Modeling of a Conventional Mid-Size Car with CVT Using ALPHA and Comparable Powertrain Technologies

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Abstract

The Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool was created by EPA to evaluate the Greenhouse Gas (GHG) emissions of Light-Duty (LD) vehicles [1]. ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types combined with different powertrain technologies. The software tool is a MATLAB/Simulink based desktop application. The ALPHA model has been updated from the previous version to include more realistic vehicle behavior and now includes internal auditing of all energy flows in the model [2]. As a result of the model refinements and in preparation for the mid-term evaluation (MTE) of the 2022-2025 LD GHG emissions standards, the model is being revalidated with newly acquired vehicle data.

In the effort to model the current and future US Light-Duty fleet there are times when complete and exact engine and powertrain component data are unavailable and must be approximated using components with comparable levels of performance and technology. This paper presents the testing and ALPHA modeling of a CVT-equipped 2013 Nissan Altima 2.5S using comparable powertrain technology inputs. A brief overview of recent improvements in CVT performance and efficiency is provided. ALPHA's CVT shift strategy, ALPHAshift-CVT, is introduced and its performance is compared with data from the Altima. Fuel economy and carbon emissions results over a wide range of drive cycles were within 5% of measured values and the city/highway weighted combined fuel economy and carbon emissions were within approximately 1% of measured values, providing confidence in the proxy powertrain approach.

Introduction

Background

During the development of the LD GHG and CAFE standards for the years 2017-2025, EPA utilized a 2011 light-duty vehicle simulation study from the global engineering consulting firm, Ricardo, Inc. The previous study provided a round of full-scale vehicle simulations to predict the effectiveness of future advanced technologies. Use of data from this study is documented in the August 2012 EPA and NHTSA "Joint Technical Support Document" [3].

The 2017-2025 LD GHG rule required that a comprehensive advanced technology review, known as the mid-term evaluation, be performed to assess any potential changes to the cost and the effectiveness of advanced technologies available to manufacturers. EPA has developed the ALPHA model to enable the simulation of current and future vehicles, and as a tool for understanding vehicle behavior, greenhouse gas emissions and the effectiveness of various powertrain technologies. For GHG, ALPHA calculates CO_2 emissions based on test fuel properties and vehicle fuel consumption. No other emissions are calculated at the present time but future work on other emissions is not precluded.

ALPHA will be used to confirm and update, where necessary, efficiency data from the previous study. 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 naturally aspirated Atkinson engines for conventional vehicles.

This Paper's Focus

EPA engineers utilize ALPHA as an in-house research tool to explore in detail current and future advanced vehicle technologies. ALPHA is being refined and updated to more accurately model light-duty vehicle behavior and to include new technologies. To validate the performance of ALPHA, EPA is using newly acquired in-depth vehicle, engine, and transmission benchmarking data from several conventional and hybrid vehicles from 2013-2015 model years.

In order to recognize the increasing market share and effectiveness of continuously variable transmissions, EPA has begun benchmarking CVT-equipped vehicles and has acquired some manufacturer-provided CVT transmission loss and shift strategy data. This paper presents the results of testing a Nissan Altima with CVT and the initial development of a CVT shift algorithm (ALPHAshift-CVT) for use with EPA's ALPHA model.

Since vehicle-specific engine and transmission data are unavailable to us at this time, the Nissan Altima has been modeled using engine and component data from comparable powertrain components. Even in the absence of precise input data for this specific vehicle reasonable modeling results (typically within 5% fuel economy and grams CO_2/mi) can still be obtained and reasonable conclusions drawn when carefully selecting the substitute powertrain components.

Benchmark Vehicle Description

The vehicle tested for this project was a 2013 Nissan Altima 2.5S as detailed in Table 1. This vehicle was chosen as representative of a midsize car with a conventional powertrain with a naturally aspirated engine and a continuously variable transmission and it performs well in fuel economy compared with its peers. The emissions road load coefficients in Table 1 are for reference. The emissions roadload was used for emissions certification and can be found in the EPA test car data files [4] and represents roadload settings that represent a group of vehicles. The test roadload was provided by the manufacturer upon request based on the vehicle's VIN and may represent the target roadload for this specific vehicle as opposed to a group of vehicles. For this paper the manufacturer-provided test coefficients were used as targets.

The Nissan CVT is of interest because it is one of Jatco's latest CVTs and includes many improvements over previous transmissions, including lighter weight and significantly lower losses.

Table 1. Vehicle description

Model	2013 Nissan Altima 2.5S
Engine	2.5L inline-4, MPFI, naturally aspirated, 136 kW (182 hp) @ 6000 RPM, 244 Nm (180 ft-lbs) @ 4000 RPM
Powertrain	Conventional FWD, Jatco CVT8 transmission
Gear Ratios	2.73 to 0.38 with 4.828 final drive
Tire Size	215/60/R16
EPA Label Fuel Economy	27 City, 38 Highway, 31 Combined MPG
Emissions Equivalent Test Weight (ETW)	3,500 lbs (1588 kg)
Emissions Target Road Load A	29.85 lbs (132.8 N)
Emissions Target Road Load B	-0.1069 lbs/mph (-1.064 N/m/s)
Emissions Target Road Load C	0.01879 lbs/mph^2 (0.4182 N/(m/s)^2)
Test ETW	3,500 lbs (1588 kg)
Test Target Road Load A	29.83 lbs (132.7 N)
Test Target Road Load B	-0.1642 lbs/mph (-1.634 N/m/s)
Test Target Road Load C	0.0202 lbs/mph^2 (0.4496 N/(m/s)^2)

Figure 1. The 2013 Nissan Altima, image from www.uftringnissan.net

Vehicle Dynamometer Testing

The Altima was tested at EPAs National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, MI. The equivalent test weight was 3500 pounds, using the test target road load listed in Table 1. Test results are listed in Table 2. Two tests were run for each drive cycle, except the UDDS and WLTC results are based on four runs and the NEDC results are based on three runs. CREE refers to carbon-related exhaust emissions in grams per mile as calculated in 40 CFR 600.113-12 and converts HC and CO emissions to CO_2 equivalent emissions on a mass basis, as follows:

$$CREE = (CWF / 0.273 \, x \, HC) + (1.571 \, x \, CO) + CO2 \tag{1}$$

Where CWF is the carbon weight fraction of the test fuel, HC, CO and CO2 are the hydrocarbon, carbon monoxide and carbon dioxide emissions as measured in grams per mile, respectively.

All tests listed were performed at ~75°F (24°C) ambient temperature on a fully warmed up vehicle. The fuel used for these vehicle tests was a custom blend (due to lack of commercial supply) meant to represent Tier 3 certification gasoline. The measured fuel properties are indicated in Table 3.

Powertrain Proxies and Modeling Assumptions for the Nissan Altima

In the absence of detailed component input data for a particular modeling exercise (due to lack of test data or the fact that the data doesn't exist yet because it represents future technology) it may be possible to substitute or modify existing data to use as a proxy. Proxy data may be based on engineering judgment, in-vehicle data acquisition or on closely related available data. This paper explores the use of a combination of these approaches, focusing on the engine and transmission and including a short exploration of the vehicle's accessory loads.

