drive or in neutral. The transmission temperature was held constant at 85 °C. The results are shown in Table 5.

Coastdown Testing

Finally, testing was performed to measure the transmission output losses in neutral, so the contribution of the transmission to vehicle losses during a coastdown could be determined. For this testing, the engine was operated at idle and the transmission was commanded to neutral. The transmission was warmed up to 85 °C, then the dynamometer was set to 800 rpm. For testing, the dynamometer speed was decreased to 100 rpm over a 180-second timespan. Transmission output shaft torque and speed data were collected at a continuous rate. The results are shown in Figure 7.

TABLE 4 Torque converter stall test data.

Test	Stall Speed	Input Torque	K factor
1	2639 rpm	203.3 Nm	185.1 rpm/$\sqrt{}$Nm
2	2622 rpm	201.0 Nm	184.9 rpm/$\sqrt{}$Nm

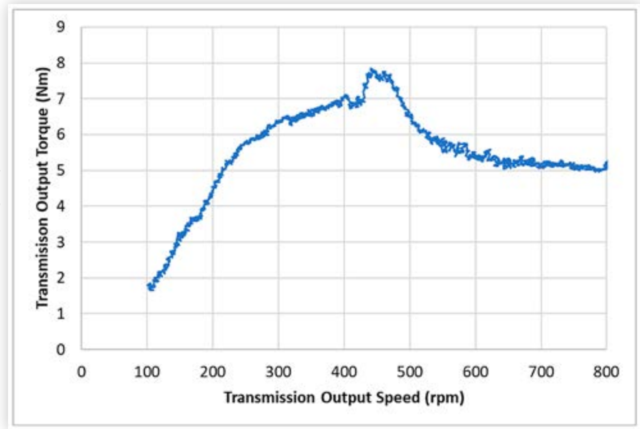
US Environmental Protection Agency.

TABLE 5 Idle torque test data.

Condition	Engine Speed	Engine Torque
Drive	601 rpm	15.8 Nm
Neutral	654 rpm	2.1 Nm

US Environmental Protection Agency.

FIGURE 7 Transmission coastdown drag.



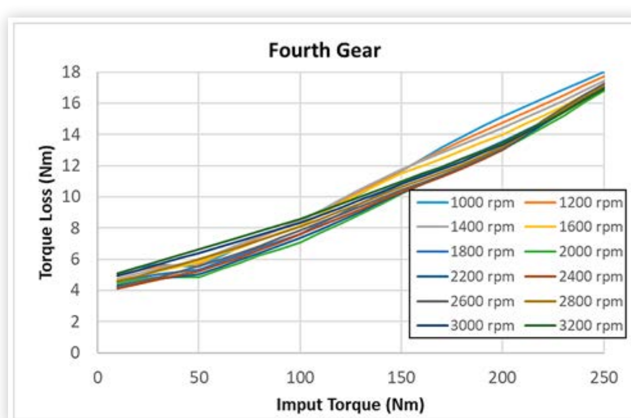
US Environmental Protection Agency.

Creating Transmission Data Inputs for ALPHA

The torque loss test data from the transmission was processed to create a smooth, consistent torque loss map to use as a modeling input. The process used was similar to that also used for engine speed-torque-fuel flow surfaces, which is described in more detail in reference [6]. For each gear a surface was fitted in MATLAB using GRIDFIT, a surface-fitting algorithm that balances the stiffness of the resulting surface and the goodness of fit with regard to the input data. This approach possesses many advantages over the more direct interpolation of the test data [18].

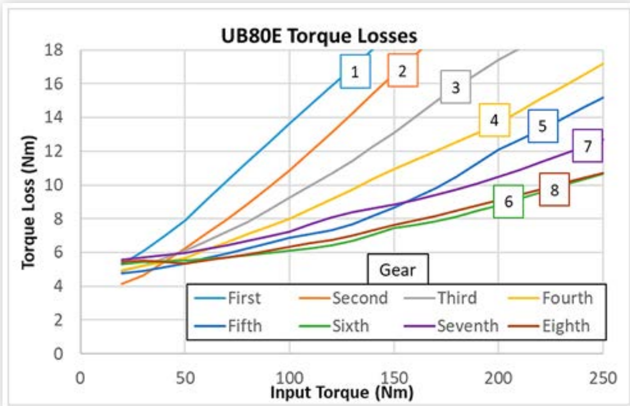
The surface fitting algorithm resulted in a smooth and consistent set of data for each gear, based on the test results. An example of the processed torque losses, in this case for fourth gear, is shown in Figure 8. The curves shown in this figure were derived from the raw test data shown in Figure 5.

FIGURE 8 Processed transmission torque losses in fourth gear, from 1000 rpm to 3200 rpm input shaft speed. The curves shown here were derived from the data shown in Figure 5.



US Environmental Protection Agency.

FIGURE 9 Average UB80E transmission torque losses in all gears, averaged from 1000 rpm to 3200 rpm input shaft speed.



As seen in Figure 8, the torque loss over the range of speeds from 1000 rpm to 3200 rpm is fairly consistent as a function of input torque. In fact, for all gears, 90% of the data are within ±1.0 Nm of the average value at that gear and input torque. The data points with the highest deviation from the average are those at the “corners” of the map, at or near the highest speeds and/or loads.

For visual convenience, the approximate losses for each of the eight gears can be displayed as the average of all losses across the range of speeds from 1000 rpm to 3200 rpm, as shown in Figure 9. Although the curves shown do not exactly match processed data across the entire speed range, they are generally representative of the losses in that gear.

