2015-01-1142
Published 04/14/2015
doi:10.4271/2015-01-1142
saeeng.saejournals.org

Development and Testing of an Automatic Transmission Shift Schedule Algorithm for Vehicle Simulation

Kevin Newman, John Kargul, and Daniel Barba
US Environmental Protection Agency

ABSTRACT

The Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool was created by EPA to estimate greenhouse gas (GHG) emissions from 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. In order to model the behavior of current and future vehicles, an algorithm was developed to dynamically generate transmission shift logic from a set of user-defined parameters, a cost function (e.g., engine fuel consumption) and vehicle performance during simulation.

This paper presents ALPHA's shift logic algorithm and compares its predicted shift points to actual shift points from a mid-size light-duty vehicle and to the shift points predicted using a static table-based shift logic as calibrated to the same vehicle during benchmark testing. An explanation of, and a process for tuning, the user defined parameters is presented and example applications of the algorithm in transmission and engine sensitivity studies are described.

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

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" [2].

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. In preparation for this evaluation, 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.

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.

This Paper's Focus

In recent years automatic transmission technology has been advancing rapidly, both in terms of the number of gears available and the transmission's overall efficiency. From a system point of view these changes affect the overall greenhouse gas emissions of a vehicle as well as its drivability. Increasing the number of gears enables optimization of where an engine operates in terms of speed and load and may simultaneously provide performance benefits. Transmissions are also being redesigned to reduce parasitic losses and enable engine start-stop, for example.

In order to model a wide variety of transmissions mated with a potentially wide variety of engines EPA has developed a transmission shift algorithm that dynamically calculates shift points during vehicle simulation based on user-defined parameters, driver demand and a cost map (e.g. fuel consumption for conventional vehicles, motor inefficiency or losses for an electric vehicle). This algorithm can be tuned very quickly to provide a reasonable shift strategy with a few easily defined generic parameters or can be tuned to emulate the shift behavior of an actual vehicle. It is also possible to vary the shift parameters to perform "what if" or optimization studies if desired.

The basic logic of the algorithm will be presented as well methods that can be used to tune the shift points based on vehicle test data. A comparison will be made between the performance of the dynamic algorithm described in this paper ("ALPHAshift") and a traditional lookup table-based shift strategy ("TableShift"), using a Chevrolet

Malibu as a test case [3]. Shift metrics will be introduced and short sensitivity studies employing the ALPHAshift algorithm will be presented.

ALPHAshift ALGORITHM OVERVIEW

The basic principle of the ALPHAshift algorithm is to optimize fuel economy - *within defined boundaries*. This is not to be confused with a pure optimization algorithm that prioritizes fuel economy above all other requirements. A properly tuned ALPHAshift parameter set should provide the same benefits as a properly tuned transmission - good fuel economy and good drivability. Because the optimization is based in large part on the engine's fuel consumption map, it follows that changes or improvements to engine fuel consumption will result in new shift points chosen by the algorithm. This allows engines in the model to be swapped or modified without being *required* to change any shift parameters, though retuning is always an available option.

ALPHAshift Parameters

ALPHAshift parameters define the operating boundaries of the shift algorithm, and fall into four categories: cost parameters, speed parameters, performance parameters, time parameters, and setup parameters.

Cost Parameters

The heart of the optimization algorithm is the cost map. This is a two dimensional table whose axes are speed in radians per second and torque in Newton-meters. For a conventional vehicle, the cost map would most likely represent the engine's fuel consumption map. One helpful modification that can be made is to divide the fuel rate at each point in the engine map by the transmission efficiency at each point as a function of load (or speed and load if a complete map is available). Even an approximate efficiency curve can be useful to encourage upshifts at light load operation and low transmission efficiency where there might not otherwise be enough benefit based on the unmodified fuel map alone.

Conceptually, the reason this table is referred to as a “cost” map and not a “fuel” map is to open up the possibility of allowing shifts to occur for reasons other than fuel rate - to avoid NVH concerns, for example. In one simulation case study we performed, there was an engine with a very wide high efficiency plateau that resulted in extended operation at high engine speeds. In this case, multiplying the efficiency map by a penalty function could discourage extended high-speed operation that might be undesirable for NVH reasons.

Also, in terms of cost, one can consider the application of the ALPHAshift algorithm to an electric vehicle where the map would represent motor losses or electrical power consumption rather than fuel consumption.

Table 1. ALPHAshift cost parameters

Parameter	Description
cost_map	A 2D lookup table of the cost of operation at various speeds and loads. Typically the engine fuel map, possibly with modifications.

In the future, we may extend the cost_map to cover costs on a per-gear basis. If, for example, one of the gear ranges is more efficient than the others (e.g., 1:1) we could represent that by having a less costly layer in the map. In this case the map would be a 3D lookup table with one 2D layer per gear.

Speed Parameters

The speed parameters determine the operating range of the transmission in terms of engine speed or transmission input speed measured in radians per second.

For each gear we define the following speed related parameters:

Table 2. ALPHAshift speed parameters

Parameter	Description
min_speed_radps	The speed below which the transmission must downshift, typically encountered during closed throttle decelerations.
max_speed_radps	The speed above which the transmission must upshift, typically encountered (if at all) during wide open throttle runs.
upshift_min_speed_radps	The minimum speed required in a gear before an upshift to that gear is allowed. Provides headroom above the min_speed_radps.
downshift_max_speed_radps	The maximum speed allowed in a gear at the time of downshifting to that gear, typically a percentage of the max_speed_radps. Provides headroom to downshift without hitting the max_speed_radps.
use_engine_speed_mask	A vector of ones and zeros, where a one indicates that engine speed should be used as the speed input to the cost lookup table and a zero indicates that the transmission input speed should be used instead. Can be used to represent gears that typically operate with an unlocked torque converter clutch (ones would be used for the unlocked gears). In the case of other transmissions (e.g. manual, DCT) the engine speed is always the transmission input speed (unless between gears) so either all ones or all zeros may be used.

For simplicity of programming, these and other gear-specific parameters are provided for all gears, including neutral, whether or not that parameter is useful. For example, there is no max_speed_radps which makes sense for top gear - no matter how fast you're going there are no further gears available. These parameters will be unused by the algorithm but simplify the programming through the elimination of special cases - all gears can be handled uniformly with the same code.

In the case of first gear, it may be possible to "downshift" to neutral in the case of a transmission with a "neutral idle" feature. At this time, we have not implemented such a feature but carrying the "neutral gear" through the calculations opens up the possibility of "neutral idle" or even various "sailing" strategies.