Table 2. Altima 2.5S test results

Drive Cycle & Phase	Min MPG	Average MPG	Max MPG	Min CREE	Average CREE	Max CREE
Hot FTP Phase 1/3	31.8	33.0	33.6	263	267	277
Hot FTP Phase 2	26.3	26.8	27.6	319	329	335
HFET	51.0	51.1	51.3	172	172	173
US06 Phase 1	17.7	18.1	18.5	476	488	499
US06 Phase 2	35.7	36.1	36.4	242	244	247
LA92 Phase 1	20.1	20.1	20.1	438	438	438
LA92 Phase 2	29.3	29.3	29.3	301	301	301
Class 3 WLTC Phase 1	21.1	21.7	22.2	398	407	418
Class 3 WLTC Phase 2	32.3	34.0	34.7	254	260	273
Class 3 WLTC Phase 3	39.2	39.8	40.1	220	221	225
Class 3 WLTC Phase 4	36.6	36.8	37.3	236	240	241
NEDC Phase 1	21.3	21.9	22.4	394	403	414
NEDC Phase 2	41.5	42.1	42.5	207	210	212

Table 3. Vehicle test fuel properties

Fuel Type (custom blend due to lack of commercial supply)	"Near" Tier 3 AKI 90
Density @ 60 F (ASTM D4052)	0.7525 kg/L
Energy Density (ASTM D240)	41.191 MJ/kg
Carbon Weight Fraction (ASTM D3343)	0.8319

Engine

The engine chosen as a proxy for the Nissan's engine was the 2013 Chevy Malibu 2.5L Ecotec as used in previous validation work [5]. Table 4 shows a comparison of the two engines. The most notable differences are the compression ratios and the fuel delivery systems. The Nissan has a lower compression ratio and is port fuel injected while the Chevy has a higher compression ratio and uses direct injection. These differences may help to explain the higher power and torque of the Malibu engine. Based solely on these specifications one might expect the Malibu to have a slight advantage in terms of engine efficiency.

Table 4. Comparison of Nissan Altima and Chevy Malibu engines

	2013 Altima 2.5L	2013 Malibu 2.5L Ecotec
Displacement [cc]	2488	2457
Air Delivery	Naturally Aspirated	Naturally Aspirated
Power [kW]	136	147
Torque [Nm]	244	259
Fuel Injection	MPFI	GDI
Cam Type	DOHC, CVVT	DOHC, CVVT
Number of valves	16	16
Bore [mm]	89	88
Stroke [mm]	100	100.8
Compression Ratio	9.6:1	11.3:1
Fuel	Regular unleaded	Regular unleaded

To equalize the engines in terms of technology, the base Malibu engine map was de-rated using a "modifier map", created by Ricardo during the original LD GHG modeling study [3], which can be used to add or subtract the effectiveness of GDI technology and increased compression ratio from an ALPHA engine map. Similar maps are used to add or remove other engine technologies such as cam phasers, variable valve lift, HCCI or cylinder deactivation. Some maps are from previous studies and some are currently under development at the NVFEL. The engine's BSFC was scaled based on changes in engine displacement in a manner consistent with [6]. The final engine BSFC map used for this modeling work is shown in Figure 9. The Malibu's full throttle torque curve was truncated to 244 Nm to match the Altima's maximum torque. No adjustment was made to the closed throttle (motoring) torque curve.

Transmission

Improvements in CVT Technology

CVT technology has continued to develop in recent years through a combination of efficiency and drivability improvements. The efficiency improvements center on reducing transmission losses or increasing the ratio spread and allowing a greater range of CVT operation. Drivability improvements center on faster response times and improved driver acceptance (particularly in North America) through ratio control which provides a more linear relationship between engine speed and vehicle speed and in some cases emulation of step-gear automatic transmission behavior. Recent papers published by Honda [7,8,9,10], Hyundai-Kia [11], Toyota [12] and Jatco [13,14] illustrate the recent trends in CVT improvement.

In terms of loss reduction, there are three primary loss factors: belt/pulley system losses, oil pump/hydraulic losses and fluid churning losses. To reduce belt/pulley losses, common approaches are:

- Reduced clamping forces: reduced safety factor based on better coordination with the engine (higher accuracy torque estimation and control), better understanding and measurement of belt slip, improved coefficient of friction due to improved lubricants and/or improved belt/pulley surface treatments

- Reduced pulley deformation: improved clamping or pulley redesign or reduced clamping pressure
- Improved pulley manufacturing tolerances
- Greater center to center pulley distance
- Optimized belt stiffness and component geometry

To reduce oil pump/hydraulic losses, common approaches are:

- Lower oil pressure: larger piston actuation surface area, pressure applied proportional to torque transmitted
- Lower pump displacement: reduced leakage due to lower pressures, tighter valve clearances, fewer valves and/or better integration and packaging of the hydraulic control unit
- Optimized pump: two-stage or dual output pumps that can vary flow or pressure output as required, off-axis or improved coaxial pumps

To reduce fluid churning losses, common approaches are:

- Reduced oil level
- Oil baffles to direct oil flow and reduce splashing of submerged gears
- Lower viscosity transmission fluid

In addition to reducing losses, CVT effectiveness is improved by increasing the ratio spread:

- Reduced pulley shaft diameter and/or increased pulley diameter
- Lower final drive ratios for better highway cruising

Other improvements include extended decel-fuel-cutoff and torque converter slip/lockup strategies to reduce fuel consumption, lower drag seals and improved bearing locations. In addition, the torque capacity of CVTs continues to improve which allows a single transmission to cover a wider range of applications, thereby increasing volume and reducing development and manufacturing costs.

Many of the developments listed here are facilitated by model based design, hardware in the loop simulation, or effective use of CFD and FEM techniques which are continually improving. Different manufacturers have taken different paths to improve their designs and it does not appear that any single manufacturer has implemented all the possible improvements listed above, in which case further improvements may be expected in the future.

Development of the Jatco CVT8 Transmission

EPA obtained a set of CVT transmission strategy and loss data from one of our OEM stakeholders. The source transmission has a slightly lower overall ratio spread and probably has higher internal losses than the Jatco CVT8 since it is based on an earlier generation CVT that may not represent current state of the art, even with incremental improvements over time. The Jatco CVT8 features approximately 40% reduced friction through [13,14]:

- Reduction of spin losses due to oil agitation due to a lower oil level, improved oil baffles and low viscosity oil
- Reduced oil pump size, reduced line pressure for equivalent clamping force and reduced leakage (pressure reduced 45% on the HFET drive cycle, for example)
- Optimized belt shape and lower clamping forces

In addition to reduced friction, the CVT8 features a wider ratio spread due to optimizing the belt shape and reducing the pulley shaft diameter. The torque converter lockup strategy was also improved to reduce slip and improve fuel economy.

Taken together, the CVT8 improvements contribute to a 10% improvement in fuel economy relative to the previous generation CVT, including benefits from the larger ratio spread.

Modifications to Create the Proxy Transmission

To equalize the source CVT in terms of overall performance and friction the spin losses and pump torque loss in the transmission were reduced by 40%. In addition, a 45% reduction in line pressure was applied, though this effect was small in comparison with the friction reduction. The source transmission's average drag (in neutral) is subtracted from the target road load's A-term to avoid double-counting internal vehicle losses and this reduction was also reduced by 40%.

Torque Converter

In addition to adjusting the CVT losses it was necessary to modify the source transmission's torque converter K-factor and lockup strategy.

K-Factor

Approximating the torque converter K-factor for this vehicle illustrates an example of using a combination of in-vehicle data and modeling results to inform engineering judgment in the selection of a comparable component.