The results roughly show losses decreasing from first through eighth gear, as loading on the differential decreases. Sixth gear, which has a 1:1 gear ratio, has the lowest losses.

In addition to the transmission torque loss maps, the ALPHA transmission description also includes the torque converter K factor, and torque converter lockup and transmission shift parameters which were characterized by analyzing vehicle dynamometer test data. More information on this characterization used in ALPHA can be found in references [22, 23].

Comparison to Other Transmissions

With the UB80E losses characterized, the torque loss data collected from this transmission can be compared to data collected earlier for other transmissions. For this paper, two transmissions previously tested by the EPA were chosen for comparison. These were:

1. Another eight-speed transmission: the eight-speed Chrysler 845RE rear-wheel drive (RWD) transmission [3, 21].
2. Another front-wheel drive (FWD) transmission: the six-speed GM 6T40 front-wheel drive FWD transmission [2, 22].

TABLE 6 Comparison of gear ratios and torque limits for the Toyota UB80E eight-speed AT (from Table 2), Chrysler 845RE eight-speed AT [21], and GM 6T40 six-speed AT [22].

Gear Ratios	UB80E	845RE	6T40
First	5.250	4.717	4.584
Second	3.028	3.143	2.964
Third	1.950	2.106	1.912
Fourth	1.456	1.667	1.446
Fifth	1.220	1.285	1.000
Sixth	1.000	1.000	0.746
Seventh	0.808	0.893	-
Eighth	0.673	0.667	-
Reverse	4.014	3.295	2.940
Differential	2.802	-	2.89
Torque Capacity	280 Nm	450 Nm	240 Nm

US Environmental Protection Agency.

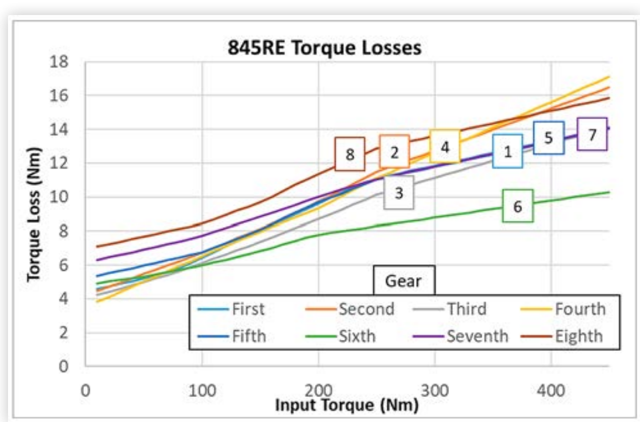
Both transmissions were tested using a dedicated transmission test stand, as described in the associated references [2, 3, 21, and 22], rather than the streamlined alternative benchmarking process used for the UB80E and described in more detail in reference [4]. However, the data collected via each process should be comparable, and reflective of losses in the unit during operation in the vehicle. For reference, the gear ratios and torque capacities for all three transmissions are given in Table 6.

Comparing the UB80E to Another Eight-Speed Transmission

The process used to characterize and display the average losses of the Toyota UB80E transmission were also used for the 845RE data, resulting in the values shown in Figure 10.

However, the 845RE is a RWD transmission, and thus the torque losses do not include the differential. Additionally, it has a higher torque capacity (450 Nm versus 280 Nm) than the UB80E, as shown in Table 6. To account for these

FIGURE 10 Average 845RE transmission torque losses in all gears, averaged from 1000 rpm to 3200 rpm input shaft speed.

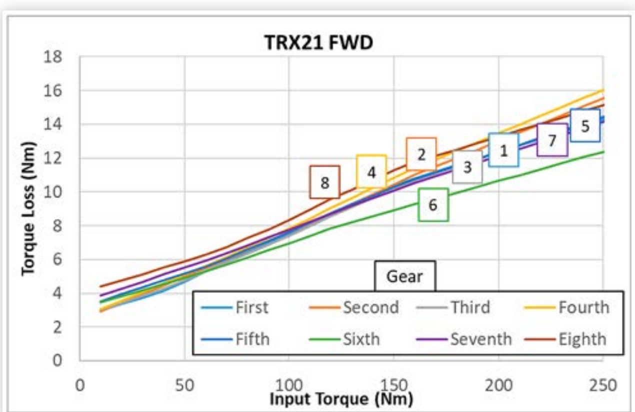


differences, the 845RE loss map was modified to account for both the absence of the differential and the higher torque capacity. Following the scaling rules in reference [23], the 845RE loss map was modified to mimic the effect of a torque capacity reduction from 450 Nm to 280 Nm. A 1.5% efficiency loss was also added to account for the differential losses in the UB80E that are not included within the 845RE data. The resulting loss map is a scaled version of what has been used previously in ALPHA modeling [12, 24]. To differentiate this from the original 845RE test data, the modified map was designated a "TRX21 FWD" transmission. The torque loss data for this transmission are shown in Figure 11.

The two transmissions - the TRX21 FWD (Figure 11) and the original UB80E (Figure 9) are now similar enough that the loss maps can be compared. The difference between each individual speed-load point for the two transmissions was calculated and the average difference across the 1000 rpm to 3200 rpm speed range is shown in Figure 12.