Performance Parameters

Several parameters define performance limits for the ALPHAshift algorithm. These are intended to provide reasonable torque and speed reserve after shifting and also prevent spurious shifts based on minimal cost improvements. In the parameters below, "kickdown" refers to shift points that represent unusually high driver demand and act similarly to a kickdown switch in an accelerator pedal that typically triggers a downshift.

Table 3. ALPHAshift performance parameters

Parameter	Description
required_cost_benefit_ratio	Represents the minimum benefit that must be available before a cost based shift will be allowed. Used to prevent spurious shifts based on negligible benefits.
upshift_min_torque_reserve_ratio	Specifies the amount of headroom, in terms of full torque, that must be available above the current load as calculated in the gears above the current gear. For example, a value of 1.1 would limit upshifts to no more than 91% of full torque available in the target gear as the expected load for that gear. Provides headroom to prevent upshifting too close to full load in a higher gear.
kickdown_trigger_ratio	Specifies the ratio of driver desired power to the available power at the current speed that will begin triggering a demand-based downshift. For example, a 1.5 would mean that the driver would have to demand over 1.5 times the available power in the current gear to start the downshift process.
max_speed_shift_increment	Determines the number of gears to shift by when upshifting at max_speed_radps. Typically a vector of ones, but in the case of heavy duty AMTs, a shift increment of two is not uncommon when shifting at redline in the lower gears due to the relatively long shift times where skipping a gear reduces the number of shifts and reduces lost momentum.
max_input_torque_curve_Nm	Used to specify the powertrain torque available (at the input of the transmission) as a function of the transmission input speed. Typically the engine full throttle torque curve. In the case of a hybrid vehicle should also include torque provided from any e-machines that boost engine torque.

At this time, the max_input_torque_curve_Nm is a static vector defined before model execution begins. In the future, we plan to calculate this parameter dynamically to account for torque curves that may vary due to, for example, engine boost pressure or hybrid battery pack state of charge.

Time Parameters

ALPHAshift time parameters implement shift delays and gear commit times. Shift delays are intended to prevent spurious shift requests based on simulation irregularities or high frequency transient driver demands.

Table 4. ALPHAshift time parameters

Parameter	Description
upshift_delay_secs	The amount of time in seconds an upshift request must hold true before an upshift will be commanded. If the upshift request is cancelled, even momentarily, the timer restarts from zero.
upshift_commit_secs	The amount of time in seconds after an upshift has occurred before another shift may take place. Intended to eliminate spurious "change mind" shifts.
downshift_delay_secs	The amount of time in seconds a downshift request must hold true before a downshift will be commanded. If the downshift request is cancelled, even momentarily, the timer restarts from zero.
downshift_commit_secs	The amount of time in seconds after a downshift has occurred before another shift may take place. Intended to eliminate spurious "change mind" shifts.
kickdown_delay_secs	The amount of time in seconds a demand based downshift request must hold true before a downshift will be commanded. If the downshift request is cancelled, even momentarily, the timer restarts from zero. The kickdown timer only increments if the previously commanded gear has been attained and the speed in at least the first gear below the current gear is not above downshift_max_speed_radps.

Setup Parameters

The next few parameters are scalar values, unlike the previous parameters that are specified for every gear (except the max_input_torque_curve_Nm and the cost_map).

Table 5. ALPHAshift setup parameters

Parameter	Description
launch_gear_num	Specifies the normal gear to use when launching from zero speed. In the case of heavy duty transmissions with high-ratio first gears this would typically be set to 2 for a second gear launch.
restrict_shift_parity	If set to 'true' prevents odd-odd or even-even numbered shifts. Used when modeling a DCT to force shifts to alternate between gearbox halves.
restrict_skip_shifts	If set to 'true' forces shifts to be sequential. Does not apply to demand based downshifts (e.g. 6-4 downshift). Typically set to true for transmissions with less than 7 gears.
	but may apply to certain engines where efficiency may be poor at low speeds and high loads.

ALPHAshift Tuning

The ALPHAshift algorithm can be set up with generic parameters or it can be tuned to emulate a specific vehicle. To mimic a particular vehicle it is necessary to have some test data available for comparison. In this section we will look at tuning the ALPHAshift algorithm using data from a 2013 Chevrolet Malibu with a GM6T40 6-speed planetary automatic transmission.

Tuning ALPHAshift is made easier through the reporting of the internal state of the algorithm. A "disability code" is calculated for each gear. The disability code is a binary integer where each bit represents one of the possible reasons why a gear might be unavailable. Another vector represents which available gears have lower cost than the current gear and meet the cost benefit ratio. In addition, the desired gear, desired shift reason, kickdown timer, kickdown ratio and minimum cost gear are logged by the model. All of these signals can be useful in determining why a particular shift did or did not occur as expected.

Tuning Speed Parameters

The speed parameters can be tuned in any order but a simple one to start with is the min_speed_radps. Figure 1 shows a plot of the GM6T40 downshift points over a UDDS drive cycle. Each colored circle represents a point at which the transmission controller declared a downshift as indicated by a CAN message containing the transmission commanded gear.

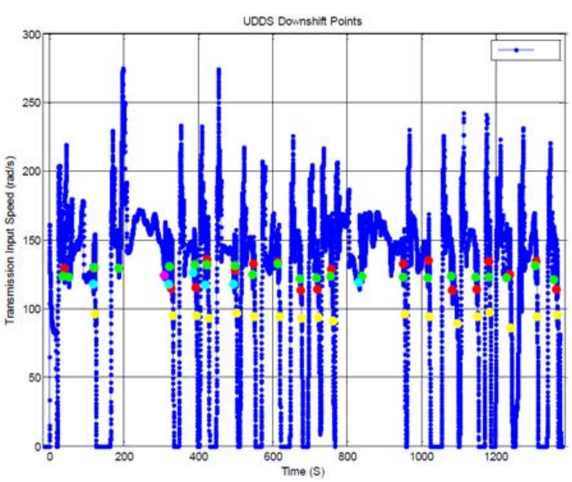

Figure 1. Downshift points over a UDDS drive cycle

One could pick the downshift points from the chart or plot a histogram as shown in Figure 2. The histogram indicates a min_speed_radps somewhere between 112 to 115 radians per second would be a reasonable starting point for second gear.

A closer inspection of the downshift points reveals a slight delay (about a half second) between the time when the gear command is declared and when the shift actually commences. This delay could be used as the downshift_delay_secs or the points could be shifted a half second later and the lower speeds used instead. Figure 3 shows the delay between commanded and actual shift points.

