

Investigating the Effect of Advanced Automatic Transmissions on Fuel Consumption Using Vehicle Testing and Modeling

Andrew Moskalik, Aaron Hula, Daniel Barba, and John Kargul
US Environmental Protection Agency

ABSTRACT

In preparation for the midterm evaluation (MTE) of the 2022-2025 Light-Duty Greenhouse Gas (LD GHG) emissions standards, the Environmental Protection Agency (EPA) is refining and revalidating their Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool using newly acquired data from model year 2013-2015 engines and vehicles. ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types with different powertrain technologies, showing realistic vehicle behavior, and auditing of all internal energy flows in the model.

As part of the validation of ALPHA, the EPA obtained model year 2014 Dodge Chargers equipped with 3.6 liter V6 engines and either a NAG1 five-speed automatic transmission or an 845RE eight-speed automatic transmission. Vehicles were tested on a chassis dynamometer; test results showed eight-speed vehicles averaging 6.5% reduction in unadjusted combined city-highway fuel consumption compared to five-speed vehicles. In addition, an 845RE eight-speed transmission was obtained and tested in a standalone transmission test rig. The measured transmission parameters were used in ALPHA to simulate the behavior and fuel consumption of the eight-speed Dodge Charger. A companion model for the five-speed Charger was also constructed; the resulting simulated fuel consumption for both vehicles closely matched the test results.

This paper uses the validated ALPHA model to predict the effectiveness improvement of real-world transmissions over a baseline circa 2008 four-speed transmission, and to predict further improvements possible from future eight-speed transmissions. To that end, transmission models for a four-speed automatic transmission and future eight-speed automatic transmissions were constructed, and ALPHA was used to predict the fuel consumption differences of a Dodge Charger equipped with these transmissions. A fuel consumption reduction of over 12% was predicted when comparing a future eight-speed transmission to a baseline four-speed. Predicted fuel consumption reduction was over 16% when the engines were resized to maintain a constant acceleration performance.

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INTRODUCTION

Increasing powertrain efficiency is a primary path manufacturers have available for reducing fuel consumption (and thus GHG emissions). In general, increasing powertrain efficiency can be accomplished by increasing engine efficiency, increasing transmission efficiency, or altering transmission shift strategy so the engine operates nearer its peak efficiency more often.

Transmission technology is a significant portion of the potential reduction in fuel usage for advanced vehicles. Automatic transmission systems can be altered to

- Contain more gears with a wider gear ratio span, allowing the engine to operate closer to its peak efficiency more often.
- Upshift earlier, so the engine operates in a more efficient portion of its map when possible.

- Lock up the torque converter earlier, resulting in fewer losses in the torque converter.
- Reduce frictional and other energy losses in the transmission itself.

Previous studies have estimated a range of potential reduction in fuel usage. For example, Argonne National Labs (ANL) examined the potential reduction in fuel consumption when installing an advanced transmission in a midsize vehicle equipped with a four-cylinder spark ignited direct injection (SIDI) engine. [1] The study predicted a 6.9% improvement in fuel consumption when comparing a 96% efficient eight-speed automatic transmission with early torque converter (TC) lockup to a 92% efficient five-speed transmission without early TC lockup. For a port fuel injected (PFI) engine, the same transmission comparison yielded a 9.0% improvement in fuel consumption. [2]

Likewise, the National Research Council (NRC) investigated the potential effects of advanced transmissions on fuel consumption in their 2015 report. [3] They examined the potential reduction in fuel

consumption for six- and eight-speed automatic transmissions with improved controls, early TC lockup, and a high efficiency gearbox. The NRC concluded that, compared to an unimproved four-speed transmission, the most likely potential reduction in fuel consumption ranged from 10.9% to 13.1%.

