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Vehicle Component Benchmarking Using a Chassis Dynamometer

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ABSTRACT

The benchmarking study described in this paper uses data from chassis dynamometer testing to determine the efficiency and operation of vehicle driveline components. A robust test procedure was created that can be followed with no a priori knowledge of component performance, nor additional instrumentation installed in the vehicle.

To develop the procedure, a 2013 Chevrolet Malibu was tested on a chassis dynamometer. Dynamometer data, emissions data, and data from the vehicle controller area network (CAN) bus were used to construct efficiency maps for the engine and transmission. These maps were compared to maps of the same components produced from standalone component benchmarking, resulting in a good match between results from in-vehicle and standalone testing.

The benchmarking methodology was extended to a 2013 Mercedes E350 diesel vehicle. Dynamometer, emissions, and CAN data were used to construct efficiency maps and operation strategies for the engine and transmission. These maps were used in EPA's Advanced Light-duty Powertrain and Hybrid Analysis Tool (ALPHA) vehicle model, which showed a good agreement between the modeled fuel economy and dynamometer test results.

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INTRODUCTION

During the development of the Light-Duty Green-house Gas (LD GHG) and Corporate Average Fuel Economy (CAFE) standards for the years 2017-2025, EPA utilized a 2011 light-duty vehicle simulation study from the global engineering consulting firm, Ricardo, Inc. This study provided a round of full-scale vehicle simulations to predict the effectiveness of future advanced technologies.

The 2017-2025 LD GHG rule required that a comprehensive advanced technology review, known as the midterm evaluation, be performed to assess any potential changes to the cost and the effectiveness of advanced technologies available to manufacturers. In preparation for this evaluation, EPA is planning to use a full vehicle simulation model, called the Advanced Light-duty Powertrain and Hybrid Analysis Tool (ALPHA) [1] to supplement and expand upon the previous study used during the Federal rulemaking. ALPHA will be used to confirm and update, where necessary, efficiency data from the previous study, such as the latest efficiencies of advanced downsized turbo and naturally aspirated engines. It may also be used to understand effectiveness contributions from advanced technologies not considered during the original Federal rulemaking, such as continuously variable transmissions (CVTs) and clean diesel engines.

To simulate drive cycle performance, the ALPHA model requires various vehicle parameters as inputs, including vehicle inertia, road loads, component efficiencies, and control strategy information. Many of these parameters can be determined by benchmarking production vehicles and their component. A full characterization of each component separately can produce very accurate and reliable efficiency maps. However, standalone component characterization can be costly and time-consuming. In addition, although parameters such as temperature can be closely monitored and controlled in standalone testing, they are typically not controlled by the test engineer and/or unknown in an actual vehicle cycle test. This makes the application of the standalone test data problematic, as additional information would be required to match standalone test data to vehicle operation conditions.

As an alternative, data on vehicle component performance and efficiency can be determined by operating the vehicle on a chassis dynamometer and extracting data on each component in the drive system. In-vehicle measurements have been performed previously to determine engine efficiencies [2,3,4] or transmission/driveline power losses [5,6].

Obtaining component efficiencies within the vehicle rather than from standalone component testing can introduce some additional uncertainties into the results, as some quantities must be calculated rather than directly measured, and parameters such as temperatures or control pressures often cannot be directly controlled by the test engineer. However, the process is less time-consuming and expensive, and has the potential advantage that, with a well-designed test, the vehicle operating parameters such as temperatures or control pressures are automatically maintained by the vehicle within the bounds of normal operation.

The in-vehicle engine efficiency testing has primarily been done using a torque sensor installed on the output of the engine, either as an additional module [2] or on the engine flywheel [3]. However, modern engine control modules (ECMs) contain software models that estimate engine torque output; these models have been shown to have a good correlation to actual measured engine torque [7].

This paper outlines a process whereby the engine torque and other information is extracted from the onboard vehicle CAN messages and used to construct engine efficiency maps and transmission power loss maps. The intent of this investigation is to create a robust test procedure that can be followed with no a priori knowledge of component performance, nor additional instrumentation installed in the vehicle.

BENCHMARKING PROCEDURE DEVELOPMENT: 2013 CHEVROLET MALIBU

For this benchmarking process development, a 2013 Chevrolet Malibu was procured. The Malibu has a conventional powertrain, with a 2.5 liter I4 naturally aspirated gasoline direct injection engine and six-speed automatic transmission.

Standalone Component Characterization

Both the engine and transmission were removed from the vehicle and separately characterized by FEV Inc. Standalone component testing gave a good opportunity to closely monitor and control engine and transmission parameters that affect efficiency. The efficiency maps produced in the engine test cells were then used in ALPHA to estimate the fuel efficiency of the vehicle [8]. These efficiency maps can also be compared to those produced in chassis dynamometer testing to determine the relative quality of the in-vehicle maps.

The engine was tested in an engine dynamometer cell using 87 ((R+M)/2) Octane E10 gasoline. The engine was warmed up and tested at steady state over a range of speeds and loads. At each point, engine parameters including speed, load, fuel flow, and temperature were monitored and recorded. Coolant temperature entering the engine was monitored and controlled to 70C, and the alternator output was limited to under 2 Amps. The data from this testing were used to construct an efficiency map for the engine, shown in Figure 1.

Likewise, the transmission (including a locked torque converter and the final drive ratio) was installed in a test stand and tested. The transmission solenoid commands were mapped and manually controlled during testing, and the transmission line pressure was externally regulated.

Zero-load spin losses were recorded at two line pressures (5 bar and 10 bar) and two oil temperatures (37C and 93C) for all six gears. This testing indicated that the 37C oil added from 3 Nm (in first gear) to 5 Nm (in sixth gear) of additional spin losses to the transmission when compared to the 93C testing. Likewise, the 10 bar line pressure added around 2 Nm spin loss in all gears when compared to the 5 bar testing. These figures are significant, as both line pressure and fluid temperature vary in chassis testing depending on the operating conditions of the vehicle.