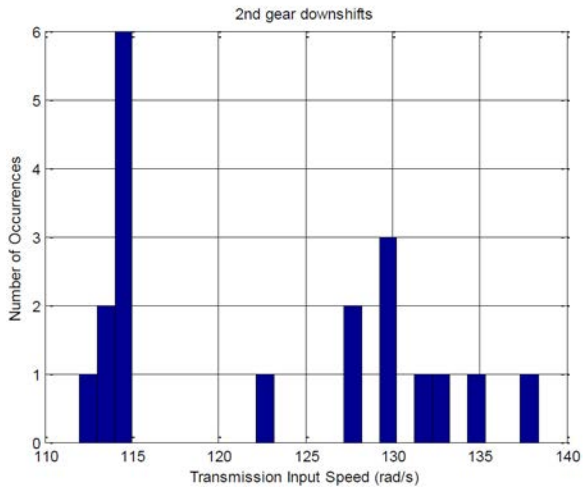

Figure 2. 2nd gear downshift speed histogram

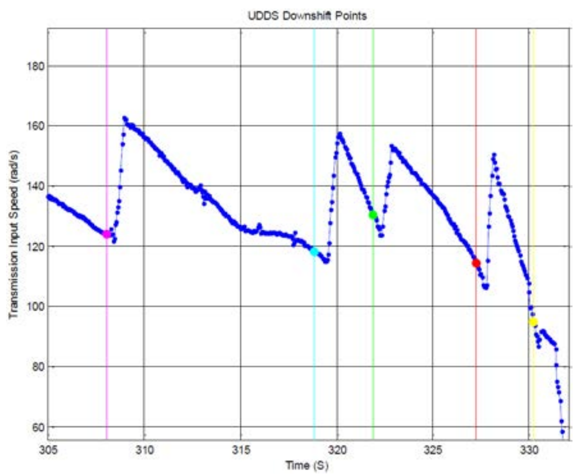

Figure 3. A slight delay between the commanded downshift and the change in speed is observed - about a half second

The upshift_min_speed_radps can be identified using similar methods. Figure 4 shows the upshift points for the same UDDS drive cycle. Clearly there is more scatter to the shift points, but we are only looking for the minimum speeds (post-upshift) for each gear.

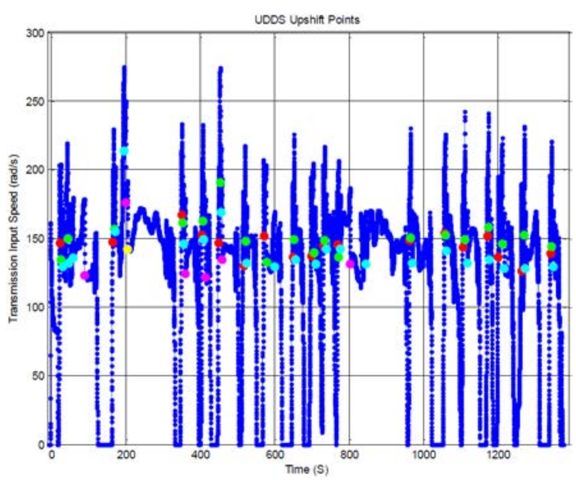

Figure 4. Upshift points over a UDDS drive cycle

The histogram in Figure 5 shows the post-upshift speeds for fourth gear. From the chart, somewhere in the neighborhood of 126 radians per second would be a good starting point for upshift_min_speed_radps for fourth gear.

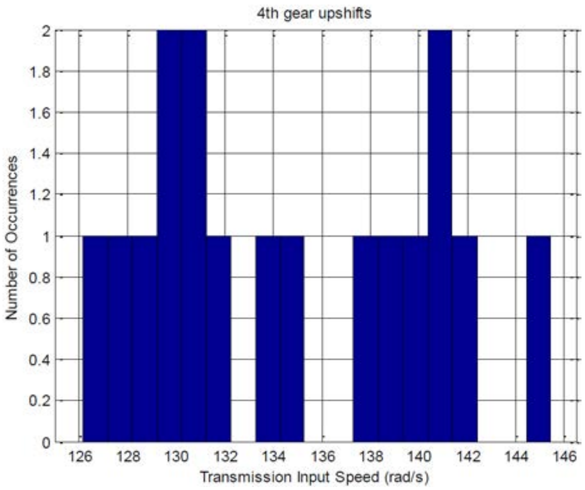

Figure 5. Post-upshift speeds for 4th gear over a UDDS drive cycle

The upshift speeds don't need to be time shifted since they are already identified accurately, as shown in Figure 6.

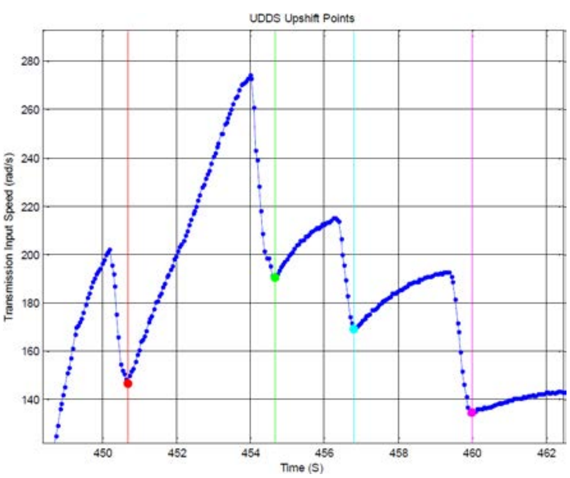

Figure 6. Post-upshift speeds don't have a time delay

The max_speed_radps can be set to the engine's redline speed or the speeds could be identified from full throttle acceleration test data or other methods [4].

The downshift_max_speed_radps may be identified from vehicle data. In the absence of vehicle data, our typical default is 85% of the max_speed_radps as a starting point. Since high speed downshifts are rarely, if ever, encountered during certification drive cycles, this parameter serves primarily as a sanity check on the model's behavior.

The use_engine_speed_mask is used for automatic transmissions with lockup torque converters. Gears that typically operate unlocked would be identified by ones in this vector, as discussed previously. Gears with a one in the mask use engine speed to calculate the speed and load points that are the inputs to the cost map lookup table. Gears with a zero in the mask use transmission gearbox input speed. The mask helps capture some of the shifts that occur across lockup boundaries, for example comparing the speed and load of 3rd gear unlocked to the speed and load of 4th gear locked.

Tuning Performance Parameters

The performance parameters are easily adjusted with the possible exception of the kickdown_trigger_ratio, discussed below.

The required_cost_benefit_ratio is typically set to require at least a 1% cost improvement before allowing an optimization-based shift. This parameter can be experimented with to see how the model responds to higher or lower values. In practice, most of the shift points are determined by driver demand and the previously tuned speed limits so this parameter is mostly used to prevent spurious shifts for benefits of negligible value.