An in-vehicle torque converter stall test was performed in order to estimate the torque converter's K-factor. The test was performed with a fully warmed up engine and transmission. Figure 2 shows the data collected from the CAN bus during the test. The engine torque is considered an estimate since the accuracy or intended use of the signal cannot be assured (i.e. is it gross torque, indicated torque or some other torque). Taking the torque at face value for this test, the K-factor was initially estimated at 159 $\mathrm{RPM}/\sqrt{Nm}$. However, upon further examination of the CAN torques compared with model torques and vehicle torque converter slip versus model torque converter slip it was determined that this did not appear to be a reasonable value. The CAN torques appear higher than expected for positive torques and lower than expected for negative (motoring) torques. Using the Malibu's K-factor resulted in slip speeds that were too high so the average of the original estimate and the Malibu K-factor and was ultimately used at value of 176 $\mathrm{RPM}/\sqrt{Nm}$ which resulted in a better match between the model and the observed data.

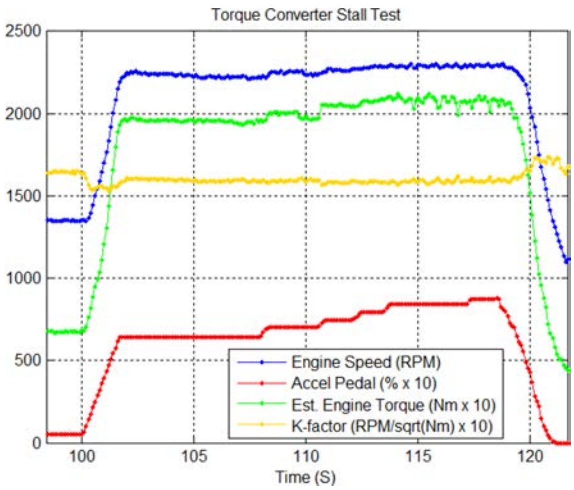

Figure 2. Torque converter stall test

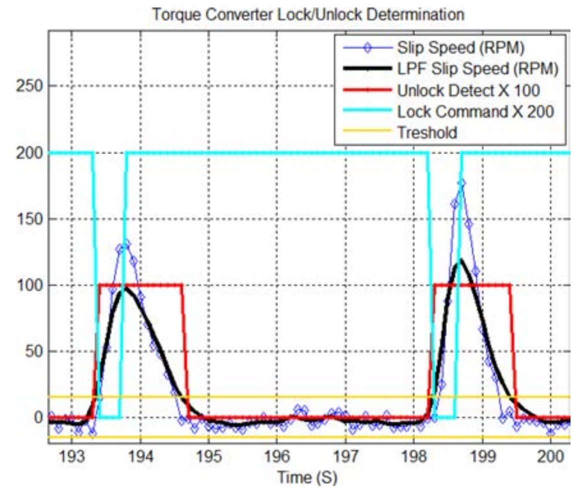

Figure 3. Torque converter slip speeds and lockup signal determination

Lockup Strategy

The Altima lockup strategy is non-trivial and appears to depend on several factors, which may include:

- Accelerator pedal tip-in
- Brake pedal tip-out
- Vehicle speed
- Rate of change of CVT ratio

Since the focus of this study is primarily the CVT and its ratio strategy, the decision was made to use the observed lock/unlock schedule as an input to the model rather than attempting to reverse engineer the clutch strategy. Even with an accurate strategy there would be significant differences in the observed result due to the dependence on driver behaviors which would necessarily vary (the model driver never drives precisely the same as the human driver). Using the observed strategy allows the results to be compared somewhat independently of driver behavior and allows a more direct comparison between the physical components involved.

Since the lock/unlock command is not one of the CAN signals already available, a slip speed calculation is made to determine the occurrence of the unlocked condition. The start of the observed unlocked condition is taken as the start of the unlock command. Since the lock command necessarily occurs prior to the observation of the locked condition, the lockup command is based on the end of unlock and time shifted earlier by a minimum of half a second or to the point of inflection of the rate of change of slip, within one second of observed lockup.

Figure 3 shows an example of the vehicle data used to determine lock and unlock commands. The dark blue dotted line is the raw slip speed data calculated from CAN logged engine speed and gearbox input speed. The black curve is the slip speed after low pass filtering at 0.75 Hz and is compared with the yellow thresholds to determine the unlocked condition. The cyan line is the clutch command signal as determined by the unlocked condition and the inflection of the derivative of the slip speed prior to lockup.

Accessories

The average electrical accessory loads were determined from Altima test data collected by Argonne National Laboratory (ANL) in their Advanced Powertrain Research Facility (APRF) since the accessory draw was not measured during testing at EPA [15]. The accessory data shows some interesting behaviors. The accessory data presented here was collected on the dynamometer, not on-road.

Table 5 shows the average alternator power and voltage for a number of the drive cycles tested at ANL. On the basis of these results, and to simplify the model for this particular study, the electrical accessory load was set to a constant 289 W with an alternator target voltage of 13.08 V. A short exploration of the data behind these results follows.

Table 5. Average alternator electrical output power and voltage

ANL drive cycle	Average alternator electrical power (W)	Average alternator voltage (V)
HFET	278	13.04
UDDS (hot)	271	13.07
JC08	277	12.96
NEDC	305	13.19
LA92	324	13.24
WLTP	277	12.95
Average	289	13.08

While not a primary focus of this paper, the following accessory discussion illustrates the process of trying to determine reasonable accessory loads during a vehicle validation, shows some of the background behind the results in Table 5, and reveals some interesting behaviors that may be modeled in the future.

Alternator Output

When examining the alternator output one of the first noticeable features is the on/off nature of the power draw and the significant variability from test to test. Figure 4 shows the alternator output power for warm and hot UDDS drive cycles. In this case, the UDDS was run three times consecutively from room temperature, the “warm” UDDS represents the second test and the “hot” UDDS represents the third test.

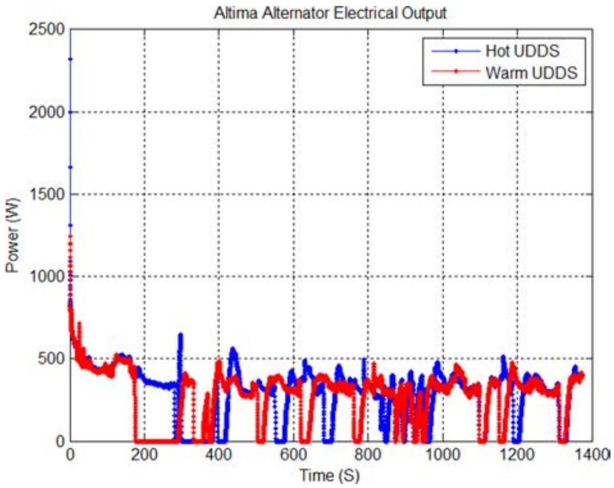

Figure 4. Warm and hot UDDS alternator output power

Upon closer examination it appears as though the Altima exhibits what might be termed “alternator regen” - periods of increased output during periods of vehicle braking or deceleration. Figure 5 illustrates this behavior. The blue line is the alternator output in Watts, the green curve is the vehicle speed in MPH x 10 and the red highlights indicate periods where the accelerator pedal is not depressed (no brake pedal indicator was available in the data set so the accelerator pedal signal was used as a proxy). It can been seen that the alternator output increases during periods of braking, for example at 300 and 382 seconds in the graph. While not of primary interest for this particular study this data may prove valuable when considering how to tune and implement alternator regen in our other modeling work.