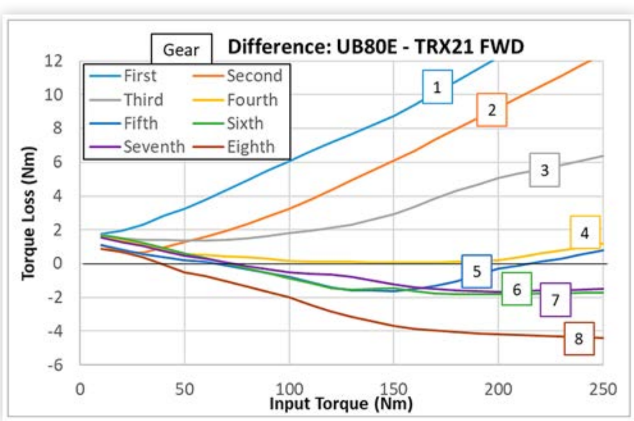
Figure 12 shows the differences between the two transmissions are roughly scaled by gear number, with first gear of the UB80E having substantially more losses than the TRX21, fourth gear being almost identical, and eighth gear of the UB80E having somewhat less losses than the TRX21. These differences may indicate that the constant 1.5% efficiency loss applied equally across all gears to account for the differential losses may be too simplistic and does not reflect the actual effect of the differential far each individual gear in this FWD transmission.

FIGURE 11 TRX21 FWD transmission torque losses in all gears, averaged from 1000 rpm to 3200 rpm input shaft speed. The loss map is modified from the 845RE by scaling and accounting for differential losses.



US Environmental Protection Agency.

FIGURE 12 Average torque loss differences between the TRX21 FWD and the UB80E transmission, gear by gear.



US Environmental Protection Agency.

Comparing the UB80E to Another FWD Transmission

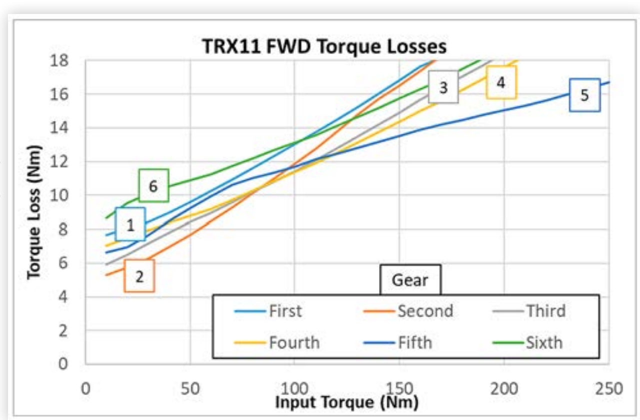
As a contrast, the UB80E was also compared to another FWD transmission, the 6T40, following a similar process. Like the UB80E, the 6T40 is a FWD transmission, and thus the losses associated with the differential are already included in the transmission loss map. However, the torque capacity of the 6T40 was 240 Nm (versus 280 Nm for the UB80E). As a result, the 6T40 losses were scaled to account for the difference, again using the process outlined in reference [23]. The final data for this scaled transmission, designated the "TRX11 FWD," are shown in Figure 13.

As Figure 13 shows, losses in the TRX11 are generally higher than the losses in the Toyota transmission shown in Figure 9. In addition, the gear-to-gear spread across the speed range indicated is tighter for the six gears of the 6T40 than it is for the eight gears of the UB80E transmission.

The TRX11 transmission losses can then be compared to the Toyota UB80E. As the TRX11 has only six gears, each gear in the TRX11 was compared to the gear from the UB80E that had the numerically closest ratio. Specifically, the first four gears of each transmission were directly compared, while fifth gear of the TRX11 (with the 1:1 gear ratio) was compared to sixth gear of the UB80E (also 1:1), and sixth gear of the TRX11 was compared to seventh gear of the UB80E. The results are shown in Figure 14.

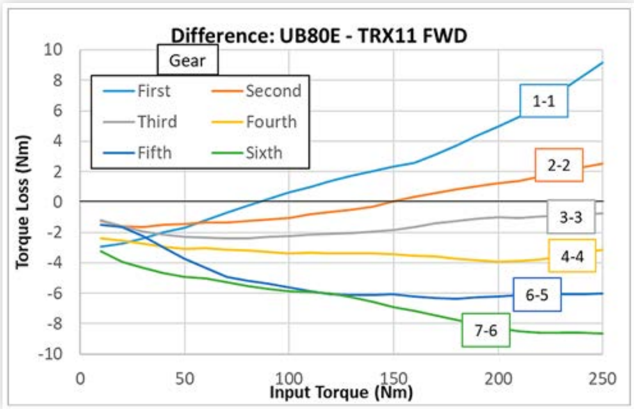
The TRX11 has significantly more losses than the UB80E for nearly the entire range of operation. In particular, the

FIGURE 13 TRX11 FWD transmission torque losses in all gears, averaged from 1000 rpm to 3200 rpm input shaft speed.



US Environmental Protection Agency.

FIGURE 14 Average torque loss differences between the TRX11 FWD and the UB80E transmission, gear by gear. Gears were matched to their counterpart with the nearest numeric ratio (see Table 6); the gear numbers compared are indicated in the figure.



losses from gears three through six of the TRX11 are higher than their counterpart at all loads, and losses for gears one and two are higher for torques below about 100-150 Nm.

Comparing Eight-Speed Transmissions over Regulatory Drive Cycles

The significance of the differences between transmissions, and the overall operational efficiency of the transmission, depends on the operation during the drive cycle. To investigate this further, a Toyota Camry equipped with the UB80E was driven on a chassis dynamometer over the urban dynamometer drive cycle (UDDS), highway cycle (HWFET) and high-speed high-acceleration cycle (US06). Dynamometer data and CAN-reported shift events were recorded. Figure 15 shows the gear shifts of the Toyota Camry during one example UDDS cycle.

FIGURE 15 Gear shifts during a UDDS cycle for a Toyota Camry equipped with a UB80E. Gear 0 represents park.