The upshift_min_torque_reserve_ratio might be observable from vehicle data but as a starting point we usually use this to limit upshifts by requiring at least 10% torque headroom (compared to the max torque curve) at the post-upshift target speed and load.

The kickdown_trigger_ratio represents the driver demand in excess of the power available from the driveline at the current speed that will begin a demand-based downshift. Available power is not calculated by the ALPHAshift algorithm but is provided by the components upstream of the transmission.

The US06 drive cycle usually provides a few opportunities to set the kickdown_trigger_ratio. An accurate engine maximum torque curve is essential for tuning this parameter. If the model's engine torque curve is unrealistically low compared to the real engine then the performance deficit is likely to trigger extra demand based downshifts. This parameter can also be sensitive to the driver model, for example if the driver model is more aggressive than an actual driver then more downshifts are likely to be triggered.

The kickdown_trigger_ratio is sensitive to the driver model and the drive trace as well as the powertrain capacity but a reasonable starting point is to set the ratio to somewhere in the range of 1.25 to 1.50. Setting the ratio too high may result in the vehicle falling off the drive cycle before requesting a downshift. Setting the ratio too low may result in aggressive downshifting depending on the driver model and target drive cycle. The second phase of the US06 (the high speed driving portion), in particular, is sensitive to driver behavior - many of the high speed high frequency “wiggles” in the drive trace are difficult to duplicate for most human drivers. The driver model, on the other hand, can and will follow every undulation of the drive cycle and this can cause some unrealistic downshifts relative to the human driver. A simple solution to this problem is to use the vehicle's recorded speed trace as the target speed for the model. One caveat with this method is to make sure that the driver model follows the target data closely to avoid adding any extra speed error relative to the original dynamometer drive cycle target. The target data should be appropriately filtered or signal conditioned to avoid the driver model also following any noise in the signal.

The max_speed_shift_increment determines whether the transmission will skip shift at max_speed_radps. This parameter is typically set to one for a light duty application. Setting it to two to allow skip shifting would be appropriate for the lower gears in a heavy duty AMT with a large number of gears, as discussed previously.

The max_input_torque_curve_Nm is calculated before the model runs and is set to the engine's torque curve for a conventional light duty vehicle.

Tuning Time Parameters

The time parameters are mostly used to prevent spurious shifts, but can also help force the optimization algorithm to delay shifts in order to match the behavior of an actual vehicle if the previously determined speed limits alone are not enough to produce accurate shifts.

A good starting point for the upshift_delay_secs and downshift_delay_secs is around 0.1 seconds, although it's typical to use higher delays in the higher numbered gears. It's good practice to leave these delays short at first and then increase as required if too many early shifts are detected.

The upshift_commit_secs and downshift_commit_secs can be determined by observation of the test data, looking for the shortest durations in each gear. Generically, for a six-speed transmission, an upshift_commit_secs of 1.5 seconds and a downshift_commit_secs of 1.0 seconds seem reasonable. Increasing the number of gears will have a tendency to decrease the commit times - transmissions with more gears typically move through them faster on a per-gear basis. For example, a commit time of 1.5 seconds on a six-speed might become 1.125 seconds for an eight-speed by the ratio of the number of gears.

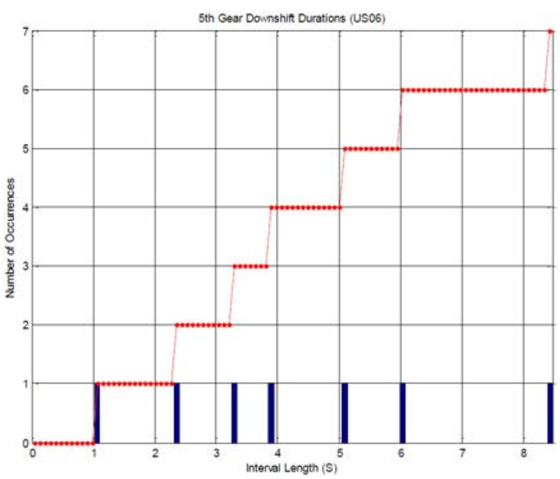

Figure 7. 5th gear downshift durations (US06)

Figure 7 and Figure 8 show downshift and upshift durations, respectively, for 5th gear over a US06 drive cycle. From this data set the minimum downshift duration was about 1 second and the minimum upshift duration was around 1.25 seconds. Multiple drive cycles can be analyzed in similar fashion to determine the most reasonable commit times.

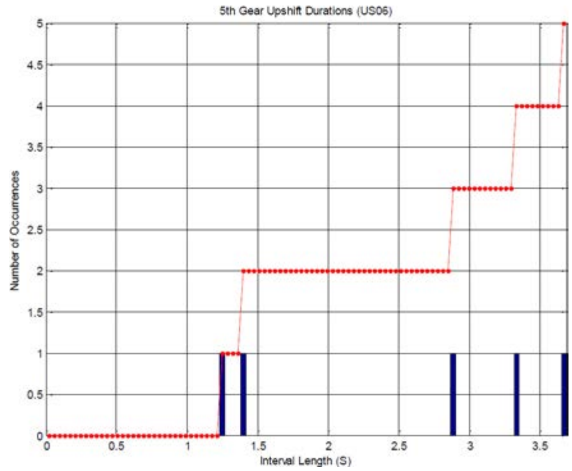

Figure 8. 5th gear upshift durations

The kickdown_delay_secs can be kept small, 0.1 seconds or less since there is already an inherent delay due to the time required for the driver demand to reach the kickdown_trigger_ratio. If the kickdown delay is too long the vehicle is likely to fall off the trace significantly before a downshift is triggered, possibly leading to fuel economy and performance penalties compared to the test vehicle. At the time of this writing, the kickdown request is also subject to the downshift_delay_secs in addition to the kickdown_delay_secs. This is likely to change in a future revision since it can make tuning the downshifts more challenging because of the relationship between the delays.

Tuning Setup Parameters

The setup parameters are essentially determined by the transmission technology and/or application. See Table 5 and the parameter descriptions for more information.

Shift Metrics

Once the basic parameters have been determined and the model has been run, it is helpful to have a set of metrics to determine the accuracy of the settings and to guide further tuning.

For multiple sets of test data over a given drive cycle, the "shift envelope" for the vehicle can be calculated. The shift envelope is determined by the highest and lowest gear selections observed during vehicle operation at each point in time on the drive cycle. Figure 9 shows an example for the first hill of the UDDS drive cycle. The red line is the maximum observed gear and the blue line is the minimum observed gear over all the tests. Where the lines are on top of each other there is no variation among the tests. Where there is space between the lines there is some variation among the tests.

