

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 that of a lookup table-based shift strategy ("Table Shift"), using a Chevrolet

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

ALPHAsift ALGORITHM OVERVIEW

The basic principle of the ALPHAsift 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 ALPHAsift 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.

ALPHAsift Parameters

ALPHAsift 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 ALPHAsift algorithm to an electric vehicle where the map would represent motor losses or electrical power consumption rather than fuel consumption.

Table 1. ALPHAsift 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. ALPHAsift 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 ALPHAsift 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. ALPHAsift 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_rads. 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

ALPHAsift 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. ALPHAsift 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_rads.

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. ALPHAsift 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 drops at low speeds and high loads.

ALPHAsift Tuning

The ALPHAsift 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 ALPHAsift algorithm using data from a 2013 Chevrolet Malibu with a GM6T40 6-speed planetary automatic transmission.

Tuning ALPHAsift 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.

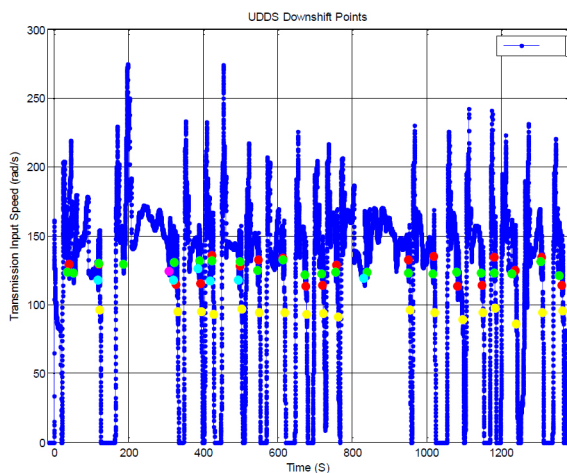


Figure 1. Downshift points over a UDDS drive cycle

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.

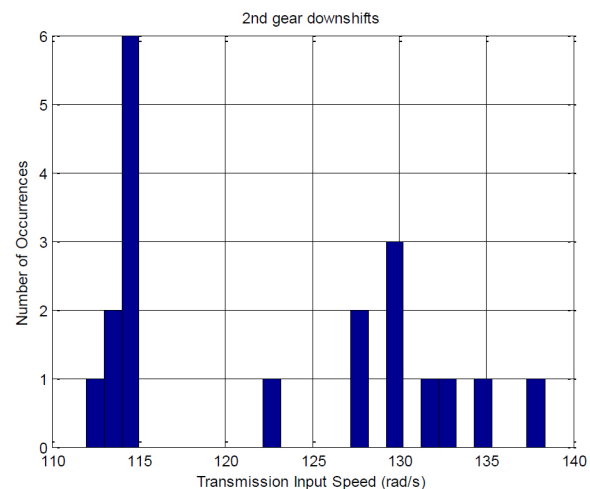


Figure 2. 2nd gear downshift speed histogram

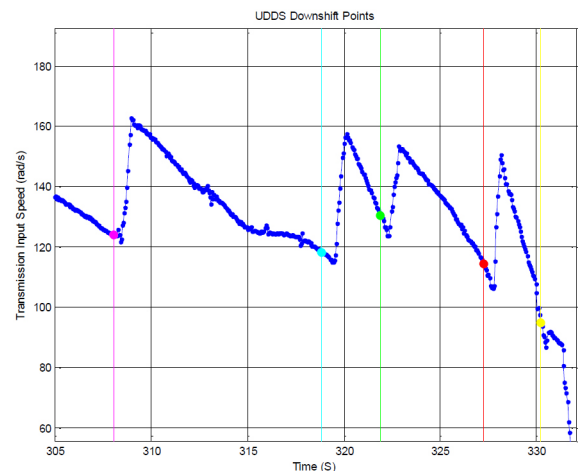


Figure 3. A slight delay between the commanded downshift and the change in speed is observed - about a half second

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.

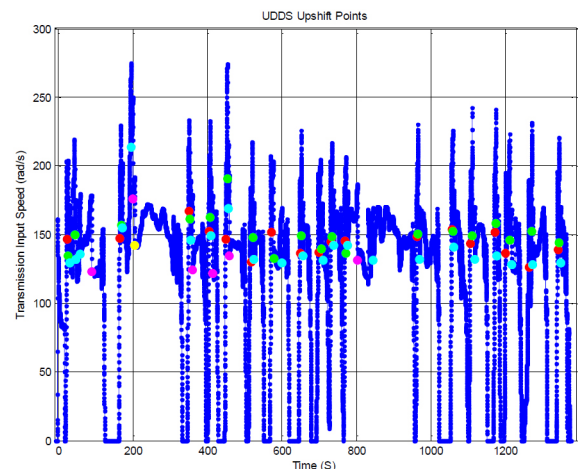


Figure 4. Upshift points over a UDDS drive cycle