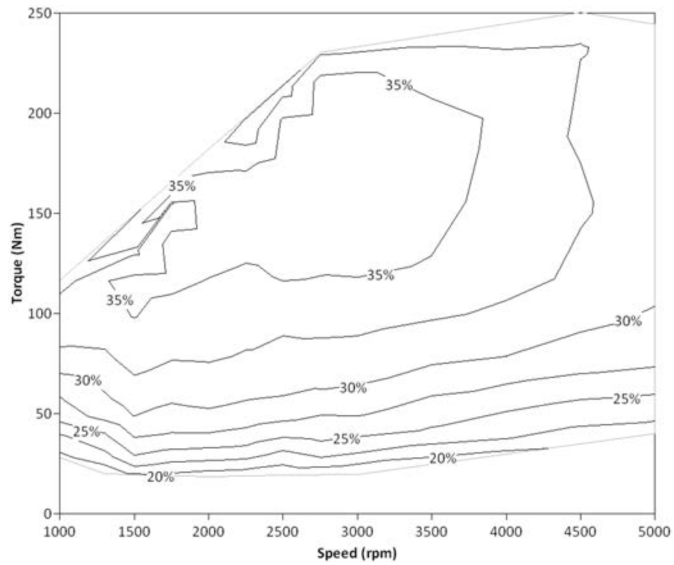

Figure 1. Efficiency map for the 2.5 liter engine in the 2013 Chevrolet Malibu developed from standalone component testing.

Finally, the transmission was tested in each gear over a range of input speeds and torques. Steady-state modes were taken with a constant line pressure (10 bar) and two oil temperatures (37C and 93C). Input and output speeds and loads were recorded, and used to determine the efficiency of the transmission at each point. The final data provided an efficiency map for the transmission as a function of speed, load, gear, and temperature.

The data from the standalone transmission testing were used to construct a torque loss map for comparison to the data collected from in-vehicle testing. To simplify the data collection process in the vehicle, the standalone component test data taken at 93C were averaged over a reasonable input speed range (1000 rpm to 3000 rpm) to produce the average torque loss over a range of speeds. For this transmission, over a range of engine speeds from 1000 rpm to 3000 rpm, the change in expected torque is on average ±0.1 Nm for first gear, ±0.5 Nm for second gear, ±0.7 Nm for third gear, ±2.2 Nm for fourth gear, ±1.1 Nm for fifth gear, and ±3.8 Nm for sixth gear. The final map is shown in Figure 2.

The final torque loss map in Figure 2 shows a generally tight cluster of torque loss across all six gears, with fifth gear (at 1:1 ratio) showing slightly less loss at high input torque. Although averaging the losses over all speeds introduces some error into the transmission efficiency calculation, particularly in the higher gears, it was judged that the decrease in complexity of the in-vehicle data collection process, and the decrease in complexity of the complexity of the resulting map, warranted the simplification. In addition, although detailed transmission maps including speed are in general preferred, it has been shown that judiciously simplifying the transmission losses, even to the point of using a single efficiency number for all speeds, loads, and gears, still produces reasonable results when used for modeling purposes [9]. Thus, the less aggressive simplification of averaging losses at different speeds was judged reasonable.

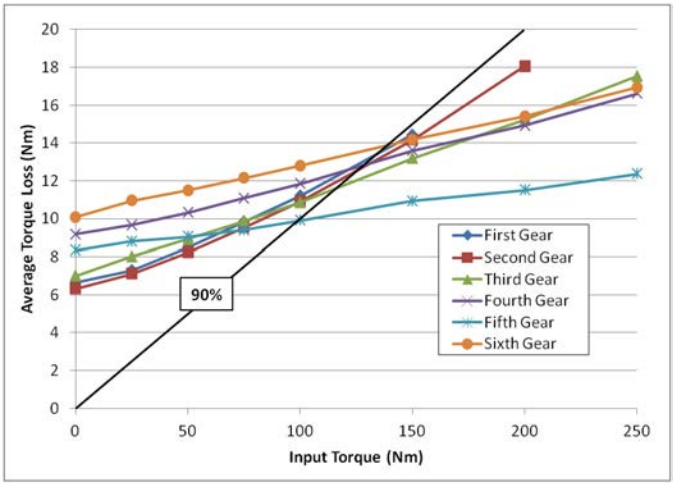

Figure 2. Torque loss map for the six-speed transmission in the 2013 Chevrolet Malibu, developed from standalone component testing at 93C and 10 bar line pressure. The 90% efficiency line is included for reference. These losses include the final drive gears, and have been averaged over 1000 rpm to 3000 rpm.

Component Characterization Using Vehicle Dynamometer Data: Testing

The vehicle was re-assembled and instrumented; the additional sensors installed included half-shaft torque sensors, a fuel flow meter, transmission fluid temperature and line pressure, and engine oil and coolant temperatures. A data collection system was installed to record data from the additional sensors as well as the vehicle CAN bus. A pedal controller was installed which would send a fixed pedal signal to the ECU, bypassing the actual physical pedal.

The vehicle was filled with 87 ((R+M)/2) Octane E10 gasoline, warmed up, and run in a chassis dynamometer over a steady-state matrix of vehicle speeds (in 10 mph increments) and pedal positions (at 10% pedal increments). At each matrix point, the paddle shifters were used to shift the vehicle into all obtainable transmission gears.

At each combination of gear, speed, and load, the vehicle was operated for a minimum of 30 seconds, allowing the engine and driveline to reach a steady-state operating condition. Data were continuously collected at a 10 Hz rate; these data included, among other items:

- Engine output speed and torque (from CAN)
- Manifold air flow (MAF) and equivalence ratio (from CAN)
- Fuel flow (from installed meter)
- Alternator current and voltage (from installed sensors)
- Engine coolant temperature (from CAN)
- Transmission input speed (from CAN)
- Transmission gear (from CAN)
- Transmission oil temperature (from CAN)
- Transmission line pressure (from installed sensor)
- Half-shaft torques (from installed sensors)
- Vehicle speed and load (from dynamometer)
- Emissions, including CO_2 (from test cell analyzer)

For each steady-state point, a 10 to 20 second segment of data was chosen where vehicle and sensor operation had stabilized and the coefficients of variation were low. Each measured signal was averaged over the chosen segment to get final results.