It can be seen from the figure that for at least one of the tests there was a downshift at about 40 seconds and for one or more tests there was not. The downshift points after 115 seconds can be seen to be highly consistent among the test cycles.

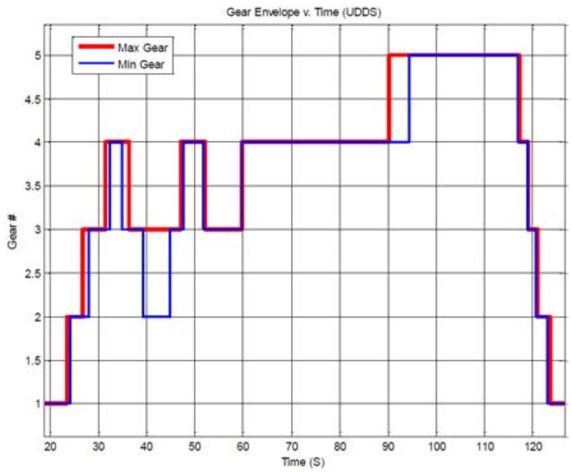

Figure 9. Example shift envelope showing normal shift variability over three tests, first hill of the UDDS

The first measure of shift accuracy is the percentage of time spent within the shift envelope while the modeled vehicle is moving (the standing idle gear is of little interest unless an idle neutral strategy or similar technology is being studied). This is shown as "Accuracy Percent" in Table 6.

The shift behavior can also be compared to the shift envelope to see if the model is shifting early or late and under what circumstances. Figure 10 shows the performance of the model for the first hill over the UDDS, and indicates good agreement between the modeled shift points and the actual shift points in the vehicle's test data.

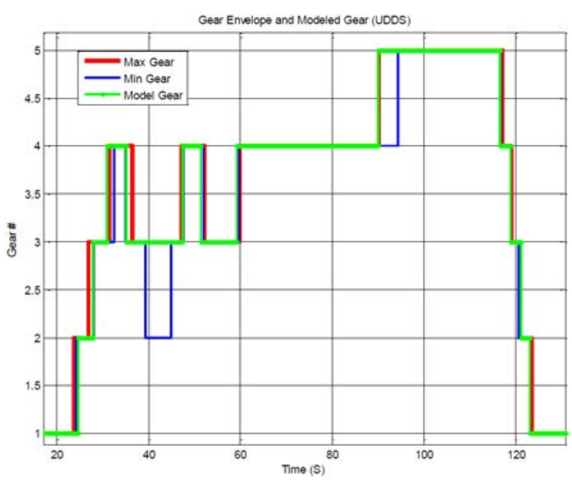

Figure 10. Shift envelope and modeled gear

As additional metrics for the model run, the total shift count, total number of upshifts and downshifts, number of shifts per gear and number of shifts per mile can be calculated.

For each gear we calculate the amount of time the modeled gear is too high (above the envelope), too low (below the envelope), how early and how late it upshifted and downshifted (all downshifts and deceleration downshifts separately) as well as the minimum duration in gear after upshifting and downshifting.

Table 6 shows the shift metrics for the complete model run partially shown in Figure 10. The results show a high accuracy of over 97% and represent a well-tuned set of parameters.

Table 6. Model shift metrics for a UDDS drive cycle

US = Upshift	*DS = Downshift*				
US Count	DS Count	Total Shift Count	Shifts per Gear	Shifts per Mile	Accuracy Percent
65	65	130	21.7	17.3	97.4
Gear Number	Too High Seconds	Early US Seconds	Late DS Seconds	Late Decel DS Seconds	Min US Seconds
1	0.00	0.00	0.00	0.00	
2	0.57	0.00	0.00	0.57	2.82
3	4.39	1.16	0.00	3.24	2.16
4	6.25	5.73	0.00	0.52	2.13
5	0.40	0.40	0.00	0.00	4.21
6	0.00	0.00	0.00	0.00	103.92
Gear Number	Too Low Seconds	Late US Seconds	Early DS Seconds	Early Decel DS Seconds	Min DS Seconds
1	9.09	8.42	0.67	0.00	0.69
2	2.43	2.42	0.00	0.01	1.09
3	2.74	1.31	0.00	1.43	1.09
4	3.27	2.33	0.48	0.45	1.65
5	0.00	0.00	0.00	0.00	9.77
6	0.00	0.00	0.00	0.00	

The late and early deceleration shift times help tune the min_gear_speed_radps as changes to the parameter are generally clearly reflected in the metrics. In general the metrics help draw attention to the shift parameters that need the most adjustment. However, the metrics should be used in conjunction with the shift envelope plot as shown in Figure 10. Sometimes a single "missed" shift can add several tens of seconds of total error time when most of the other shifts might be quite good. Of course one could add more statistics such as median error time or the standard deviation of the error time, etc, but the given metrics are a good aid in tuning the ALPHAshift parameters.

Care should be taken to avoid moving error from one metric to another. For example, there is the risk of taking a gear's late upshift time and turning it into the next gear's early upshift time depending on the width of the shift envelope.

The shift metrics should be observed over as many drive cycles as possible. A good starting point for tuning seems to be the first phase of the UDDS (the first 505 seconds). If the basic shift points are well matched then the whole UDDS may be studied followed by the US06 for the high performance shift points.

COMPARISON OF ALPHAshift AND TABLESHIFT BEHAVIOR

This section compares the tuned Malibu ALPHAshift model runs with a traditional lookup table-based shift strategy (TableShift) model runs. The TableShift data for the Malibu was gathered during a previous in-vehicle test program [3]. Figure 11 shows the shift point data. Note that the table is somewhat incomplete due to the inability to encounter all possible shift points during testing, particularly the 5th and 6th gear loaded downshifts.

The upshift points were gathered by driving the vehicle on level ground and applying fixed pedal increments (as close as possible while driving) and progressing through the gears until the vehicle speed stabilized.

Downshifts were measured on a chassis dynamometer at the same pedal positions used previously to determine upshift points by allowing the vehicle to accelerate to top speed for the given pedal position and then applying a 30 second dynamometer deceleration (with pedal position still fixed) to zero vehicle speed.

The data were parameterized to accelerator pedal position in percent and transmission output shaft speed in RPM.