In the original analysis of LD GHG emissions standards, EPA created a lumped parameter model (LPM) to estimate the CO₂ reduction (and thus fuel consumption) of various technologies. For a standard or large car containing a high-efficiency eight-speed transmission with early upshift and early TC lockup, the LPM predicts 17.8%-17.9% CO₂ reduction over a base four-speed, when paired with a base PFI engine with no cam phasing. [4]

In preparation for the midterm evaluation (MTE) of the 2022-2025 Light-Duty Greenhouse Gas (LD GHG) emissions standards, the EPA performed a new examination of the potential for transmission technology to reduce GHG emissions (and fuel consumption), using a two-pronged approach. First, current vehicles were experimentally tested to determine the effect of advanced transmission technology. Then, the experimental data were used to computationally predict the effect of wider transmission changes.

For this paper, the computational tool used was EPA's Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) model. ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types with different powertrain technologies, showing realistic vehicle behavior. Powertrain components (such as engines or transmissions) are individually parameterized and can be exchanged within the model. ALPHA audits all internal energy flows through the powertrain model during simulation runs, and the energy audit is used both to monitor losses and to confirm an accurate energy-balanced simulation. Vehicle data were used to calibrate and validate this model. [5] Then, using the calibrated model, the potential effectiveness of a range of transmissions could be extrapolated.

Vehicle Choice

The MY 2014 Dodge Charger was chosen as a test vehicle. The 3.6 liter V6 Charger was offered with two different transmissions: a NAG1 five-speed transmission in the SE trim package or an optional 845RE eight-speed transmission in the SXT trim package. The powertrains of these vehicles were otherwise identical, with the same engines, rear end ratios, and tires. This unique offering presented an ideal case study to examine the effect of an improved transmission on vehicle fuel economy and operation. Vehicle and transmission specifications for the two Charger trim packages are given in [Table 1](#).

There are some significant differences, noted in [Table 1](#), between the vehicles with the five- and eight-speed transmission. The eight-speed has a much wider gear spread with a higher reported label fuel economy. In addition, performance testing of Chargers with the same powertrains (but from earlier model years) by *Car and Driver* showed the eight-speed had noticeably better acceleration performance than the five-speed, gaining 0.5 seconds in 0-60 time and 0.4 seconds over the quarter mile. [6] [7]

Table 1. Vehicle and transmission specifications (including gear ratios) and acceleration performance metrics for the five-speed and eight-speed Dodge Chargers trim packages. Acceleration times are from *Car and Driver* road tests. [6] [7]

	Five-Speed	Eight-Speed
Trim package	SE	SXT
Transmission	NAG1 (5-speed)	845RE (8-speed)
Engine	3.6-Liter V6 24-Valve VVT Engine	
Rear End Ratio	2.65	
Drive	Rear wheel drive (RWD)	
Gear 1	3.59	4.71
Gear 2	2.19	3.14
Gear 3	1.41	2.10
Gear 4	1.00	1.67
Gear 5	0.83	1.29
Gear 6	N/A	1.00
Gear 7	N/A	0.84
Gear 8	N/A	0.67
Label FE	18/27/21	19/31/23
0 to 60 mph time	7.2 sec [6]	6.7 sec [7]
30-50 mph time	3.7 sec	3.8 sec
50-70 mph time	5.3 sec	4.5 sec
¼ mile time	15.7 sec @ 94mph	15.3 sec @ 95 mph

TEST PROCEDURE

Four vehicles were leased and tested for this project. All were MY 2014 Dodge Chargers with the same 3.6L engine, final drive ratio, and body style. Two vehicles had five-speed transmissions and the other two had eight-speed transmissions. The vehicle basics are shown in [Table 2](#).

Table 2. The four test vehicles, including vehicle identification number (VIN). The tires and equivalent test weight (ETW) are identical for all vehicles.

	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4
Trim package	SE		SXT	
Transmission	NAG1 (5-speed)		845RE (8-speed)	
ETW	4250 lbs			
Tires	P215/65R17 BSW All Season Tires			
VIN	2C3CDXBG 4EH108228	2C3CDXBG 0EH180351	2C3CDXHG 1EH232271	2C3CDXBG XE284491

Test Site and Vehicle Prep

Vehicle testing took place in the same chassis dynamometer test cell at the EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL). Testing occurred at various times over a one-year period from June of 2014 to July of 2015.