Engine Efficiency Calculation

The fuel flow rate was calculated for each steady-state point from the MAF and equivalence ratio reported by the vehicle CAN. This was compared to the fuel flow calculated from a carbon balance on the measured emissions, and to the fuel flow reported by the installed fuel meter during that time segment. In general, the match among the three measurement methods was good. Because the intent of this process was to develop a procedure requiring minimal instrumentation, the fuel flow derived from the MAF was used to develop a final efficiency map.

The efficiency map was developed based on the engine speed, engine torque, and the fuel flow calculated from the MAF reported by the vehicle CAN. By virtue of being developed within the vehicle, this map contains losses associated with the alternator. For the Malibu, the average in-vehicle current draw was 17 Amps (compared to a cap of 2 Amps in the standalone engine testing). For modeling purposes, an engine map containing realistic in-use alternator losses may be preferable to one where the losses are capped at an arbitrary threshold.

However, to keep the efficiency map consistent, and to directly compare to the test cell efficiency map (Figure 1) where the alternator current was limited, the efficiency calculation was adjusted to emulate the lower alternator load. To do this, the alternator electrical power was measured, and the equivalent input mechanical power was calculated, assuming a constant 66% efficient alternator. From this, the effective engine-out torque was calculated as the sum of the CAN-reported crankshaft torque and the torque required to power the alternator; this torque was then used to calculate overall engine efficiency. The final map is shown in Figure 3.

The efficiency map developed in-vehicle does not quite extend to the full mapping boundaries shown in Figure 1. In particular, the high speed and high load sections of the map are not included in Figure 3. In this in-vehicle procedure, the testing was focused on the areas of the map most likely to be used in the UDDS and HWFET cycles, and no attempt was made to ensure maximum torque and speed points were reached. If full map coverage were important, the matrix of test points could be judiciously re-evaluated to expand coverage.

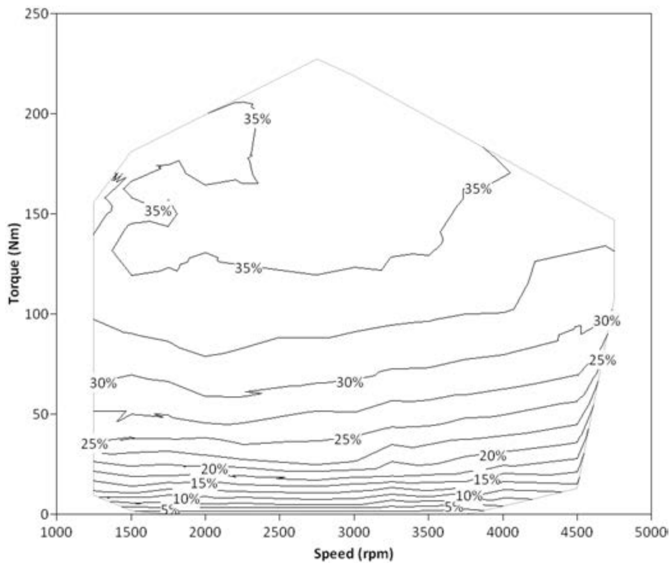

Figure 3. 2013 Chevrolet Malibu engine map developed in the vehicle using the chassis dynamometer.

The engine efficiency map developed from in-vehicle testing (Figure 3) was compared to the efficiency map developed for the same engine tested on an engine dynamometer (Figure 1). The comparison was in general very good (Figure 4), with a near-perfect match across most of the map. Although not directly controlled by the test engineer during the in-vehicle testing, the CAN-reported engine coolant temperature remained between 90C and 100C through most of the map.

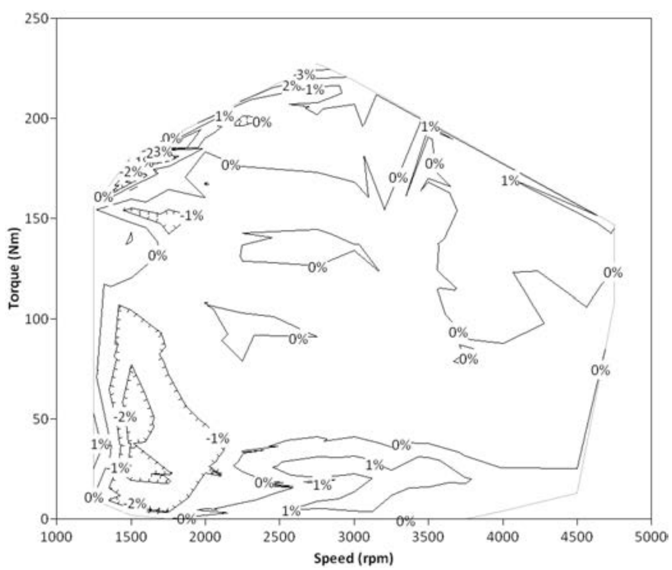

Figure 4. Comparison between the 2013 Chevrolet Malibu engine map developed in a dynamometer test cell and the engine map developed in the vehicle using the chassis dynamometer.

The only points on the map with significant differences between in-vehicle and standalone component test results lie near the wide open throttle (WOT) line at lower speeds, and along the 1500 rpm line at lower torques. It was observed during vehicle testing that the engine operated at higher load than the WOT line reported from standalone engine testing [8]. It is suspected that the data obtained from the standalone engine testing may be in error in this area. Likewise, there is some indication that the in-vehicle efficiency data obtained at 1500 rpm may be more accurate than the standalone engine testing data.

Driveline Loss Calculation

Before calculating efficiencies for the transmission, the losses in the driveline between the transmission neutral disconnect and the chassis dynamometer were estimated. The vehicle transmission was placed in neutral and the vehicle dynamometer was operated through a range of speeds. The load required to rotate the driveline and tires was recorded as a function of vehicle speed. As might be expected, the load was very close to the difference between the loads calculated using the coastdown (target) coefficients (representing the total losses of the vehicle when coasting in neutral) and the dynamometer (set) coefficients (representing the losses not included in the driveline).