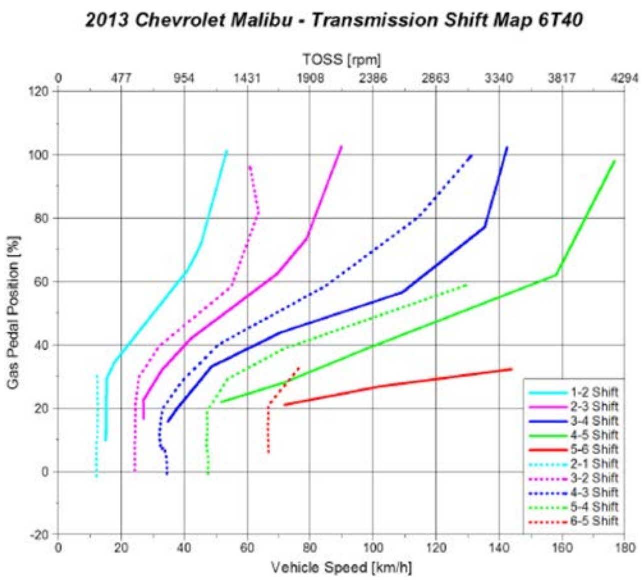

Figure 11. A partial shift table for the Chevy Malibu generated from in-vehicle test data

An issue with the use of in-vehicle shift tables is that they are typically parameterized to accelerator pedal position. In order to work properly in a model there must be some correlation between the vehicle's pedal position and the model's pedal position as a function of powertrain load. Such a mapping can be difficult to obtain or model and usually requires remapping the model's driver demand (which might be in terms of wheel torque, for example) to something resembling a pedal position. In the case of the Malibu, the vehicle's pedal correlates well with power demand, as seen in Figure 12.

The Chevrolet Malibu was modeled in ALPHA using both the TableShift and ALPHAshift strategies. The fuel economy results were within about 1% of each other and the shift points were fairly well matched over the UDDS and HWFET drive cycles. On the US06 drive cycle, TableShift experiences more shifts than ALPHAshift, it also upshifts earlier and in general seems to “hunt” more. For the sake of simplicity, the shift envelope is not plotted in the figures below, however the envelope accuracies are presented in Table 7 for both algorithms.

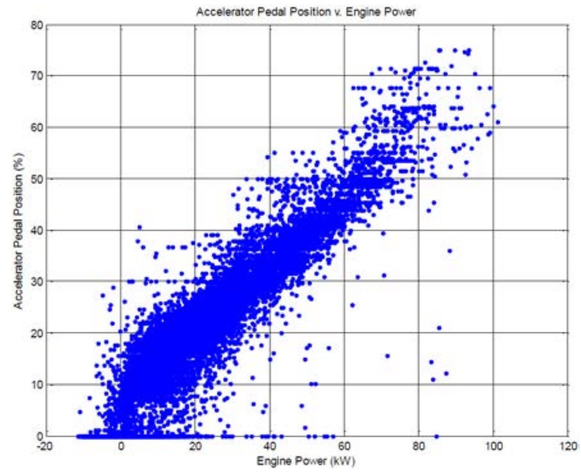

Figure 12. Malibu accelerator pedal position versus (estimated) engine power

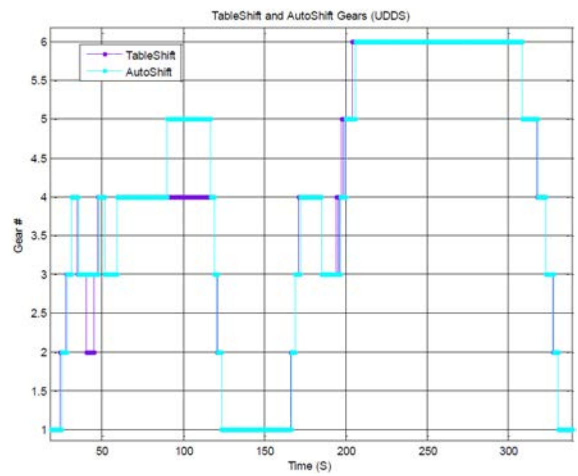

Figure 13. TableShift and ALPHAshift at the beginning of the UDDS

For the UDDS, as partially shown in Figure 13, the downshift points generally matched well. There was some variability on the first hill and the TableShift hunted a little accelerating up the second hill (around 200 seconds on the chart).

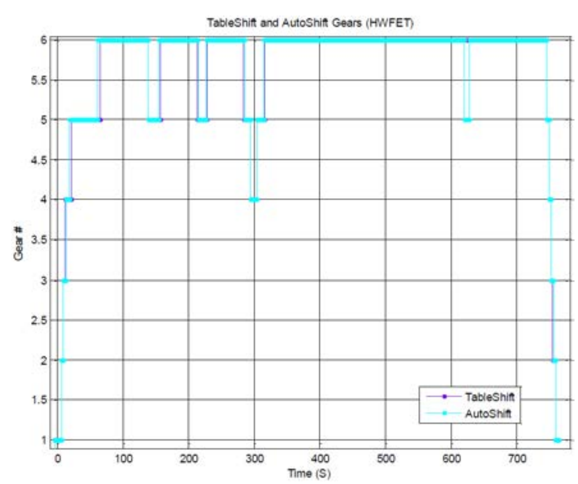

Figure 14. TableShift and ALPHAshift over the HWFET

For the HWFET, as shown in Figure 14, the two strategies were closely matched. The ALPHAshift had an extra high demand downshift towards the end of the cycle for this particular model run.

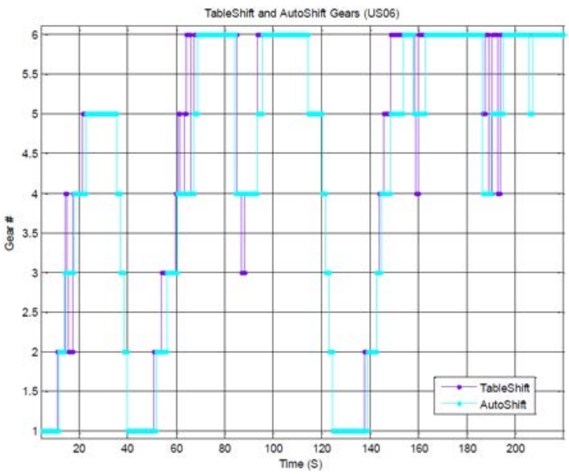

Figure 15. TableShift and ALPHAshift at the beginning of the US06

For the US06, as shown in Figure 15, there was much more variability between the strategies. In general, the TableShift had more shifts, had a tendency to upshift earlier and seemed to hunt quite a bit more. In general, we found that the TableShift strategy could perform well for either the UDDS/HWFET or the US06 but not both. It's possible that either the pedal map was inaccurate or there are other delays or timing variables required to make the strategy work properly.