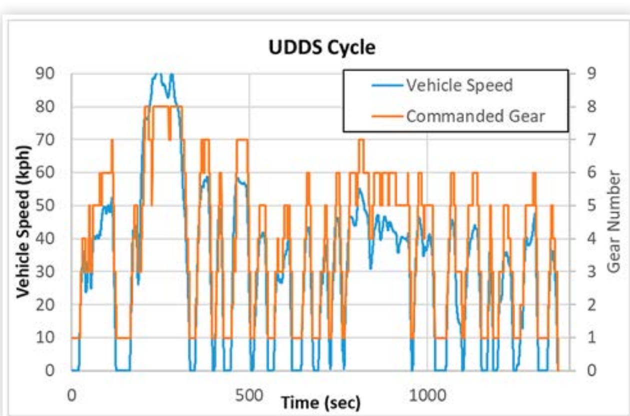


TABLE 7 The percent operation in each gear over one UDDS, HWFET, and US06 cycle, weighted by time and by energy delivered to the wheels.

Gear	UDDS % time	UDDS % energy	HWFET % time	HWFET % energy	US06 % time	US06 % energy
First	27.0%	3.8%	1.3%	0.4%	12.7%	4.7%
Second	4.7%	12.7%	0.4%	0.4%	4.3%	12.5%
Third	15.8%	27.8%	1.9%	3.1%	7.%	9.4%
Fourth	8.3%	14.2%	1.1%	2.6%	3.1%	2.6%
Fifth	17.6%	15.9%	2.0%	3.6%	5.3%	11.5%
Sixth	14.5%	10.0%	8.2%	15.9%	6.9%	13.7%
Seventh	6.1%	7.7%	18.1%	20.9%	13.3%	16.2%
Eighth	6.0%	8.0%	66.9%	53.0%	46.6%	29.4%

US Environmental Protection Agency.

As Figure 15 shows, the transmission is often in first gear. In fact, the transmission is in first gear about a quarter of the time during the cycle. However, much of that time is during idle, with the output shaft at zero speed, and thus the power losses in the transmission itself (ignoring the torque converter) are also zero.

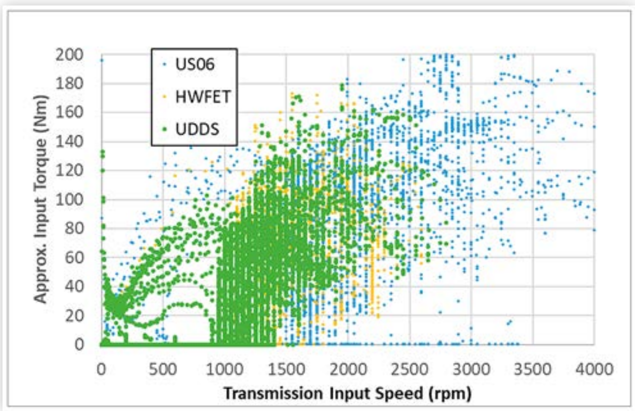
Rather than looking at time in gear, the operation of the transmission can be weighted by positive energy flow; in other words, the percent of energy delivered at the wheels while in each gear. To examine this, the transmission operation in each gear over each of the three cycles tested was both time- and energy-weighted. Results are given in Table 7. Note these example data were taken from specific dynamometer tests; data from additional tests would likely have some variability due to test-to-test variation.

Less than five percent of the energy was expended in first gear for all three of the cycles. Generally, most of the energy-weighted operation is concentrated in gears three through six (for the UDDS) or gears six through eight (for the HWFET and US06). This suggests that the fairly high difference between gears one and two of the UB80E and TRX21 (Figure 12) may not be significant during cycle operation. In contrast, the differences between the UB80E and the TRX11 in the higher gears are likely to be much more significant.

Table 7 establishes the usage of each gear over the three cycles, but not necessarily the actual speed and torque delivered to the transmission. To estimate this, a torque-speed operation map was created using the CAN-reported transmission input speed, recorded at 10 Hz, along with an estimate of the transmission input torque based on the dynamometer power at the wheels and an approximate driveline efficiency. The resulting speed and torque data are shown in Figure 16 for all three cycles.

Over the UDDS and HWFET cycles, 99% of the operation is below 125 Nm and 2500 rpm (for the US06, over 85% of the operation is below these values). In this operating zone, the torque loss for gears three through seven for the UB80E and TRX21 are within ±2 Nm of each other (as seen in Figure 12). These results suggest that when used over these regulatory cycles, the two transmissions are generally comparable.

FIGURE 16 Recorded 10 Hz transmission input speed and estimated input torque for the Toyota Camry across the UDDS (green), HWFET (yellow), and US06 (blue) cycles.



US Environmental Protection Agency.

Validation of the UB80E Transmission Data Using ALPHA Simulation

To more accurately compare transmissions over regulatory drive cycles, the transmissions were modeled within the ALPHA full-vehicle simulation tool and their performance simulated over the drive cycles. The first step in this process was to model the 2018 Toyota Camry and compare the emissions estimate from the ALPHA simulation to actual emission results recorded during chassis dynamometer testing of the vehicle.

An ALPHA model of the UB80E transmission was constructed using the transmission test results described previously, including the transmission loss maps, torque converter K factor, and coastdown losses. Additionally, transmission and torque converter operational strategies were recorded from chassis dynamometer testing and modeled in ALPHA. A model of the entire 2018 Camry vehicle was constructed by incorporating the transmission, engine efficiency data for the 2.5L A25A-FKS engine [1], and vehicle data from reference [25]. The pertinent vehicle parameters are given below in Table 8.