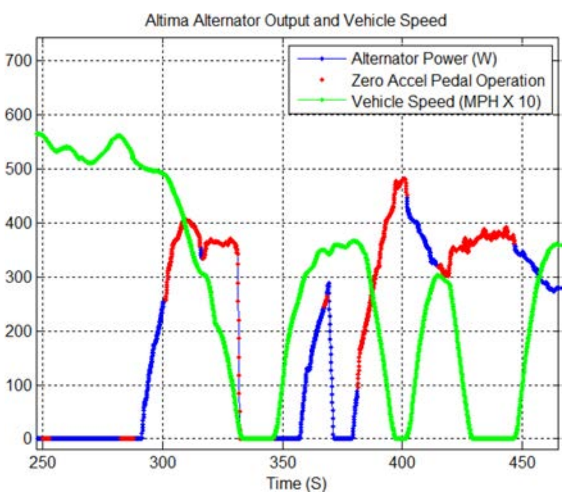

Figure 5. Alternator output and vehicle speed

Figure 6 shows the battery voltage for the same tests as Figure 4. The initial operation shows a higher output voltage that drops during the rest of the test. The battery voltage swings up and down as the alternator activates and deactivates. The average battery voltage for the hot UDDS was 13.07 V.

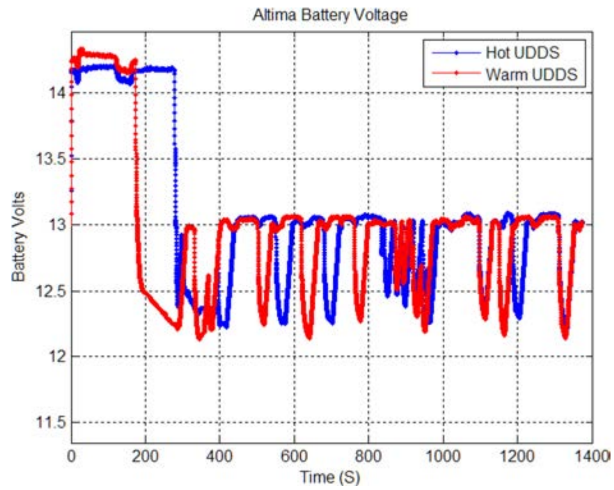

Figure 6. Warm and hot UDDS battery voltage

Figure 7 shows the variation in electrical power steering load for the Altima over the LA92 as driven at ANL. Overall, the trend is decreasing electrical load as vehicle speeds increase, although there is some variation or hysteresis along the way. While not part of this study, trends such as these are interesting to note and may become part of future modeling efforts as work progresses to understand what is reasonable in terms of expected electrical loads for vehicles with electrified accessories.

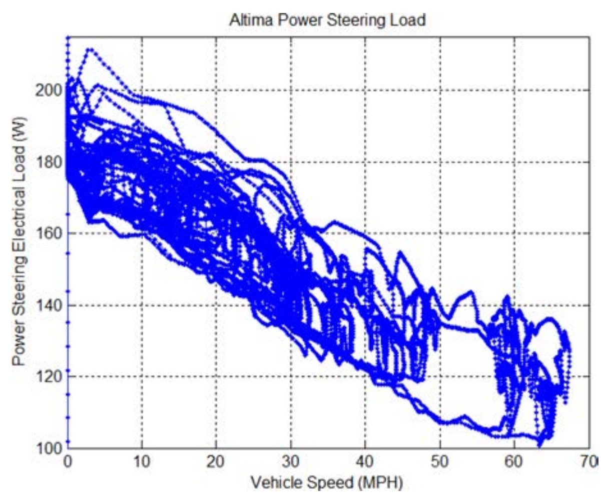

Figure 7. Altima power steering load

The Altima’s accessory loads and alternator strategy may be further investigated at a later date during consideration of how to update accessory models to represent current and future technologies, but for the modeling results in this study the average loads shown in Table 5 were used.

ALPHAshift-CVT

Background

In order to model a vehicle with a CVT it is necessary to implement a gear ratio strategy. For conventional step-gear transmissions, an algorithm called ALPHAshift is used, as documented in a previous paper [16]. This paper introduces the initial version of ALPHAshift-CVT. EPA plans to continue to refine the model as part of future validations.

Algorithm

The basic algorithm of ALPHAshift-CVT is quite simple - attempt to operate the engine along its minimum BSFC line with the addition of a minimum speed constraint. Unlike the conventional ALPHAshift algorithm which evaluates a cost map during operation, ALPHAshift-CVT pre-computes a target engine speed curve as a function of desired engine power based on the engine's BSFC map and an estimated CVT transmission efficiency as a function of speed and load. This curve, combined with a minimum desired engine speed lookup table, forms the basis of the algorithm.

To calculate the minimum BSFC target speed as a function of engine power, the engine fuel map is queried along lines of constant power at 2.5 kW intervals. Points above the engine's maximum torque curve are discarded. The engine speed at which fuel consumption is minimized is recorded for each power, an example is shown in Figure 8.

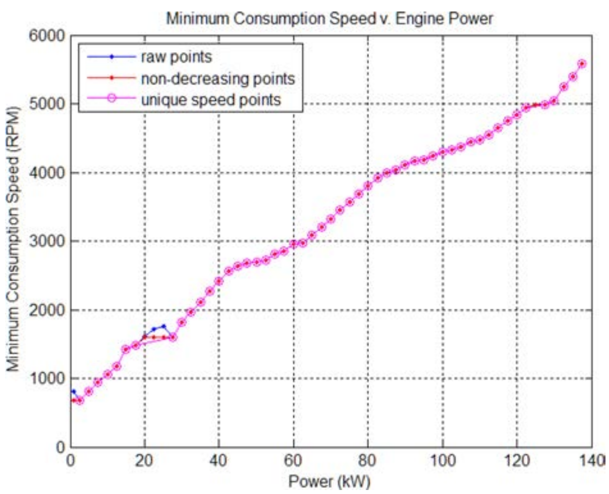

Figure 8. Minimum consumption speeds versus power

As a second step, the speed points are processed to prevent BSFC target operation curves that back-track or zig-zag across the engine map (i.e. a transition from a low power/high speed point to a slightly higher power/lower speed point or vice versa). The red curve in Figure 8 shows the first step, where each speed must be less than or equal to the speed of the next higher power point, shown in the 20 to 25 kW range in this example. The last step is to take only the unique speed points, preferring the highest powered point for each speed, as shown by the magenta curve in Figure 8. While the post-processing step may traverse non-ideal portions of the engine map at certain points, at least the overall path is reasonable and should avoid strange behaviors associated with noise or other inconsistencies in the engine map. Other algorithms for calculating the minimum BSFC curve are, of course, possible and methods may be revised in the future.

Further enhancements to the overall CVT ratio algorithm are possible, potentially including:

- Target speed rate limiters for increasing and decreasing speed targets
- Low pass filtering of the target ratio or speeds to avoid dithering
- Dynamic BSFC curve calculation during model execution
- Step gear simulation during high power or other operation

Although there are many possible CVT ratio control schemes [17,18], at this time the algorithm has been kept simple since it appears adequate to model the vehicles tested so far. For example, the Altima 3.5 with CVT is capable of mimicking a step gear transmission when using paddle shifters but evidence of this behavior was not observed on the Altima 2.5S during normal operation. As new vehicles and data become available ALPHAshift-CVT may see further development as required.

During operation, the target speed is divided by the transmission output speed to determine a target CVT ratio. The calculated ratio is saturated to the limits of the transmission spread.

Figure 9 shows the Altima engine map (as derived from the Chevy Malibu) and highlights the pre-computed minimum BSFC curve, the minimum speed constraint is not pictured.