Table 7. ALPHAshift and TableShift comparisons

Cycle	Error Time (Seconds)	Accuracy (%)	Number of Shifts	Model Fuel Economy (MPG)
UDDS	29.14	97.4	130	28.54
ALPHAshift				
UDDS TableShift	62.50	94.4	134	28.86
HWFET ALPHAshift	12.85	98.3	20	45.29
HWFET TableShift	18.45	97.6	18	45.21
US06 ALPHAshift	32.77	94.1	77	27.51
US06 TableShift	43.52	92.2	83	27.48

Table 7 shows some of the shift metrics for the ALPHAshift and TableShift strategies. We are very pleased with the 94- 98% accuracy shown by this tuned ALPHAshift parameter set.

The TableShift has higher error times (which include both times too high and times too low) and somewhat higher shift count but the overall effect on fuel economy is small due to the fact that most of the extra downshifts (which tend to reduce fuel economy) were caused by early upshifts (which tend to improve fuel economy).

Compared to TableShift, we feel ALPHAshift is easier to tune, matches shift timing as well as or better, can be tuned without requiring a special test matrix, does not require a conversion between vehicle pedal and model "pedal", can adapt automatically to changes in engine efficiency and is easily extensible to higher or lower numbers of gears. For these reasons, we will continue to use and develop the ALPHAshift algorithm and will no longer be gathering shift table information from future vehicle and transmission benchmarking programs.

USING ALPHAshift IN SENSITIVITY STUDIES

Since the ALPHAshift algorithm is parameterized, it is relatively easy to perform sensitivity studies by varying some or all of the parameters (or the engine itself) and observing the results.

Effect of Varying Minimum Shift Speed

A sensitivity study was performed to analyze the effect of minimum shift speed on the number of shifts and fuel economy.

For the Malibu we ran the study by varying the min_speed_radps from 126 rad/s (1200 RPM) down to 83.8 rad/s (800 RPM). The upshift_min_speed_radps was set to min_speed_radps + 10 rad/s to provide headroom. The speeds were made constant across all gears, for simplicity, and the vehicle was driven over the UDDS drive cycle. Using flat minimum speeds across all the gears resulted in a slight positive offset to the fuel economy originally modeled.

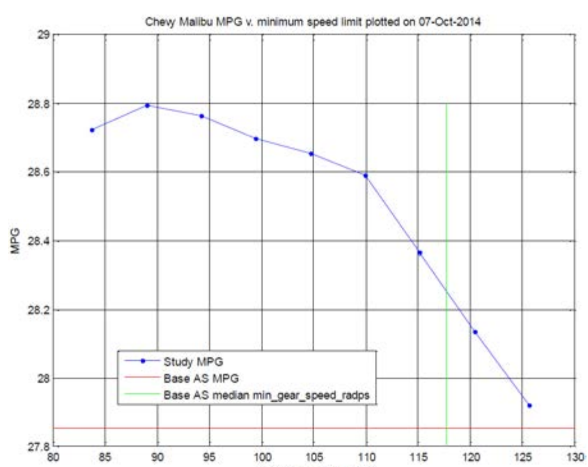

Figure 16. Fuel economy versus min_gear_speed_radps

Figure 16 shows the results in terms of MPG versus min_gear_ speed_radps. For reference, the horizontal red line represents the model fuel economy running the original ALPHAshift parameter set, which varies min_speed_radps on a per-gear basis. The vertical green line is the median min_gear_speed_radps from the original

ALPHAshift parameter set. On the basis of this chart it appears there may be some potential benefit to reducing the minimum shift speed on the Malibu. Below 110 rad/s the returns diminish but some small gains might still be possible.

Figure 17 shows the number of shifts versus the minimum shift speed. For reference, the horizontal red line represents the number of shifts of the original ALPHAshift parameter set. The vertical green line is the median min_gear_speed_radps from the original ALPHAshift parameter set. Below 110 rad/s the number of shifts over the drive cycle increase significantly for only marginal fuel economy benefits. The increased number of shifts can be partially explained by the limited available engine torque at low engine speeds causing an increased number of demand-based downshifts. The remainder are probably due to the reduced speed hysteresis in the lower gears compared to the original ALPHAshift parameter set.

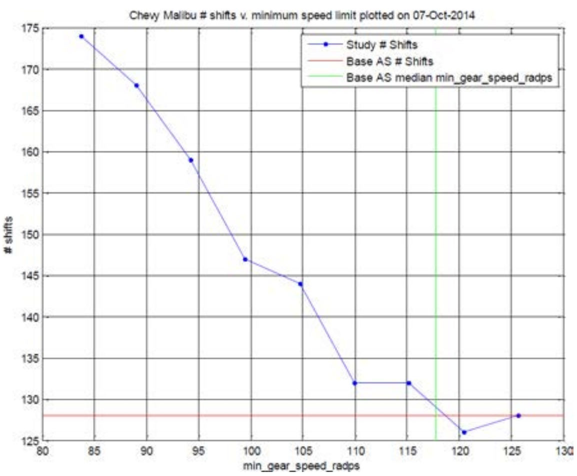

Figure 17. Number of shifts versus min_gear_speed_radps

Figure 18 compares the shift points for the lowest speed in the study to the original vehicle shift points and clearly shows an increased affinity for 5th and 6th gears as might be expected from a 40 rad/s drop in minimum shift speed.

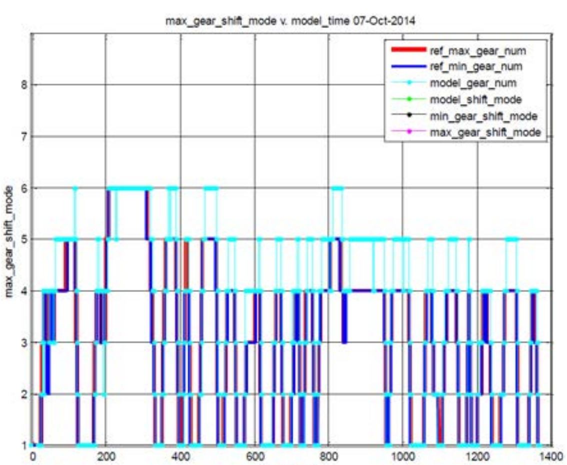

Figure 18. Case study shift points versus baseline shifts points for an 83.8 rad/s minimum speed

Effect of Changing Engines

Since the ALPHAshift algorithm calculates shift points dynamically it's possible to run different engines without being required to alter any shift parameters.