To validate this model, four repetitions of the UDDS and three repetitions of the HWFET test cycles were run in a chassis dynamometer and the CO_2 emissions recorded. Prior to driving these cycles on the dynamometer, prep cycles were run so that the transmission oil temperature reached at least 80 °C. For each cycle, an ALPHA validation was run using the recorded drive cycle, transmission shift times, and alternator loads as input to the simulations. The test data and corresponding ALPHA validations are shown in Table 9.

TABLE 8 2018 Toyota Camry vehicle parameters for regulatory testing.

Parameter	Value (English)	Value (SI)
Equivalent test weight (ETW)	3625 lbs-mass	1644 kg
Target A coefficient	25.587 lbs	113.82 N
Target B coefficient	0.19688 lbs/mph	0.5442 N/kph
Target C coefficient	0.016371 lbs/mph^2	0.02811 N/kph^2

US Environmental Protection Agency.

The ALPHA simulation results match the corresponding dynamometer test data within three percent for all but one run, and match within two percent, on average. While the ALPHA results tend to exhibit lower CO_2 emissions than the test data, overall the variation in simulation results tends to track similar variations in the dynamometer tests. Thus, the transmission model used in the ALPHA simulation is a reasonable representation of the physical UB80E transmission in the vehicle.

Comparison of Various Transmissions Using Vehicle Simulation

With a validated model of the Toyota UB80E transmission, the ALPHA simulation tool can be used to compare this transmission to other transmissions when operated over the regulatory cycles. To that end, ALPHA models were constructed using the 2018 Camry vehicle and the Camry engine data, along with four simulated FWD transmissions scaled to the torque capacity of the UB80E transmission [23]. The four transmissions were:

1. The original Toyota UB80E eight-speed transmission (Figure 9).

TABLE 9 CO_2 values for the 2018 Toyota Camry on UDDS and HWFET test cycles. ALPHA validation runs are compared against specific vehicle tests.

	Chassis Dyno Tests			ALPHA Validation			Comparison		
	UDDS bag 1	UDDS bag 2	HW FET	UDDS bag 1	UDDS bag 2	HW FET	UDDS bag 1	UDDS bag 2	HW FET
CO_2 values	g/mile	g/mile	g/mile	g/mile	g/mile	g/mile	% diff	% diff	% diff
Test 1	230.6	256.3	162.2	221.5	249.2	161.1	-3.9%	-2.8%	-0.7%
Test 2	224.9	254.9	160.3	219.7	249.7	160.1	-2.3%	-2.0%	-0.1%
Test 3	225.7	256.1	155.0	220.5	249.3	155.2	-2.3%	-2.6%	+0.1%
Test 4	227.5	254.0	--	222.8	249.9	--	-2.1%	-1.6%	--
Average	227.2	255.3	159.2	221.1	249.5	158.8	-2.7%	-2.3%	-0.3%
St. Dev	4.39	2.16	7.44	2.68	0.68	6.32			

US Environmental Protection Agency.

TABLE 10 CO_2 values from ALPHA simulations of 2018 Toyota Camry with four different transmissions, compared to the tested 2018 Camry in EPA's "Data on Cars used for Testing Fuel Economy" [25] in orange.

	FTP (city)		HWFET		Combined city-HW	
	g/mile CO_2	% diff from FE data	g/mile CO_2	% diff from FE data	g/mile CO_2	% diff from FE data
EPA TRX11 six-speed AT	268.0	9.1%	168.1	7.8%	223.0	8.7%
Toyota UB80E AT	252.0	2.6%	158.8	1.9%	210.1	2.4%
EPA TRX21 eight-speed AT	248.9	1.4%	158.8	1.8%	208.4	1.5%
2018 Toyota Camry in EPA Fuel Economy Data [25]	245.6	--	155.9	--	205.3	--
EPA TRX22 eight-speed AT	226.4	-7.8%	154.1	-1.2%	193.9	-5.5%

US Environmental Protection Agency.

2. An eight-speed transmission of a similar makeup, in this case the TRX21 transmission (Figure 10).
3. A transmission with fewer gears and higher losses, in this case the TRX11 six-speed transmission (Figure 12).
4. An eight-speed transmission with fewer losses, in this case a TRX22 eight-speed transmission [24], which is a modified version of the TRX21 transmission with a higher spread, more efficient oil pump, and other efficiency improvements which are may be possible in a future transmission package [3].

In addition to having different torque loss characteristics, each transmission also had its own torque converter lockup and shifting strategies. For each transmission, the operation of the vehicle was simulated over the Federal Test Procedure (the FTP, or "city" cycle) and the HWFET. Transmission shifting for each transmission was simulated using the ALPHAShift shift schedule algorithm [19]. The input cycle trace data, alternator loads, and engine cold-start penalty for the FTP were identical for all runs, so the simulated operation would be comparable across transmissions.

The cycle CO_2 results for all four transmissions are shown in Table 10, along with the combined city-highway results (weighted 55-45). These ALPHA results are compared to the test data from the FTP and HWFET CO_2 values from EPA's "Data on Cars used for Testing Fuel Economy" [25] for the 2018 Toyota Camry.

The simulation results show that the Toyota UB80E transmission CO_2 numbers are slightly higher than the test data from reference [25], but again match within two to three percent despite the incorporation of slightly different assumptions on shift schedule and warm-up rates than could be observed in an actual fuel economy test.

Significantly, the UB80E results and the TRX21 results are within one percent of each other on the combined city-highway cycle, despite there being multiple differences between the two transmissions, including different gear efficiencies, gear ratios, shift strategies, and torque converter lockup strategies. However, the differences between the transmissions are relatively small, and each contributes only a small fraction (under one percent) of the overall difference in CO_2. In particular, the gear-to-gear torque loss differences come very close to averaging out over the combined cycle, as suggested by Figure 12.