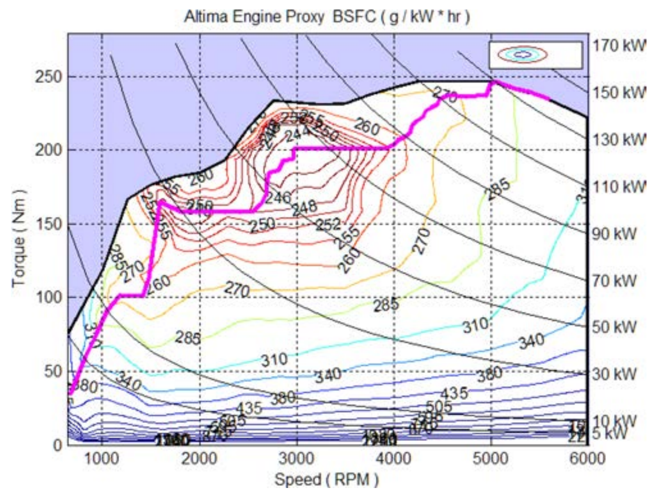

Figure 9. Altima proxy engine map showing ALPHAshift-CVT minimum BSFC curve

Figure 10. Minimum transmission input speed target as a function of vehicle speed, target is 1150 RPM for all speeds above 25 MPH

The Altima exhibits a variable minimum speed as a function of vehicle speed. When the driver is on the accelerator pedal the minimum speed is 1150 RPM, when coasting or on the brakes, the minimum speed varies from 1150 RPM above 40 km/h (25 MPH) to 1100 RPM below 36 km/h (22 MPH). Figure 10 shows this curve and can be compared with Figure 13. This curve is used to limit the minimum target transmission input speed when calculating the desired CVT gear ratio.

Since the CVT target speeds are based on the engine's BSFC map, ALPHAshift-CVT will automatically adjust for alternative engines and engine maps.

Comparison with Vehicle Data

This section compares and contrasts the performance of the ALPHA model and ALPHAshift-CVT with test data from the Nissan Altima. The first set of charts are with reference the UDDS drive cycle and the second set refers to the US06 drive cycle for a look at more aggressive operation. It should be kept in mind that the ALPHAshift-CVT calibration here is determined solely on the basis of the derived engine map, with the exception of the minimum speed limits which are set to match the vehicle behavior. Accordingly, the behavior of the model and the vehicle should not be expected to be identical, although it can be seen that they are quite comparable. A significantly different engine map or vehicle strategy could result in vastly different behaviors and the observation that the vehicle and model results are similar gives confidence in the basic CVT strategy, at least for this vehicle.

UDDS

Figure 11 shows a sample of UDDS vehicle speeds for four tests and one of the modeling results. Some test to test variability can be seen here. Vehicles with conventional automatic transmissions show some variability from test to test based on driver behavior, CVTs show increased variability (with respect to real-time behavior, not necessarily fuel economy) from test to test since the ratio strategy is closely tied to driver demand. A closer view of the vehicle speed variance as a result of variable driver behavior is provided in Figure 12.

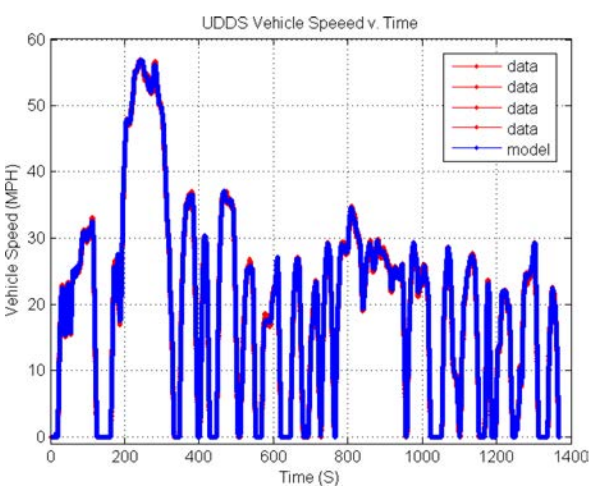

Figure 11. A sample of UDDS test and model vehicle speeds

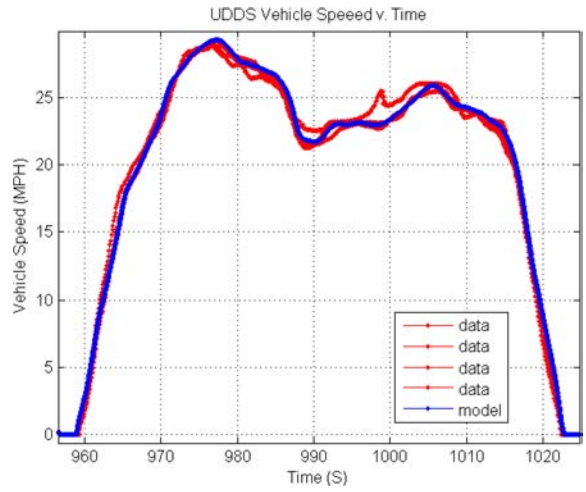

Figure 12. Test to test variability and modeled vehicle speed close-up

Figure 13 shows a plot of UDDS transmission gearbox input speed versus vehicle speed. Note there are three ranges of operation - fixed high ratio below ~7 MPH, followed by variable ratio up to ~47 MPH and variable ratio with a minimum speed determined by vehicle speed at higher speeds. Even though the CVT has an aggressive overdrive (0.38:1 for the Altima as opposed to 0.746:1 for the Malibu, a nearly 2:1 difference) the N/V ratio in top gear only differs by about 15% due to the difference in final drive ratios. The Altima has a 4.828:1 final drive while the Malibu has a 2.89:1 final drive. The advantage of the CVT and its wide range of variable ratios in mid-speed driving is somewhat offset during high speed driving where overall gearing is similar (at least at light loads such as cruising on the HFET) but the CVT may have higher losses than the conventional automatic transmission. The minimum speeds from Figure 10 may also be noted in this figure.

Figure 13 does not include the effects of torque converter operation since it represents gearbox input speed so differences observed are differences in ratio strategy. Keeping in mind that the ALPHAshift-CVT strategy is independent of the Altima strategy (except for the minimum speeds mentioned earlier) one may still observe that the overall behaviors are quite comparable. The yellow lines represent the minimum and maximum N/V limits.

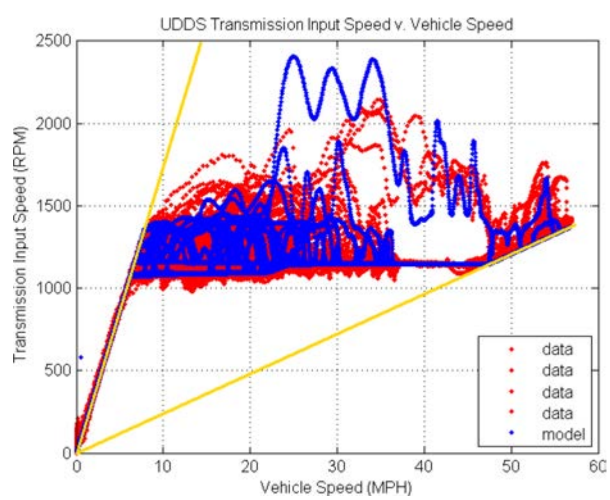

Figure 13. UDDS transmission input speed versus vehicle speed

Figure 14 shows CVT ratio versus vehicle speed for the UDDS. The lower limit of the ratio curve over the variable ratio operating speeds is determined largely by the minimum speed curves. Operation above this curve represents downshifts to accommodate increased driver demand. The ALPHAshift-CVT ratio strategy shows similar behavior to the Altima.