The next few figures demonstrate the operation of the stock Malibu engine, an alternative engine and the alternative engine with disable_cost_saving_downshifts set to false (cost saving downshifts enabled). All three are run with the same ALPHAshift speed and performance parameters over the UDDS drive cycle. Compared to the stock engine, the alternative engine has a high efficiency plateau that covers lower torques and higher speeds.

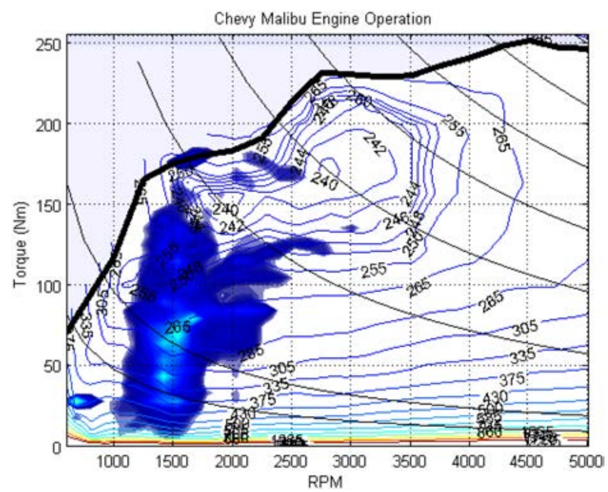

Figure 19. Baseline engine operation

The baseline engine rarely, if ever, reaches its peak efficiency over the UDDS drive cycle, as seen in Figure 19. The blue highlighted area in this figure and others represents a two-dimensional histogram of the mechanical energy produced by the engine at each speed and load point.

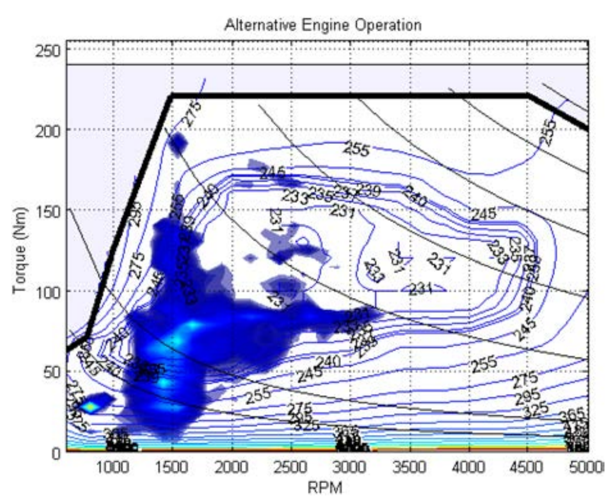

Figure 20. An alternative engine with the same shift parameters

When applying the alternative engine in Figure 20, there is some operation at higher speeds at about 80 Nm of torque. This operation may, or may not, be acceptable behavior from the point of view of a real-world vehicle but for the purposes of this demonstration it shows ALPHAshift following the outlines of the high efficiency plateau.

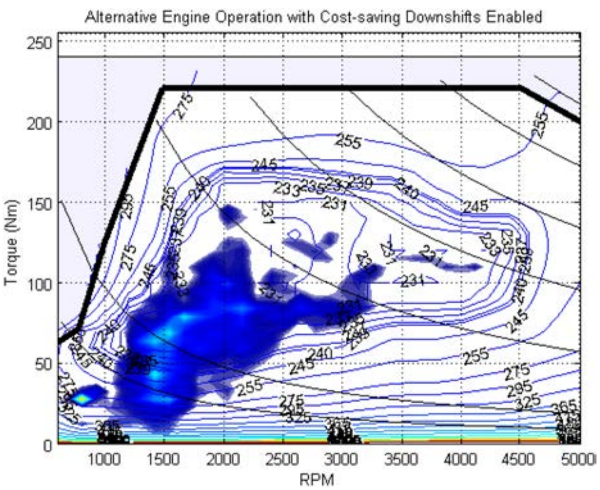

Figure 21. An alternative engine with cost saving downshifts enabled

As seen in Figure 21, for this particular alternative engine, enabling cost saving downshifts allows further operation at high efficiency since the less efficient high torque operation at 1500 RPM has been shifted to the middle of the plateau.

SUMMARY/CONCLUSIONS

The ALPHAshift algorithm works well to predict real vehicle shift points when tuned with vehicle data and enables automatic adjustment for changes in the engine or the number of gears in the transmission. The parameters can be quickly set up for a generic case or can be tuned to a specific vehicle relatively quickly even with a limited set of test data. In addition to the work presented in this paper, the ALPHAshift algorithm has been tested against 5 and 8 speed Light Duty automatic transmissions and also Medium and Heavy Duty transmissions for use in EPA's next-generation GEM [5] Heavy Duty Greenhouse Gas certification tool.

Work on ALPHAshift is ongoing and improvements to the algorithm will likely continue. We anticipate obtaining more information about how various transmissions (both light duty and heavy duty) operate, and adding the ability to model additional features such as neutral idle. Development of the ALPHAshift algorithm for CVTs is planned as we gather data on the operation and characteristics of the latest CVT implementations.

REFERENCES

1. Lee, B., Lee, S., Cherry, J., Neam, A. et al., "Development of Advanced Light-Duty Powertrain and Hybrid Analysis Tool," SAE Technical Paper 2013-01-0808, 2013, doi:10.4271/2013-01-0808.
2. US EPA, DOT/NHTSA, "Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards, Joint Technical Support Document," http://www.epa.gov/otaq/climate/regulations/420r10901.pdf, Aug. 2012
3. Newman, K., Kargul, J., and Barba, D., "Benchmarking and Modeling of a Conventional Mid-Size Car Using ALPHA," SAE Technical Paper 2015-01-1140, 2015, doi:10.4271/2015-01-1140.
4. Kim, N., Rousseau, A., and Lohse-Busch, H., "Advanced Automatic Transmission Model Validation Using Dynamometer Test Data," SAE Technical Paper 2014-01-1778, 2014, doi:10.4271/2014-01-1778.
5. US EPA, "Greenhouse Gas Emissions Model (GEM) for Medium- and Heavy-Duty Vehicle Compliance," http://www.epa.gov/otaq/climate/gem.htm, May 2013.

CONTACT INFORMATION

Kevin Newman, M.Eng.
National Center for Advanced Technology
US EPA - Office of Transportation & Air Quality
newman.kevin@epa.gov

ACKNOWLEDGMENTS

Thanks to Anthony Neam, US EPA, for the use of his original shift optimizer implementation.

DEFINITIONS/ABBREVIATIONS

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

UDDS - US EPA Urban Dynamometer Driving Schedule

HWFET - US EPA Highway Fuel Economy Test

US06 - US EPA Supplemental Federal Test Procedure (SFTP)