Although there would be some additional losses as driving torque increased, it was assumed that the neutral load would remain reasonably representative of the driving losses from the neutral disconnect in the transmission though the tires. The driveline power loss was then calculated as the product of vehicle speed and the measured load.

Transmission Efficiency Calculation

To determine the power losses in the transmission for each point in the steady-state matrix of vehicle speeds and pedal positions, the power output of the engine (calculated from the CAN-reported engine speed and load) and the power at the wheels (calculated from the CAN-reported vehicle speed and dynamometer load) was determined. CAN-reported vehicle speed was used in preference to dynamometer speed to exclude tire slippage from the calculation.

To determine the power input to the transmission at each steady-state point, the transmission input speed was compared to the engine output speed to determine the torque converter speed ratio. It was found that the torque converter was rarely locked; however, it was assumed that the torque ratio was very near one, so that the torque converter efficiency could be approximated by the torque converter speed ratio. In these cases, the transmission input power was calculated as the engine output power multiplied by the torque converter efficiency.

To determine the power output from the transmission, the experimentally determined driveline power loss found in the previous Driveline Loss Calculation section was added to the power at the wheels. Finally, the power lost in the transmission at each steady-state point was calculated as the difference between the power into and out of the transmission.

The losses for each of the six gears were converted into equivalent input torque losses. As the torque loss is nearly linear as a function of input torque (Figure 2), a simple linear regression was used to estimate the average torque loss as a function of input torque for each gear. An example (fourth gear) is given in Figure 5.

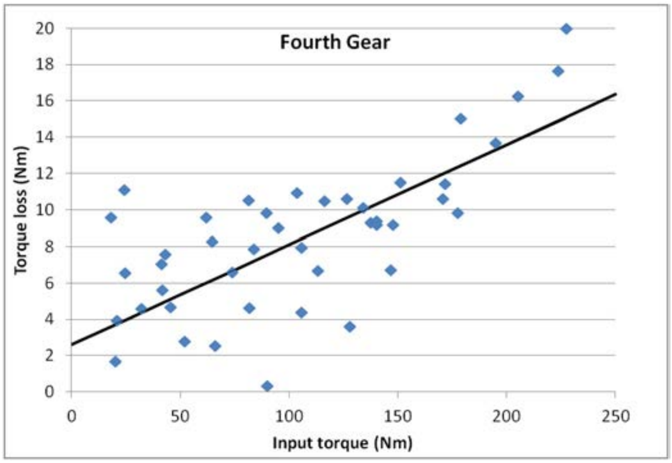

Figure 5. 2013 Chevrolet Malibu transmission losses (4th gear) developed in the vehicle using the chassis dynamometer. The solid line represents the best-fit linear regression.

The data for each transmission gear included a range of input speeds, which contributes to some of the observed scatter in Figure 5. Although the effect of speed could have been considered, it was decided to minimize the complexity of the map and average the torque loss over the range of tested speeds. This also avoids the confounding effect of the varying oil temperature and line pressure, which are not controlled by the test engineer.

For all six gears, this process resulted in the torque losses shown in Figure 6.

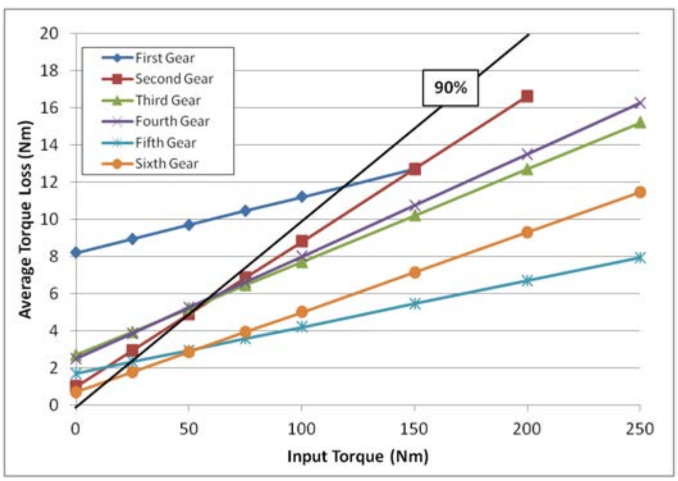

Figure 6. 2013 Chevrolet Malibu average transmission losses for all gears developed in the vehicle using the chassis dynamometer. The 90% efficiency line (running near the second gear losses) is included for reference. These losses do not include portions of the transmission downstream from the neutral disconnect, such as the final drive gears.

It should be noted that there are significant differences in the testing conditions between the in-vehicle transmission testing results (Figure 6) and the component test rig transmission testing results (Figure 2). Three of these differences can be significant:

1. Spin losses downstream from the neutral disconnect (for example, those associated with the final drive ratio) are not included in the in-vehicle test results shown in Figure 6, but are included in the standalone results shown in Figure 2.
2. Transmission oil temperatures vary over the in-vehicle test results shown in Figure 6, but are set to a constant 93C for the standalone results shown in Figure 2.
3. Line pressures vary over the in-vehicle test results shown in Figure 6, but are set to a constant 10 bar in the standalone results shown in Figure 2. The line pressure in first gear in the vehicle testing (Fig. 6) ran between 20 bar and 25 bar, which likely contributes to the higher torque losses in first.

To more accurately compare the results from the in-vehicle testing to the results from the standalone testing, the effects of these three differences were estimated and applied to the in-vehicle results.

Effect of Downstream Spin Losses

The standalone transmission testing was done using the entire transmission, from the locked torque converter through the final drive ratio to the half-shafts. In particular, this means that components downstream from the neutral disconnect contributed to measured transmission losses in the standalone testing (Figure 2), but not in the in-vehicle testing (Figure 6). Thus, on average, one would expect the transmission torque losses recorded in the vehicle to be lower than those recorded in standalone component testing.