This compares with results from the other two simulated transmissions, which were chosen to demonstrate a range of CO_2 emissions performance potentially due to transmission selection. The TRX11 results are about seven percent higher than the UB80E/TRX21, and the TRX22 results are about seven percent lower than the UB80E/TRX21, demonstrating a fairly wide span of potential CO_2 emissions reduction due to transmission technology.

In addition to affecting CO_2 emissions, the choice of transmission also affects acceleration performance. However, specific acceleration metrics (for example, 0-60 mph [0-96 kph] times, or various passing times) can be affected in different ways depending on transmission gear ratios, shift times, and shift strategies, or, more generally, engine size and vehicle weight. In the simulations performed for this paper, multiple acceleration metrics were calculated and compared across vehicles with different transmissions. Generally, the TRX11 had longer acceleration times than the other transmissions, and the TRX22 shorter acceleration times. The additional changes in acceleration performance accentuates the difference between the two transmissions: the TRX11 has poorer performance for both acceleration and CO_2 emissions, and the TRX22 has better performance for both acceleration and CO_2 emissions.

Summary and Conclusions

EPA has benchmarked a Toyota Camry eight-speed UB80E transmission, recording torque losses in each gear over a range of speeds and loads. Additionally, the torque loss changes with temperature, torque converter K factor, idle torque, and coast-down drag were tested.

The benchmark testing was performed in an engine dynamometer test cell, using the vehicle engine along with the stock ECU and TCU, with both engine and transmission tethered to the vehicle. This test method is relatively quick and cost-effective compared to testing in a dedicated transmission test cell. Additionally, it ensures the transmission is controlled by the original manufacturer's calibration.

The torque losses for the eight-speed UB80E transmission were compared to an eight-speed Chrysler 845RE transmission previously tested by EPA. The 845RE transmission is a RWD unit (compared to the FWD UB80E) and has a higher torque capacity. Thus, the 845RE losses were scaled to account for the torque capacity difference, and additional losses were added to the torque loss map to represent the differential. This process produced a simulated FWD "TRX21" transmission map for comparison to the UB80E.

The resulting comparison shows gear-to-gear differences between the transmissions spanning a range of values. This suggests, unsurprisingly, that the differential efficiency is dependent on speed and torque, rather than being constant as assumed for the simulated FWD differential, and that adjusting the simulation to account for variable differential losses may bring the results more in line. However, the observed gear-to-gear differences are, on average, near zero, which also suggests that the UB80E and TRX21 transmissions are comparable.

Moreover, on the regulatory cycles, the bulk of the transmission operation occurs at speeds, loads, and gears where these transmissions have similar losses. In contrast, the UB80E was compared to a simulated FWD "TRX11" transmission, based on a GM six-speed 6T40 transmission. This comparison showed that the UB80E generally had lower losses than the TRX11 and performed better over the regulatory cycles.

The transmission data were used in ALPHA full-vehicle simulation runs to determine the effect on CO_2 emissions of using different transmissions. In this simulation, the UB80E and TRX21 transmissions performed similarly, with combined cycle CO_2 within one percent. Simulating other plausible transmissions - a less-efficient six-speed transmission and a potential future eight-speed transmission - showed a span of about 14% change in CO_2 emissions, highlighting the significant opportunity for more reductions due to transmission technology.