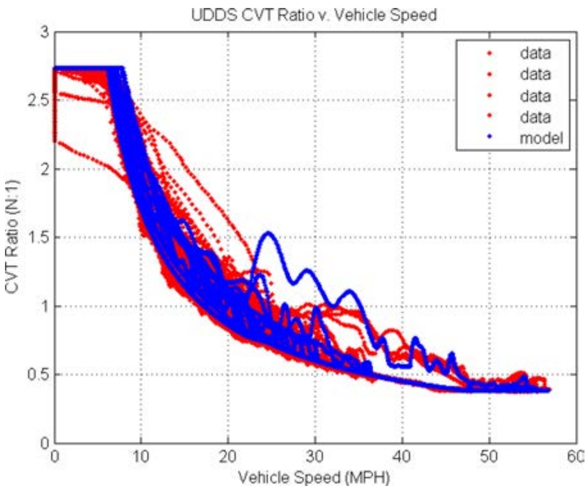

Figure 14. UDDS CVT ratio versus vehicle speed

Figure 15 shows CVT ratio versus time over the UDDS drive cycle, Figure 16 shows a closer view over a segment of the same cycle. In these graphs the test to test variability in the CVT ratio can be seen. Overall behavior is similar although the Altima appears to roll off the high initial gear ratio a little earlier and more gradually than the model. Overall behavior is quite similar even though the strategies are independent.

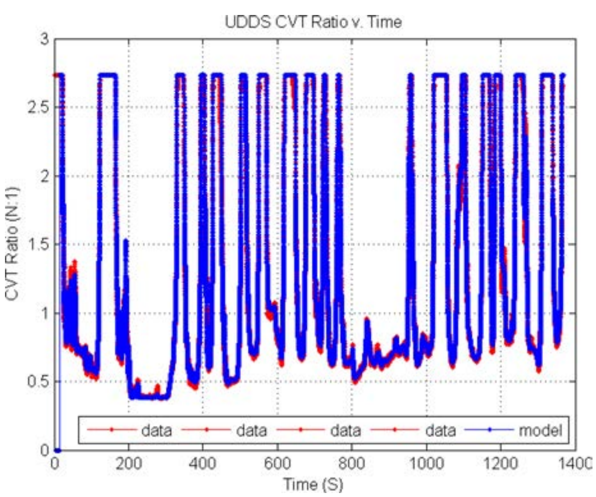

Figure 15. UDDS CVT ratio versus time

Figure 17 shows engine speed versus time for the UDDS and Figure 18 shows a closer view over the same drive segment as Figure 16. These charts illustrate the variability mentioned previously and in the close-up view one can see that the torque converter operation during launch is comparable. Also visible is the long ramp down to minimum idle speed starting at about 427 seconds. The test vehicle used for this study had a minimum idle speed of around 800 RPM, while the vehicle tested at ANL showed a minimum idle speed of around 635 RPM. This was detected early in the modeling process when it was noticed that the initial model results showed significantly lower fuel consumption during the second phase of the UDDS versus our test vehicle. Upon further investigation it was determined that our vehicle had been programmed with a 200 RPM idle offset as reported by an OEM scan tool. It is not clear why this offset was in place, how it got there, or if other Altimas have also been programmed with this offset. The vehicle was procured from available dealer stock and was not a manufacturer emissions test vehicle.

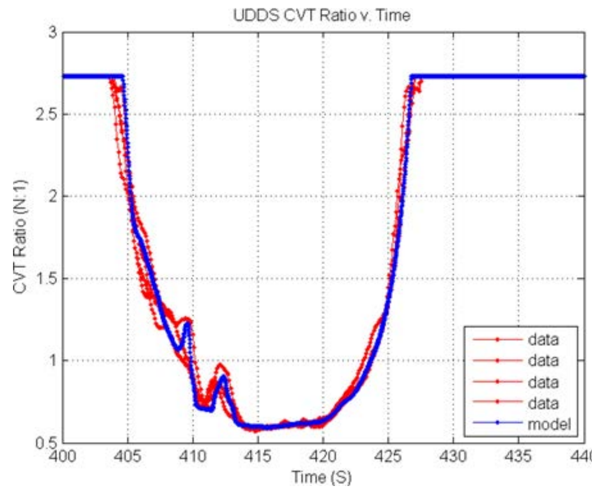

Figure 16. UDDS CVT ratio versus time close-up

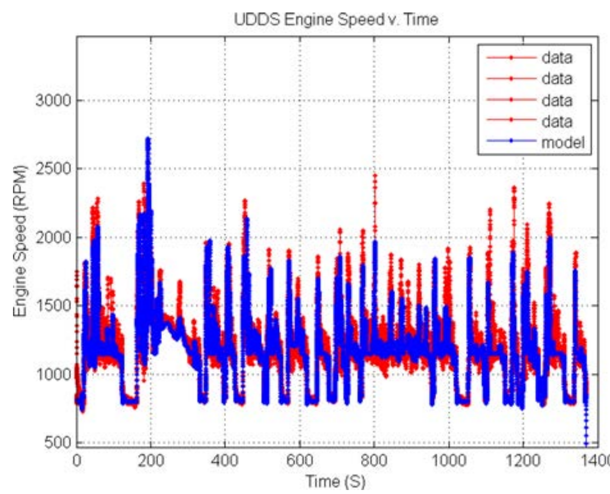

Figure 17. UDDS engine speed versus time

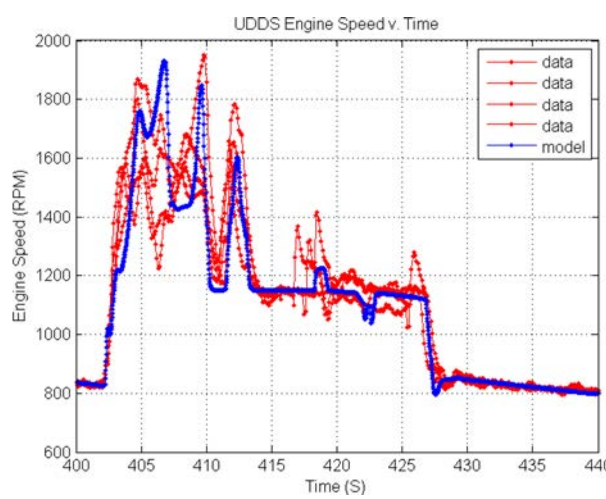

Figure 18. UDDS engine speed versus time close-up

Figure 19 and Figure 20 show the energy weighted operation of the engine for the test vehicle and the model respectively. Since the CAN torques are of unknown calibration (to EPA), these charts should only be considered on a qualitative basis. Generally speaking the CAN torques appeared significantly higher than the expected torques and may represent gross torques instead of shaft torques, for example. Overall operation appears comparable as might be expected from the previous figures even though the strategies are independent.