The vehicles were fueled with Tier 2 certification gasoline and put into rolls mode by the manufacturer to allow testing on the 2WD dynamometer while avoiding fault codes related to the front wheels remaining stationary. One vehicle (vehicle 3) arrived new, and was driven until there were 1000 miles on the odometer as a break in to ensure engine and transmission frictional performance had stabilized. The remaining vehicles were received with 16,000 to 25,000 miles on the odometer.

A road load derivation was performed on vehicle 1 (a five-speed vehicle) based on the target coefficients obtained from the manufacturer. The targets, and resulting set coefficients, are given in [Table 3](#). Once this derivation was completed, all vehicles were tested with the same derived set coefficients, so that the dynamometer loading on all vehicle powertrains was identical.

Table 3. Road Loads: Target coefficients for vehicle 1 and set coefficients derived therefrom. The same set coefficients were used to load all vehicles.

	A (lbs)	B (lbs/mph)	C (lbs/mph ²)
Target Coefficients	26.37	0.8544	0.01152
Set Coefficients	9.68	0.3981	0.01547

Test Methodology (Cycle Testing)

Multiple 4-bag FTP, HWFET, and US06 tests were recorded. The test procedures were performed according to the test cycle description, 40 CFR part 86 or 40 CFR part 1065. During each cycle, bag emissions and summary dynamometer data were taken, and used to determine cycle fuel economy.

In addition, data were obtained from the onboard vehicle CAN system during many, although not all, of the test cycles. CAN data were recorded at a 10 Hz frequency using the OBD port, a commercially available ValueCAN connector, and a laptop running “Krakspy,” a custom data-logging software developed by engineers at the EPA. The CAN data recorded included vehicle-reported engine speed, engine torque, vehicle speed, transmission gear, and other engine and transmission parameters which varied from vehicle to vehicle.

RESULTS

At least two sets of tests (FTP, HWFET, and US06 test cycles) were run on each vehicle. Two additional tests were run on vehicles 1 and 3, to make a total of six tests for the five-speed Chargers and six tests for the eight-speed Chargers. The unadjusted fuel economy results for the twelve test runs of the three test cycles are given in Table 4, along with the combined city/highway fuel economy, calculated using a weighted 55%/45% average of the FTP and HWFET.

Table 4. Fuel economy test results for four vehicles, including the FTP, HWFET, US06, and the 55/45 combined city/highway. The average fuel economy for each vehicle type (five-speed and eight-speed) is also given, as well as the differences between the average results.

Vehicle number	Vehicle type	FTP (mpg)	HWFET (mpg)	US06 (mpg)	Combined (mpg)
1	5-spd	21.32	36.98	23.88	26.34
1	5-spd	20.92	36.76	23.38	25.95
1	5-spd	21.51	37.04	23.76	26.51
1	5-spd	21.67	36.75	23.88	26.58
2	5-spd	21.55	37.25	23.99	26.59
2	5-spd	21.75	37.46	24.00	26.80
AVG 5-speed	5-spd	21.45	37.04	23.81	26.46
3	8-spd	22.69	40.39	24.90	28.26
3	8-spd	22.34	40.01	24.68	27.88
3	8-spd	22.68	39.97	25.46	28.16
3	8-spd	22.57	40.15	25.10	28.11
4	8-spd	23.28	39.81	25.99	28.63
4	8-spd	23.21	40.31	25.83	28.68
AVG 8-speed	8-spd	22.79	40.11	25.33	28.29
DIFF (mpg)	5-spd to 8-spd	1.34	3.07	1.51	1.82
Percent increase in FE	5-spd to 8-spd	6.3%	8.3%	6.4%	6.9%
Percent reduction in fuel consump.	5-spd to 8-spd	5.9%	7.7%	6.0%	6.5%

Table 4 also shows the average results for the five- and eight-speed vehicles, and a comparison between them, both in increase in fuel economy and decrease in fuel consumption. The fuel consumption of

the eight-speed vehicle was lower by 5.9% over the FTP, 7.7% over the highway cycle, and 6.0% over the US06. Fuel consumption for the combined city and highway cycles was lower by 6.5%.