References

1. Kargul, J., Stuhldreher, M., Barba, D., Schenk, C. et al., "Benchmarking a 2018 Toyota Camry 2.5-Liter Atkinson Cycle Engine with Cooled-EGR," SAE Technical Paper 2019-01-0249, 2019, https://doi.org/10.4271/2019-01-0249.
2. Newman, K., Kargul, J., and Barba, D., "Benchmarking and Modeling of a Conventional Mid-Size Car Using ALPHA," SAE Technical Paper 2015-01-1140, 2015, https://doi.org/10.4271/2015-01-1140.
3. Moskalik, A., Hula, A., Barba, D., and Kargul, J., "Investigating the Effect of Advanced Automatic Transmissions on Fuel Consumption Using Vehicle Testing and Modeling," *SAE Int. J. Engines* 9(3):1916-1928, 2016, https://doi.org/10.4271/2016-01-1142.
4. Stuhldreher, M., Kim, Y., Kargul, J., Moskalik, A. et al., "Testing and Benchmarking a 2014 GM Silverado 6L80 Six Speed Automatic Transmission," SAE Technical Paper 2017-01-5020, 2017, https://doi.org/10.4271/2017-01-5020.
5. Stuhldreher, M., "Fuel Efficiency Mapping of a 2014 6-Cylinder GM EcoTec 4.3L Engine with Cylinder Deactivation," SAE Technical Paper 2016-01-0662, 2016, https://doi.org/10.4271/2016-01-0662.
6. Dekraker, P., Barba, D., Moskalik, A., and Butters, K., "Constructing Engine Maps for Full Vehicle Simulation Modeling," SAE Technical Paper 2018-01-1412, 2018, https://doi.org/10.4271/2018-01-1412.
7. Stuhldreher, M., Kargul, J., Barba, D., McDonald, J. et al., "Benchmarking a 2016 Honda Civic 1.5-Liter L15B7 Turbocharged Engine and Evaluating the Future Efficiency Potential of Turbocharged Engines," *SAE Int. J. Engines* 11(6):1273-1305, 2018, https://doi.org/10.4271/2018-01-0319.
8. Stuhldreher, M., Schenk, C., Brakora, J., Hawkins, D. et al., "Downsized Boosted Engine Benchmarking and Results," SAE Technical Paper 2015-01-1266, 2015, https://doi.org/10.4271/2015-01-1266.
9. Ellies, B., Schenk, C., and Dekraker, P., "Benchmarking and Hardware-in-the-Loop Operation of a 2014 MAZDA SkyActiv 2.0L 13:1 Compression Ratio Engine," SAE Technical Paper 2016-01-1007, 2016, https://doi.org/10.4271/2016-01-1007.
10. Lee, B., Lee, S., Cherry, J., Neam, A. et al., "Development of Advanced Light-Duty Powertrain and Hybrid Analysis Tool," SAE Technical Paper 2013-01-0808, 2013, https://doi.org/10.4271/2013-01-0808.
11. Dekraker, P., Stuhldreher, M., and Kim, Y., "Characterizing Factors Influencing SI Engine Transient Fuel Consumption for Vehicle Simulation in ALPHA," *SAE Int. J. Engines* 10(2):529-540, 2017, https://doi.org/10.4271/2017-01-0533.
12. Kargul, J., Moskalik, A., Barba, D., Newman, K. et al., "Estimating GHG Reduction from Combinations of Current Best-Available and Future Powertrain and Vehicle Technologies for a Midsized Car Using EPA's ALPHA Model," SAE Technical Paper 2016-01-0910, 2016, https://doi.org/10.4271/2016-01-0910.
13. U.S. Environmental Protection Agency and Department of Transportation, "2017 and Later Model Year Light-duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards: Final Rule," Federal Register 77(199), October 15, 2012.
14. Toyota USA, "2018 Camry Product Information," November 02, 2017, available at https://pressroom.toyota.com/2018-toyota-camry-product-info-sheet/, retrieved 5/9/2019.
15. Aisin AW Co., Ltd., "New Camry Equipped with 2-Motor FWD Hybrid Transmission, 8-Speed FWD Automatic Transmission and Dynamic Navigation," July 14, 2017, available at https://www.aisin-aw.co.jp/en/news/detail/2017714.html, retrieved 5/9/2019.
16. Aisin AW Co., Ltd., "Technology and Products: Product Lineup: AT," n.d., available at https://www.aisin-aw.co.jp/en/products/drivetrain/lineup/at.html, retrieved 5/9/2019.
17. Michikoshi, Y., Kusamoto, D., Ota, H., Ikemura, M. et al., "Toyota New TNGA High-Efficiency Eight-Speed Automatic Transmission Direct Shift-8AT for FWD Vehicles," SAE Technical Paper 2017-01-1093, 2017, https://doi.org/10.4271/2017-01-1093.

18. D'Errico, J.R., "Surface Fitting Using Gridfit," 2016. Information available at: https://www.mathworks.com/matlabcentral/fileexchange/8998-surface-fitting-using-gridfit.

19. Newman, K., Kargul, J., and Barba, D., "Development and Testing of an Automatic Transmission Shift Schedule Algorithm for Vehicle Simulation," *SAE Int. J. Engines* 8(3):1417-1427, 2015, https://doi.org/10.4271/2015-01-1142.

20. Newman, K. and Dekraker, P., "Modeling the Effects of Transmission Gear Count, Ratio Progression, and Final Drive Ratio on Fuel Economy and Performance Using ALPHA," SAE Technical Paper 2016-01-1143, 2016, https://doi.org/10.4271/2016-01-1143.

21. 2014 FCA HFE 845RE Transmission Mapping - Test Data Package, Version 2019-04, Ann Arbor, MI: US EPA, National Vehicle and Fuel Emissions Laboratory, National Center for Advanced Technology, 2019, Available at https://www.epa.gov/vehicle-and-fuel-emissions-testing/benchmarking-advanced-low-emission-light-duty-vehicle-technology.

22. 2013 GM 6T40 Transmission Mapping - Test Data Package, Version 2019-0,. Ann Arbor, MI: US EPA, National Vehicle and Fuel Emissions Laboratory, National Center for Advanced Technology, 2019, Available at https://www.epa.gov/vehicle-and-fuel-emissions-testing/benchmarking-advanced-low-emission-light-duty-vehicle-technology.

23. Dekraker, P., Kargul, J., Moskalik, A., Newman, K. et al., "Fleet-Level Modeling of Real World Factors Influencing Greenhouse Gas Emission Simulation in ALPHA," *SAE Int. J. Fuels Lubr.* 10(1):217-235, 2017, https://doi.org/10.4271/2017-01-0899.

24. Moskalik, A., Bolon, K., Newman, K., and Cherry, J., "Representing GHG Reduction Technologies in the Future Fleet with Full Vehicle Simulation," *SAE Int. J. Fuels Lubr.* 11(4):469-482, 2018, https://doi.org/10.4271/2018-01-1273.

25. US EPA, "Data on Cars Used for Testing Fuel Economy," https://www.epa.gov/compliance-and-fuel-economy-data/data-cars-used-testing-fuel-economy.

Contact Information

Andrew Moskalik
National Center for Advanced Technology
US EPA - National Vehicle and Fuel Emissions Laboratory
2565 Plymouth Rd., Ann Arbor MI 48105
moskalik.andew@epa.gov

Mark Stuhldreher
National Center for Advanced Technology
US EPA - National Vehicle and Fuels Emissions Laboratory
2565 Plymouth Rd., Ann Arbor MI 48105
stuhldreher.mark@epa.gov

Acknowledgments

The authors would like to thank Karla Butters, Brian Olson, Raymond Kondel, and Greg Davis, in the National Center of Advanced Technology at the National Vehicle and Fuel Emissions Laboratory for their assistance and contributions.