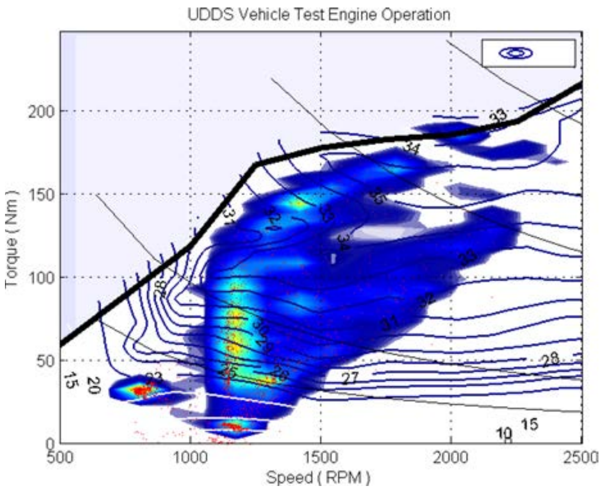

Figure 19. UDDS test data energy weighted engine operation estimate

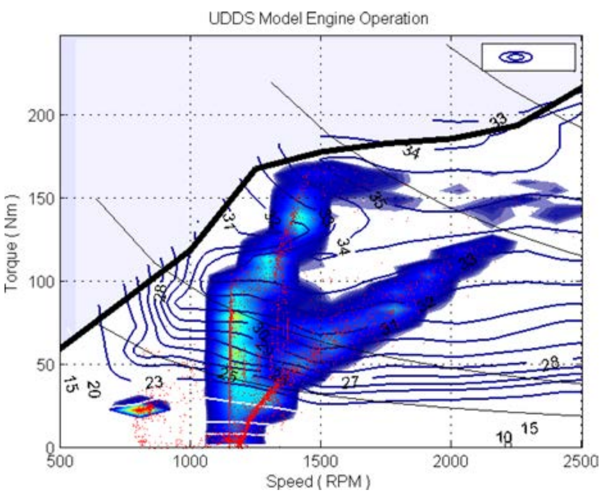

Figure 20. UDDS model energy weighted engine operation

Real-time test vehicle fuel consumption data was obtained from an in-line fuel meter as had been done previously on the Malibu. The meter volume correlated well with the carbon balance test fuel volume, with a linearity of 0.993 and an R-squared of 0.998. However, since the exercise here was to explore the use of proxy powertrain components, the previously determined Malibu transient fuel penalties were used for this study. The fuel meter data was used to compare decel fuel cutoff events and to explore the discrepancy in fuel consumption at light loads, as discussed in the results section.

US06

The US06, while not part of standard two-cycle fuel economy testing, represents a more aggressive drive cycle that better represents real-world driving. As such it provides the opportunity to observe the behavior of the CVT under more realistic speeds and loads.

Figure 21 shows the transmission gearbox input speed versus vehicle speed for the US06. Compared with Figure 13 one can see the effect of the more demanding drive cycle and the overall similarity between the model and the test data. The yellow lines represent the minimum and maximum N/V limits.

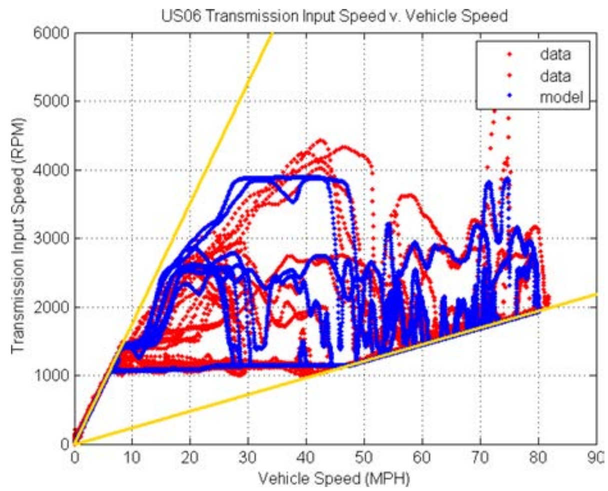

Figure 21. US06 transmission input speed versus vehicle speed

Figure 22 shows the CVT ratio versus vehicle speed for the US06. Once again the transmission operates at higher ratios to deliver the higher power required to meet the drive cycle, as compared with Figure 14. The behavior of ALPHAshift-CVT compares well with the Altima data over the US06.

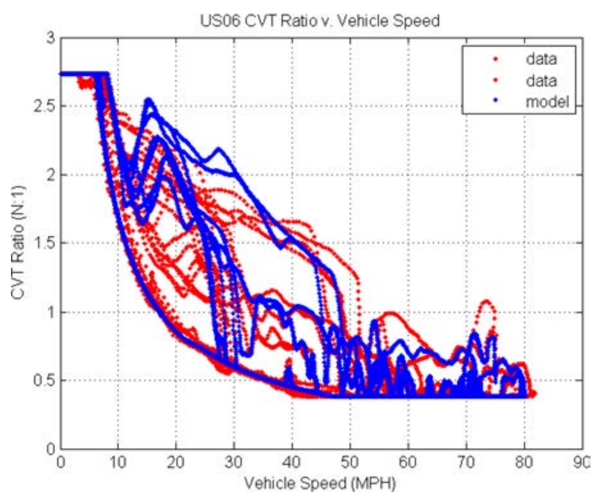

Figure 22. US06 CVT ratio versus vehicle speed

Figure 23 and Figure 24 show the energy weighted engine operation of the test vehicle and the model respectively. Again these charts should be compared qualitatively but one can see the trends are similar. The ALPHAshift-CVT shows some significant operation in the peak efficiency zone of the proxy engine map.

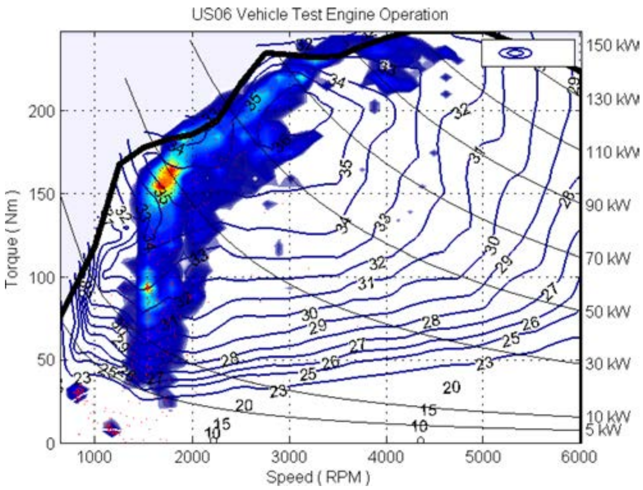

Figure 23. US06 test vehicle energy weighted engine operation estimate

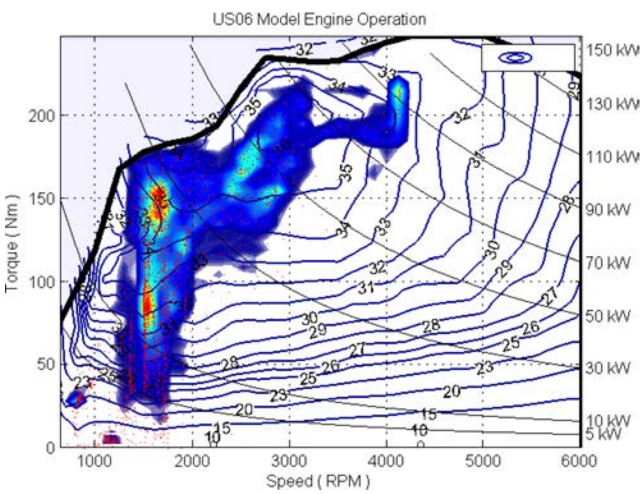

Figure 24. US06 model energy weighted engine operation

Similar plots for the other drive cycles could be analyzed but the UDDS and US06 provide a nice range of opportunities to showcase the performance of ALPHAshift-CVT over low speed and high speed operation and over mild and aggressive drive cycles.