To estimate the differences between the in-vehicle and standalone component test results due to the spin losses downstream from the neutral disconnect, torque sensors were installed on the vehicle half-shafts. The half-shafts represented the boundaries of the transmission during standalone testing. Thus, the torque measured on these sensors during the driveline loss testing (see the Driveline Loss Calculation section) should indicate the torque required to rotate the portions of the transmission downstream from the neutral disconnect, such as the final drive gears and associated seals and bearings. These losses are included in the standalone component testing results (Figure 2) but not the in-vehicle testing results (Figure 6).

During the driveline loss testing, the torque on the half-shafts in neutral was found to be approximately 0.12 Nm per kph of vehicle speed. It should be noted that this torque, being a function of speed, accounts for some of the averaged speed losses that were not explicitly included in the simplified transmission map show in Figure 2.

Effect of Varying Fluid Temperature and Line Pressure

Both the transmission oil temperature and line pressure varied during the in-vehicle testing. This introduced a significant uncertainty into the results when compared to the transmission testing in the standalone component testing. To compensate for the varying temperature and pressure during comparison of the in-vehicle and standalone results, temperature and pressure adjustment factors were calculated from the standalone zero-load spin loss tests.

Spin loss testing indicated that the transmission with 37C oil required an additional torque of 3 Nm (in first gear) to 5 Nm (in sixth gear) when compared to the 93C testing. Testing with 10 bar line pressure required an additional torque of around 2 Nm in all gears when compared to the 5 bar testing.

The losses as a function of temperature and pressure were linearly interpolated or extrapolated to estimate an average change per degree temperature or per bar pressure. In some cases, the level of adjustment could be quite significant. As an example, the line pressure in first gear in the vehicle testing ran between 20 bar and 25 bar, compared to the constant 10 bar maintained in the component testing. Extrapolating the 0.4 Nm of additional torque loss per bar of line pressure measured in the standalone testing gives an adjustment of 4 to 6 Nm for comparison purposes.

Comparison of Adjusted Transmission Losses

The in-vehicle transmission losses recorded were adjusted to reflect the estimated effect of line pressure and fluid temperature, and the measured spin losses downstream from the neutral disconnect were added in. This allowed a direct comparison between the in-vehicle results and those obtained from standalone component testing. This comparison is shown in Figure 7.

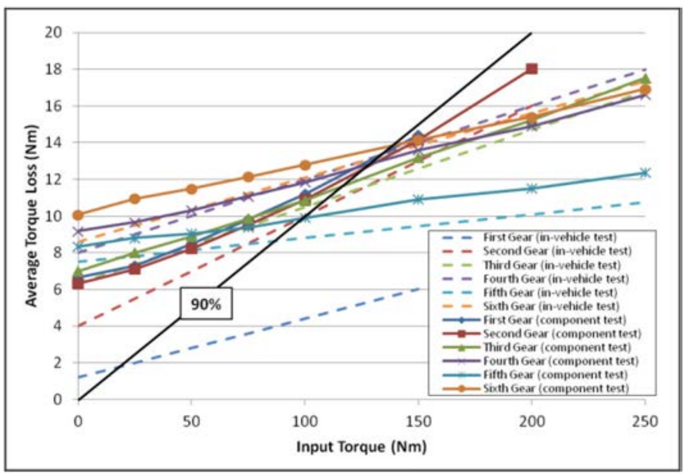

Figure 7. Component test results (Figure 2) compared to the in-vehicle test results (Figure 6) for transmission torque loss. The 90% efficiency line is included for reference. The in-vehicle test results have been adjusted to account for spin losses downstream from the neutral disconnect, fluid temperature, and line pressure.

Overall, the results from the vehicle test and the component rig test match quite well, with the exception of first gear. The differences between results for gears two through six are within 2 Nm for nearly all torques - typically within 1% of transmission efficiency for torques over 100 Nm and within 2% for torques over 50 Nm. The in-vehicle torque loss results for first gear are substantially lower than those measured in the standalone component testing, but this may be because the line pressure in first gear is quite high (over 20 bar), and the adjustment factor accounting for line pressure, which was extrapolated from 5 and 10 bar data, overcompensates for the line pressure effect. Thus, it is likely that the first gear discrepancy is more an effect of attempting to match in-vehicle test results to component test results than an issue with the underlying data.

Considering that the results in Figure 7 are averaged over a range of speeds, and that the effects of the differences due to pressure and temperature are linearly extrapolated from two distinct points, the match between in-vehicle and component test stand results is quite good.

Model Usage of Results

It should be noted that the raw in-vehicle testing losses (Figure 6) are likely more representative of the operation of the vehicle during actual cycle testing than the consistently controlled results shown in Figure 2. Temperature and line pressure in the in-vehicle results are variable, but controlled by the vehicle. Although, to simplify the comparison, temperature and pressure adjustment factors were applied to the in-vehicle results, accurate modeling would require the standalone testing results be adjusted to reflect actual vehicle operation parameters.

In addition, the in-vehicle process is internally consistent, in that although spin losses downstream from the neutral disconnect (from, for example, the final drive gears) are not included in the transmission losses (Figure 6), they are included in the neutral spin losses of the entire driveline. Thus, the transmission losses captured by in-vehicle testing can be directly used in models such as ALPHA which use the losses reflected by the coastdown (target) coefficients as input; component test results which include the downstream losses would have to be adjusted before use in ALPHA to avoid double-counting losses.

BENCHMARKING PROCEDURE APPLICATION: 2013 MERCEDES E350

The benchmarking of the 2013 Chevrolet Malibu demonstrated a good correlation between component efficiencies measured in standalone component testing and in-vehicle. The next step was to extend this in-vehicle benchmarking procedure to another vehicle where standalone component test results were not available.

The vehicle chosen was a 2013 Mercedes E350, with a 3.0 liter V6 turbodiesel engine and 7-speed automatic transmission. This vehicle was borrowed, so components could not be removed and additional sensors could not be added to the chassis. Therefore, to characterize the vehicle, it was necessary to rely on minimal instrumentation and testing within the chassis dynamometer test cell.

This vehicle was tested over FTP, HWFET, and US06 drive cycles. Fuel economy data were recorded, as well CAN data describing component behavior for use in later tuning of an ALPHA model [1,10].