Disclaimer

Definitions/Abbreviations

6T40 - designation for the GM FWD six-speed transmission

845RE - designation for the FCA RWD eight-speed transmission

ALPHA - Advanced Light-duty Powertrain and Hybrid Analysis

AT - automatic transmission

BCM - body control module

CAN - controlled area network

CV - constant velocity half-shaft

CVT - continuously variable transmission

ECU - engine control unit

EPA - Environmental Protection Agency

ETW - equivalent test weight

FWD - front wheel drive

FTP - Federal Test Procedure - the "city" cycle with a cold start

GHG - greenhouse gas

HWFET - Highway Fuel Economy Test, the "highway cycle"

iTest - test cell data acquisition and dynamometer control software

K factor - semi-dimensionless parameter used to compare torque converters

NCAT - National Center for Advanced Technology

NVFEL - National Vehicle and Fuel Emissions Laboratory

PRNDL - park, reverse, neutral, drive, low gear selector

RPECS - Rapid Prototyping Engine Control Unit

RWD - rear wheel drive

TCU - transmission control unit

TRX11 - designation for a scaled six-speed transmission

TRX21 - designation for a scaled eight-speed transmission

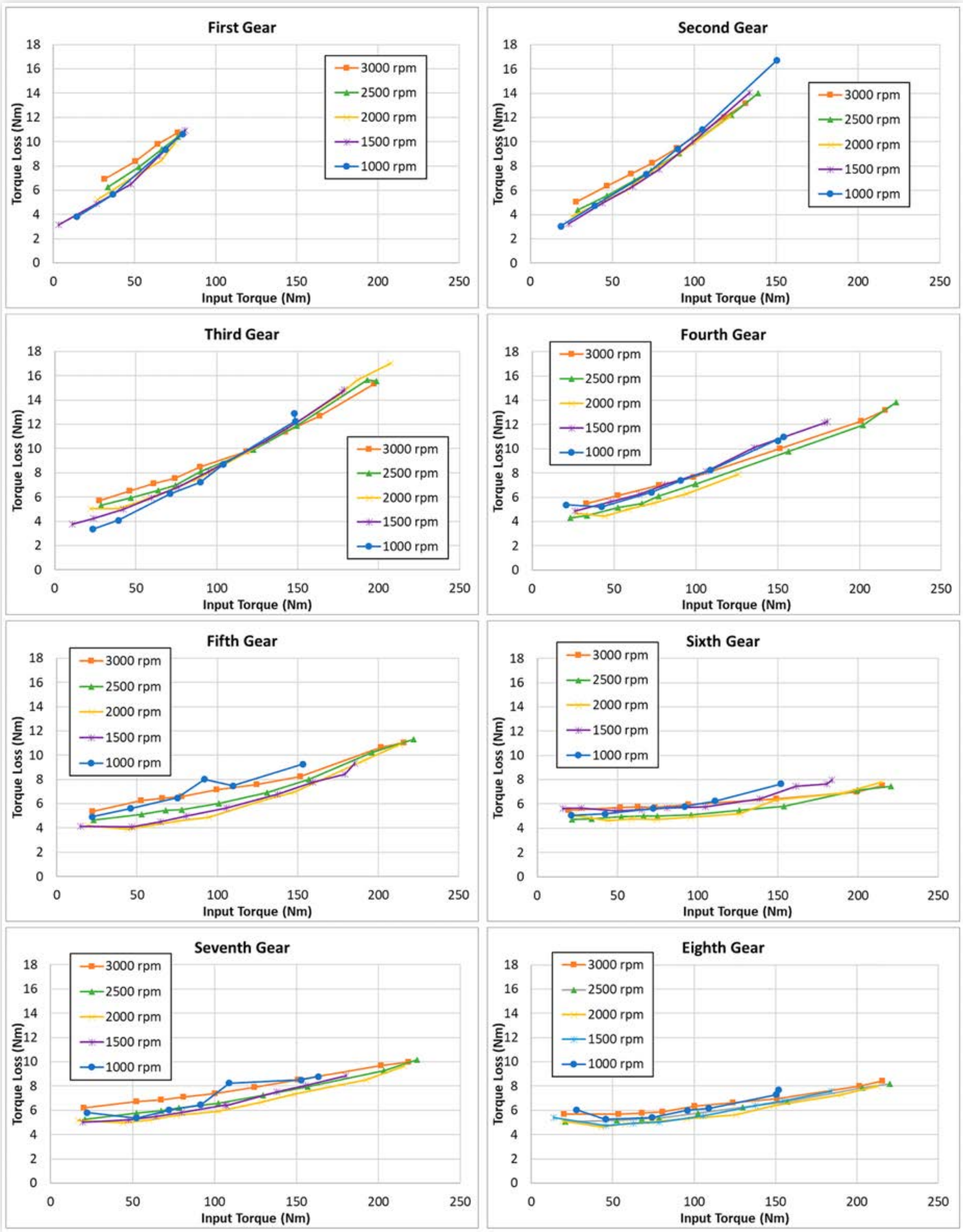
TRX22 - designation for a scaled eight-speed transmission with advanced efficiency improvements

UB80E - designation for the Toyota FWD eight-speed transmission

UDDS - Urban Dynamometer Drive Cycle, the first two bags of the "city cycle" with a warm start

US06 - high-speed and high-acceleration dynamometer cycle

Appendix A: UB80E Torque Loss Data, All Gears



ISSN 0148-7191