Fuel Economy and CO_2 Results

Modeling results using the modified engine and transmission with ALPHAshift-CVT are shown in Figure 25 and Table 6. The observed vehicle speed trace was used as the target speed for each modeling run to approximate some of the driver behavior and to capture some of the test to test variability. The results presented here represent the averages of the test results and model runs.

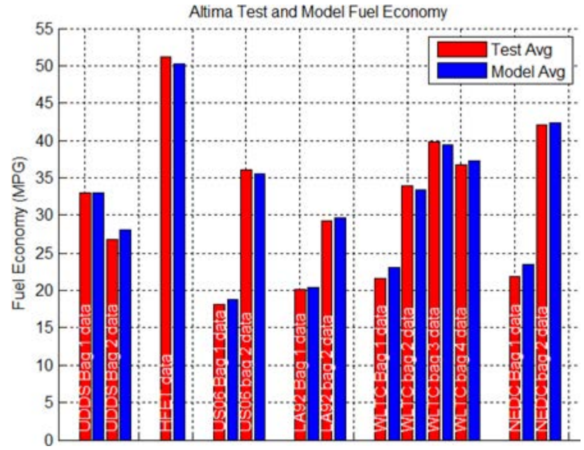

Figure 25. ALPHA MPG modeling results using modified engine map and transmission with ALPHAshift-CVT and observed lockup strategy

Table 6. Average fuel economy and CO_2 results by phase

Drive Cycle	Avg. Test MPG	Avg. Model MPG	MPG Error %	Avg. Test CREE	Avg. Model gCO2/mi	CO_2 Error %
UDDS Phase 1	33.0	33.0	0.1%	267	267	-0.2%
UDDS Phase 2	26.8	28.1	4.6%	329	314	-4.4%
HFET	51.1	50.3	-1.6%	172	175	1.5%
US06 Phase 1	18.1	18.8	3.8%	488	470	-3.7%
US06 Phase 2	36.1	35.5	-1.6%	244	249	1.7%
LA92 Phase 1	20.1	20.4	1.6%	438	432	-1.5%
LA92 Phase 2	29.3	29.6	1.0%	301	298	-1.0%
WLTC_c3 Phase 1	21.7	23.0	6.3%	407	383	-5.8%
WLTC_c3 Phase 2	34.0	33.4	-1.9%	260	265	2.0%
WLTC_c3 Phase 3	39.8	39.5	-0.9%	221	223	0.9%
WLTC_c3 Phase 4	36.8	37.2	1.2%	240	237	-1.1%
NEDC Phase 1	21.9	23.4	7.2%	403	376	-6.7%
NEDC Phase 2	42.1	42.5	0.9%	210	208	-0.9%
Combined EPA City/HWY	36.4	36.9	1.2%	225	224	-0.2%

Given the approximate nature of the input data for these runs a reasonable goal was to obtain modeling results within a 5% tolerance of fuel economy and consumption. As can be seen, the results are satisfactory, many of the results are within 3% and all but 2 are within 5%. For the results with the largest error, the first phases of the WLTC and NEDC drive cycles, it was observed that the engine's fuel rate was significantly higher than the modeled fuel rate in operation at very light loads during torque converter unlocked operation during vehicle braking. This behavior was also noted during the UDDS phase 2. A limitation of the source Malibu fuel map is that no mapping was performed below 20 Nm shaft torque. For this reason, all fuel consumption at light loads is extrapolated from the available test data. In this case there happens to be a discrepancy but a review of test data from other vehicles failed to reveal a similar trend in fuel consumption at light loads (in fact fuel consumption for the Altima appeared higher at 10 Nm load than 20 Nm) so perhaps this behavior is unique to the Altima. In any case, based on our experience with the Malibu, engine mapping procedures have been updated to include light load points in order to obtain accurate results in this area of future maps.

The EPA weighted combined city/highway fuel economy results were excellent as indicated by the last entry in Table 6.

As a thought experiment, alternative scenarios can be run to see what effect they have on fuel economy. The first alternative is to run without de-rating the Malibu engine map or improving the base transmission data. To save space, only the results for the UDDS and HFET drive cycles are presented in Table 7 and subsequent tables.

Table 7. Results without modifying the base engine or transmission data

Drive Cycle	Avg. Test MPG	Avg. Model MPG	MPG Error %	Avg. Test CREE	Avg. Model gCO2/ mi	CO_2 Error %
UDDS Phase 1	33.0	33.4	1.1%	267	264	-1.1%
UDDS Phase 2	26.8	28.0	4.5%	329	315	-4.3%
HFET	51.1	51.6	0.9%	172	171	-0.8%

As another experiment, the unmodified Malibu engine can be paired with the improved transmission (essentially taking the Altima of today and adding GDI), results are in Table 8. In this case there was improvement across the board of roughly 2 to 4% when compared with Table 6.

Table 8. Hypothetical Altima with Malibu engine and proxy Jatco CVT

Drive Cycle	Avg. Test MPG	Avg. Model MPG	MPG Delta %	Avg. Test CREE	Avg. Model gCO2/ mi	CO_2 Delta %
UDDS Phase 1	33.0	34.6	4.9%	267	255	-4.7%
UDDS Phase 2	26.8	29.2	8.9%	329	302	-8.1%
HFET	51.1	53.0	3.6%	172	167	-3.4%

As a sensitivity study the model was run using the observed CVT ratios in place of the ALPHAshift-CVT algorithm. Results are in Table 9. For this test the assumptions were the same as for the runs shown in Table 6 except for the commanded gear ratios. The results show no significant change for the HFET and a slight reduction in fuel economy for the UDDS. This would seem to indicate that the ALPHAshift-CVT algorithm does a reasonable job of approximating the vehicle's ratio strategy.

Table 9. Proxy powertrain results using observed ratio strategy

Drive Cycle	Avg. Test MPG	Avg. Model MPG	MPG Error %	Avg. Test CREE	Avg. Model gCO2/ mi	CO_2 Errpr %
UDDS Phase 1	33.0	32.9	-0.4%	267	268	0.3%
UDDS Phase 2	26.8	27.8	3.6%	329	317	-3.5%
HFET	51.1	50.4	-1.4%	172	175	1.5%

Summary

A Nissan Altima with CVT was modeled using ALPHA. The Altima's powertrain was approximated using available engine and transmission data that was adjusted to provide a comparable powertrain in terms of technology and performance. ALPHAshift-CVT was introduced and its output compared with data from the test vehicle. Even though there was no attempt made to reverse engineer the Altima's transmission strategy, results were similar in terms of observed behavior and fuel economy. Fuel economy and carbon emissions results over a wide range of drive cycles were within 5% of measured values and the city/highway weighted combined fuel economy and carbon emissions were within about 1% of measured values, providing confidence in the proxy powertrain approach.

Development of ALPHAshift-CVT will continue as test data is gathered from CVT-equipped vehicles and their behavior observed. In addition, EPA has a test program underway to gather detailed CVT loss data for the Jatco CVT8 and this data will be used in future modeling work.

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Definitions/Abbreviations

ALPHA - Advanced Light-Duty Powertrain and Hybrid Analysis modeling tool

CREE - Carbon-related exhaust emissions, see 40 CFR 600.113-12

CVVT - Continuously Variable Valve Timing

DOHC - Dual Overhead Camshaft

GDI - Gasoline Direct Injection

HFET - EPA Highway Fuel Economy Test

MPFI - Multi-port Fuel Injection

NVFEL - EPA’s National Vehicle and Fuel Emissions Laboratory located in Ann Arbor, MI

UDDS - EPA Urban Dynamometer Drive Cycle, a.k.a. the “city” cycle

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