Component Characterization Using Vehicle Dynamometer Data: Testing

A data collection system was installed in the E350 to record data from the dynamometer and vehicle CAN bus and a pedal controller was installed which would send a fixed pedal signal to the ECU, bypassing the actual physical pedal during the steady-state operation testing on the dynamometer. The vehicle was filled with certification diesel fuel, warmed up, and run in a chassis dynamometer over a steady-state matrix of vehicle speeds (in 10 mph increments) and pedal positions (at 10% pedal increments) similar to the way the Malibu was mapped, as described in previous sections of this paper. At each matrix point, the paddle shifters were used to shift the vehicle into all obtainable transmission gears.

At each point in the matrix, the vehicle was operated for a minimum of 30 seconds, allowing the engine and driveline to reach a steady-state operating condition. Data from the vehicle CAN, as well as emissions and dynamometer speed and load, were continuously collected for each point at a 10 Hz rate. From each steady-state operating point, a 10 to 20 second segment of data was chosen where vehicle and sensor operation characteristics had stabilized and the coefficients of variation were low. Each measured signal was averaged over the chosen segment to get final results.

Engine Efficiency Calculation

The fuel flow rate was calculated for each steady-state point from the CAN-reported fuel flow. This was compared to the fuel flow calculated from a carbon balance of the measured emissions during that segment. In this case, there was a consistent directional bias between the CAN-reported fuel flow and the fuel usage calculated from emissions as reported by the analyzer. A correction factor was developed and applied to the CAN-reported fuel flow [11]. As a verification, the correction factor was applied to the CAN data recorded during the FTP, HWFET, and US06 drive cycles, with the result that the totalized fuel, when corrected, matched the fuel usage reported in the vehicle's emission test report.

Instantaneous Fuel Flow Measurement Results

For the Mercedes, the CAN-reported fuel flow was very stable and repeatable. The matrix of steady-state points was supplemented with instantaneous points from low-acceleration portions of the dynamic cycles. An example of these sweep data are given in Figure 8, which indicates engine efficiency as a function of torque for points near 1900 rpm.

The data in Figure 8 exhibit two interesting phenomena. The first is the efficiency dip in the range of 200-250 Nm. This is apparently a real phenomenon, as the CAN-reported equivalence ratio decreases as a function of torque until about 200-250 Nm, and then stays reasonably constant thereafter. Presumably the turbocharger is being controlled to provide different boost characteristics between these two regimes, but we could not verify that assumption since the turbocharger operation was not monitored during this test.

The second phenomenon was the appearance of spurious high-efficiency points at high torque values. Similar behavior was seen in the steady-state testing; this underscores a potential pitfall of relying on CAN-reported data in developing efficiency maps. During the benchmarking of the Mercedes E350, points with dubiously high efficiency were eliminated from the final results used to build the fuel consumption map.

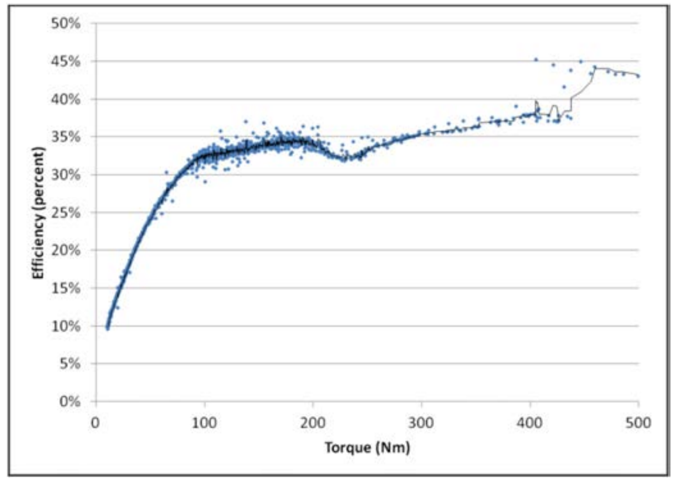

Figure 8. 2013 Example Mercedes E350 engine efficiency points developed from low-acceleration portions of the dynamic cycles. These data are taken near 1900rpm.

Final Efficiency Map

The efficiency match between the two data collection methods - steady-state mapping and instantaneous dynamic data - was very good in the areas where the two maps overlapped, and the inclusion of dynamic sweeps allowed the engine map to be easily expanded. An efficiency map was developed combining data from both data collection methods, based on the engine speed, engine torque, and the fuel flow reported by the vehicle CAN. Fuel flow was corrected as described above. The final map is shown in Figure 9. Again, no attempt was made to cover the full range of engine speeds and loads, so the boundaries of the map in Figure 9 do not represent the performance limits of the engine.

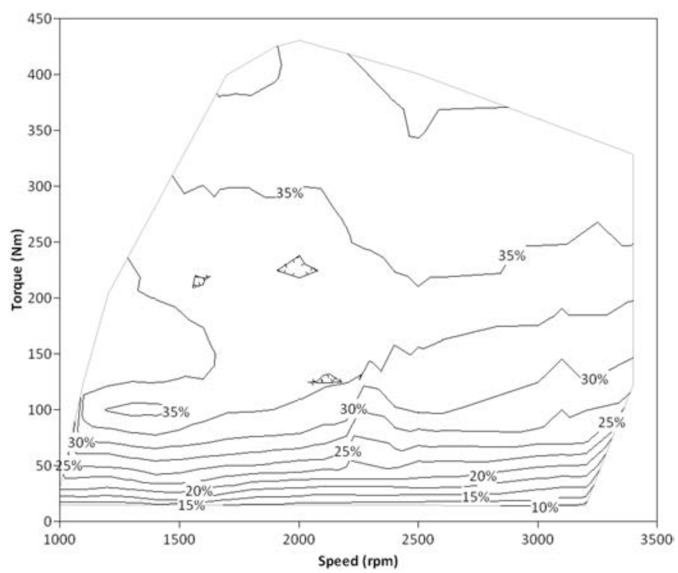

Figure 9. 2013 Mercedes E350 engine map developed in the vehicle using the chassis dynamometer.