Engine Operation and Efficiencies

Insight into the reasons for the decrease in fuel consumption in the eight-speed vehicle can be gained by estimating and comparing the average efficiency of the engine to that of the drivetrain over each of the cycles for each vehicle. To estimate efficiencies, the total cycle energy was calculated for each test run in three locations along the powertrain. The energy calculations were restricted to “positive engine power” points, where the engine was producing torque and the vehicle was moving (i.e., not at idle). The three energy quantities calculated were:

1. The *fuel energy* going into the engine over each cycle, which was calculated by using the total CO₂ emissions data for the cycle, then subtracting the proportion of fuel used at idle (estimated from CAN manifold airflow data).
2. The *engine shaft energy* (going out of the engine and into the drivetrain) over each cycle, which was calculated by multiplying the engine speed and torque obtained from the vehicle CAN, then integrating over the cycle. Only positive engine power points were counted.
3. The *vehicle energy* going out of the drivetrain over each cycle, which was calculated by multiplying the vehicle speed and load obtained from the recorded dynamometer data, then integrating over the cycle. Only positive vehicle power was counted; negative power (braking energy) was ignored.

From these cycle energy values, the approximate engine efficiency and drivetrain efficiency were calculated for each cycle, with engine efficiency = (engine shaft energy)/(fuel energy) and drivetrain efficiency = (vehicle energy)/(engine shaft energy). Although the drivetrain efficiency reflects losses in the entire drivetrain from the torque converter through the drive tires, the *difference* in efficiency between the five- and eight-speed vehicles should be due only to the components that are different: the transmission and torque converter.

This methodology should produce reasonable approximations for engine and drivetrain efficiencies, although not necessarily exact values. In particular, the methodology relies on CAN signals, which, while useful, can have some limitations, as they lack resolution and calibration of dedicated sensors. In addition, CAN-reported torque may be less accurate than measured torque (although prior studies have shown that the information used by the ECM to estimate torque has a good correlation to actual measured engine torque [8]).

Thus, the engine shaft energy is likely approximate, as are the resulting efficiencies. However, since the data are from vehicles with the same engine and ECU, and the methodology is applied in the same fashion to all vehicles, the comparison of values between five- and eight-speed vehicles should result in a reasonable estimation of the relative change in efficiencies between vehicles.

In addition, all three quantities - fuel energy, engine shaft energy, and vehicle energy - were not available from all 36 test runs represented in Table 4 (six repeats of three cycles on two types of vehicles). The quantities were available for three repeats of the three cycles on both transmission versions; however, the final average fuel consumption data of the three repeat tests were slightly different than for the full suite of six repeat tests.

For the cycles where all signals were available, the engine and drivetrain efficiencies were calculated using the methodology above, and averaged for both five- and eight-speed vehicles. The average resulting efficiencies, as well as the differences between the five-speed and eight-speed results, are given in Table 5 for each test cycle. Because of the differences in data sets, there is a slight discrepancy between the total efficiency differences in Table 5 (which is based on three repeat tests) and the overall fuel consumption differences in Table 4 (which is based on six repeat tests).

Table 5. Engine and drivetrain efficiencies for each transmission over the FTP, HWFET, US06: Energy-weighted averages are of “positive engine power” points, where the engine was producing torque and the vehicle was not at idle.