It should be noted that the dip in efficiency around 200 - 250 Nm, as shown in Figure 8 and discussed above, can be seen across the center of the efficiency map in Figure 9.

Driveline Loss Calculation

Before calculating efficiencies for the transmission, the losses in the driveline between the transmission and the chassis dynamometer were estimated using the same test procedure used for the Malibu. The vehicle transmission was placed in neutral, the vehicle dynamometer was operated through a range of speeds, and the load required to rotate the driveline and tires was recorded as a function of vehicle speed. As might be expected, the load was very close to the difference between the force calculated using the coastdown (target) coefficients and the force calculated using the dynamometer (set) coefficients. The driveline power loss was then calculated as the product of vehicle speed and the measured load.

Transmission Efficiency Calculation

To determine the power output from the transmission at each steady-state point, the experimentally determined driveline power loss found in the previous section was added to the power at the wheels.

To determine the power input to the transmission at each steady-state point, the engine output power was calculated from the CAN-reported speed and load. Then the transmission input speed was compared to the engine output speed to determine the torque converter speed ratio. Unlike the Malibu, the E350 torque converter was often fully locked, in which case it was assumed that the transmission input power matched the engine output power. For the points (primarily in first gear) where the torque converter was unlocked, it was assumed that the torque ratio was very near one, so that the torque converter efficiency could be approximated by the torque converter speed ratio. In these cases, the transmission input power was calculated as the engine output power multiplied by the torque converter efficiency.

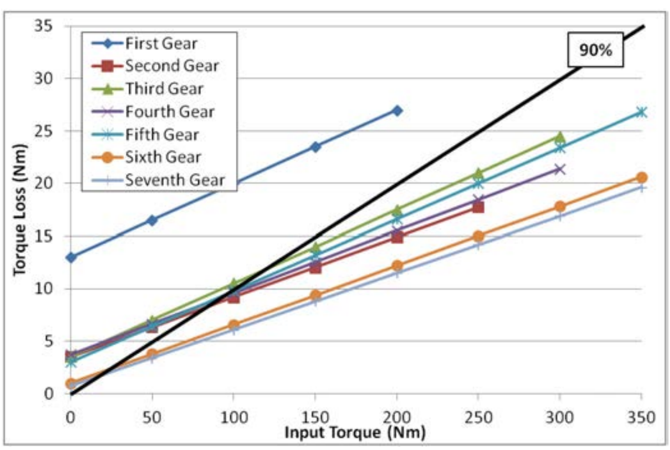

Figure 10. Mercedes E350 transmission map developed in the vehicle using the chassis dynamometer. The 90% efficiency line is included for reference. These losses do not include portions of the transmission downstream from the neutral disconnect, such as the final drive gears.

The power lost in the transmission was calculated as the difference between the power into and out of the transmission each transmission gear, speed, and load. The losses for each of the seven gears were converted into equivalent input torque losses. A simple linear regression was used to estimate the average torque loss as a function of input torque, ignoring any function of speed. The losses for all seven gears are given in Figure 10.

It should be noted that, like the Malibu in-vehicle transmission map (Figure 6), the Mercedes E350 transmission map in Figure 10 does not include spin losses of the final drive ratio or other pieces downstream of the neutral disconnect. However, the losses downstream of the neutral disconnect are included in the losses measured during neutral coastdown testing. These losses, in the form of the coastdown (target) coefficients, are used as input to the ALPHA model. Thus, all drivetrain losses are accounted for, and the transmission losses captured by in-vehicle testing are consistent with the other ALPHA inputs.

ALPHA Modeling

The data generated from the in-vehicle testing (Figures 9 and 10) were configured into input parameter files for the ALPHA model, along with the vehicle inertia and coastdown parameters. Shift performance data from dynamic cycles was used to tune the dynamic shift schedule algorithm used in ALPHA so that there was a good match between modeled and actual shift points. Further information on the dynamic shift schedule algorithm and tuning procedure is given in a separate paper [10].

The ALPHA vehicle model was run over the HWFET, US06, and hot portions of the UDDS drive cycles. ALPHA currently does not include a temperature modeling strategy, so the cold start (Bag 1) of the UDDS was not modeled. These model fuel economy results were compared to chassis dynamometer cycle runs, with results shown in Table 1.

Table 1. Mercedes E350 laboratory fuel economy results compared to ALPHA model fuel economy results using vehicle-generated parameters and efficiencies as input.

Test	Average Test MPG	Model MPG	Error %
UDDS Bag 2	28.518	28.820	1.06%
UDDS Bag 3	32.465	32.914	1.38%
UDDS Bag 4	29.715	28.820	-3.01%
HWFET	49.150	50.075	1.88%
US06 Bag 1	18.065	18.041	-0.13%
US06 Bag 2	37.395	36.621	-2.07%

In general, the model results showed a good fuel economy correlation to actual test results, on both the UDDS and HWFET over which the light-duty vehicle greenhouse gas emissions are calculated, and also over the more aggressive US06.

SUMMARY/CONCLUSIONS

This paper describes the development of an in-vehicle process for determining the efficiency of vehicle components on a chassis dynamometer, using minimal instrumentation. The process is intended to produce reasonably accurate and complete vehicle component data suitable for use in vehicle simulation models with a small investment in cost and time.

The in-vehicle benchmarking process was developed using a 2013 Chevrolet Malibu, for which standalone component test data was available, and in which various additional sensors were installed to cross-check operational parameters. The intent of this investigation, though, was to create a robust test procedure that could be followed with no a priori knowledge of component performance, nor additional instrumentation installed in the vehicle. Thus, CAN signals were used preferentially when developing efficiency maps.

The efficiency maps developed for the Malibu components from in-vehicle testing closely matched those developed from the standalone component testing.

There were, however, some significant differences in gathering and processing the data, particularly in the transmission mapping. For example, the in-vehicle torque losses calculated for the transmission do not include losses downstream from the neutral disconnect, while torque losses from standalone testing do include these downstream losses. However, these losses are factored into the measurement of the coastdown coefficients, and so are accounted for in the ALPHA model in a consistent way.

In addition, parameters such as fluid temperature and line pressure vary over the in-vehicle testing and are not controlled by the test engineer. As the vehicle strategy for controlling these parameters may be unknown, there may be some additional uncertainty in the results. However, the in-vehicle testing strategy does ensure that the parameters are maintained according to the vehicle's own control strategy, and within a range consistent with that seen in dynamic cycle testing. For example, the original standalone component testing of the transmission was done only at 5 bar and 10 bar line pressure; however, it was found that the transmission line pressures in first gear were typically between 20 bar and 25 bar, well above pressures used in the standalone component testing. The in-vehicle results line pressure results indicate a substantial adjustment that would be required to be applied to standalone test results, which may be difficult to apply to a fully modeled vehicle without encountering some discrepancies [8].

The robustness of this method was demonstrated on a Mercedes E350, where component data were not available. In addition, vehicle operation parameters (notably temperatures) were both unmonitored and uncontrolled by the test engineer. Both engine and transmission maps were developed using only available vehicle-reported CAN data and data available from the vehicle dynamometer. With this method, component maps were produced that, when used in the ALPHA model, closely predicted actual vehicle fuel economy.

FUTURE WORK

Although satisfactory results were produced in both the Malibu and E350 testing, there are some areas where the process could be adjusted, depending on the vehicle and the completeness required of the resulting data. This process is designed to obtain the best set of component data with the least investment in time and cost; the process can be adjusted to obtain more or less data with more or less investment in time and cost.

For example, the transmission maps produced using the in-vehicle process described in this paper are mapped only as a function of only gear number and input torque, without adding the additional dimension of input speed, or accounting for oil temperature.

However, with more testing time, the effect of transmission oil temperature could be determined with a judicious design of the test matrix and the monitoring of the transmission oil temperature. Transmission temperature is often available via the vehicle CAN, and thus additional instrumentation would not be needed. However, since temperature is uncontrolled by the test engineer, an understanding of the warm-up rate of the transmission would be required to design an appropriate matrix of test points to properly account for the effect of temperature.

Temperature effects, particularly in the transmission, likely account for the differences seen in the test data between the UDDS bags 2 and 4 (see Table 1). Although these two bags have the same speed trace, there is a slight but consistent improvement in fuel economy in bag 4 over bag 2. There is currently no temperature modeling in ALPHA (and so the modeled results of the two bags are identical), but the effects of transmission temperature may explain the differences between the bag results and inform potential future expansion of the model detail.

Transmission Map Dimensions

In general, a full transmission map determines losses as a function of gear, input speed, and input load, as in the standalone characterization performed by FEV Inc on the Malibu transmission. However, dimensions required for transmission loss mapping can vary over a wide range including:

1. Full losses as a function of gear, input speed, and input load, as in the standalone characterization performed by FEV Inc
2. Speed-averaged losses as a function of gear and input load, as reported in this paper
3. Average efficiencies for each gear
4. A single average efficiency for the transmission[9]

Depending on the level of transmission map detail required, the number of dimensions considered in the transmission mapping can be altered by modifying the level of effort.

For example, with some additional effort, a full mapping of the transmission can be achieved. The data in Figure 5 (fourth gear losses of the Malibu transmission) are reproduced in Figure 11, but with engine speeds noted. A temperature correction factor, estimated from the standalone component testing, was used to adjust the data to a nominal 93C to minimize confounding of the factors.

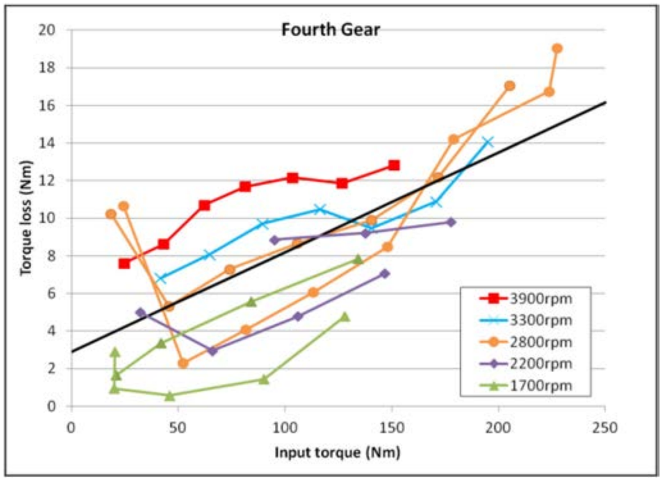

Figure 11. 2013 Chevrolet Malibu transmission losses (4th gear), showing the engine speeds. A temperature correction factor has been applied to adjust the data to a nominal 93C. The solid line represents the best-fit linear regression, using the original data from Figure 5.

In this case, the data are in general arranged according to engine speed, with enough spread that a speed effect could be estimated. However, obtaining a complete map, including speed, with high confidence would require a larger test matrix, more care in choosing test points, a closer monitoring and control of transmission temperature to prevent a confounding effect.

Likewise, if fewer dimensions are required for transmission mapping, there is an opportunity to simplify this procedure. If it is desired to produce a transmission efficiency that is a function only of gear number, or at the extreme only a single averaged number, fewer points in the test matrix are required.

Other Considerations

In some cases, the vehicle may provide additional opportunity to obtain more data in less time. For example, the Mercedes produced repeatable engine efficiency data, even using instantaneous points from low-acceleration portions of the dynamic cycles. These data were used to supplement the steady-state points and produce the final engine map. If data can be quickly produced this way, the time and cost of testing is reduced.

In general, the detail of the test plan may vary from vehicle to vehicle, depending on the availability and reliability of in-vehicle measurements, and the sensitivity of the final model to these measured parameters. Further work is expected to extend this methodology to other vehicles.

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DEFINITIONS/ABBREVIATIONS

ALPHA - advanced light-duty powertrain and hybrid analysis tool

CAFE - corporate average fuel economy

CAN - controller area network

COV - coefficient of variation

ECM - engine control module

EPA - Environmental Protection Agency

GHG - greenhouse gas

HWFET - highway fuel economy test

kph - kilometer per hour

LD - Light-duty

UDDS - urban dynamometer driving schedule