Cycle	Parameter	Five-speed	Eight-speed	Difference	% Difference
FTP	Engine Effic.	20.6%	21.4%	0.8%	+3.8%
	Drivetrain Effic.	69.6%	72.3%	2.7%	+3.8%
HWFET	Engine Effic.	25.5%	27.0%	1.5%	+5.9%
	Drivetrain Effic.	73.6%	74.5%	0.9%	+1.2%
US06	Engine Effic.	30.2%	31.1%	0.9%	+3.0%
	Drivetrain Effic.	75.4%	78.8%	3.4%	+4.5%

In Table 5, the final column (% Difference) reflects the relative reduction in energy losses in the engine and the drivetrain. On the FTP, the engine and drivetrain (i.e., transmission) have approximately similar increases in efficiency, while on the HWFET the increase in engine efficiency makes up the bulk of the efficiency improvement. Over the US06, the drivetrain is responsible for a slightly larger proportion of the efficiency increase than the engine.

The efficiency values given are approximate, but should demonstrate proportionally where the increases in efficiency are realized. These values give an important insight into the causes of the decrease in fuel consumption in the eight-speed vehicle:

- An increase in the *engine efficiency* is likely due to changing operational points of the engine (due to the additional gears and/or earlier upshift strategy), resulting in more operation closer to peak engine efficiency points.
- An increase in *drivetrain efficiency* is likely due to an earlier lock up in the torque converter (resulting in fewer losses in the torque converter), and/or reduced frictional and other energy losses in the transmission itself.

The increase in engine efficiency is typically due to operation at lower speeds and higher torques (i.e., “downspeeding”), which is an area of the engine map that tends to be more efficient. To determine if this was indeed the case, the CAN-reported engine speed and torque were examined for each cycle for both the five-speed and eight-speed vehicles.

In general, high power operational points have high fuel consumption, and have a more significant effect on cycle fuel consumption than low-power points. Thus, to emphasize the higher fuel consumption points, the CAN-reported engine speed and torque points were energy-weighted. For all “positive engine power” points (where the engine was producing torque and the vehicle was not at idle), the energy-weighted engine speed and torque were then averaged; the average values for the three cycles are given in Table 6.

Table 6. Energy-weighted average engine operation points for each transmission over the FTP, HWFET, US06: Energy-weighted averages are of “positive engine power” points, where the engine was producing torque and the vehicle was not at idle

Cycle	Parameter	Five-speed	Eight-speed	Difference	% Difference
FTP	Speed (rpm)	1479	1363	-116 rpm	-8%
	Torque (Nm)	101	105	+5 Nm	+5%
HWFET	Speed (rpm)	1493	1215	-278 rpm	-19%
	Torque (Nm)	99	116	+17 Nm	+18%
US06	Speed (rpm)	2153	1874	-280 rpm	-13%
	Torque (Nm)	172	186	+14 Nm	+7%

The data in Table 6 clearly show that the engine in eight-speed transmission vehicles indeed runs at a lower speed when compared with the five-speed transmission vehicles. Moreover, on the HWFET cycle, the change in the energy-weighted average values is fairly substantial, which is reflected by the large engine efficiency gain shown in Table 5.

STANDALONE TRANSMISSION TESTING

In an effort to further understand the operation of the eight-speed transmission, a separate vehicle equipped with the 3.6 liter V6 and 845RE eight-speed transmission was procured, instrumented, and driven for 3000 miles as a break-in. During break-in, the transmission solenoid control signals were mapped and the main line pressures were recorded as a function of gear, speed, and load. After break-in, the transmission was removed and tested on a standalone transmission test stand.

Once in the test stand, the torque converter was locked to eliminate its associated losses. The transmission parameters were externally adjusted: the solenoids were manually controlled to choose the appropriate gear, the line pressure was externally regulated to match in-vehicle values, and the oil temperature was independently controlled. The TCM was not included in the controls in order to avoid any hard-coded operation range limitations.

For testing, zero-load spin losses were recorded at three oil temperatures (35 °C, 60 °C, and 100 °C) for all eight gears over a range of speeds. In addition, efficiency testing was performed in each gear over a range of input speeds and torques, and at the same three oil temperatures. Steady-state modes were taken at discrete speed and load points; in general these points were between 1000 and 4000 rpm input speed and up to 250 Nm input torque.