Constructing Engine Maps for Full Vehicle Simulation Modeling

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Abstract

The Environmental Protection Agency (EPA) has collected a variety of engine and vehicle test data to assess the effectiveness of new automotive technologies in meeting greenhouse gas (GHG) and criteria emission standards and to monitor their behavior in real world operation. EPA's Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool was created to estimate GHG emissions from vehicles using various combinations of advanced technologies and has been refined using data from testing conducted at EPA's National Vehicle and Fuel Emissions Laboratory.

This paper describes a process for constructing complete engine maps using engine dynamometer and in-vehicle test data for use in ALPHA or any other full vehicle simulation which performs similar analyses. The paper reviews how to use available steady state and transient test data to characterize different operating conditions, and then combine the data to construct a complete engine map suitable for ALPHA model simulation. The paper also discusses the use of default values when specific engine test data are unavailable. Finally, tools used to assess the quality of the generated complete engine maps are presented.

Introduction

Expanded availability of complete, well documented engine data is needed by the broad technical community to accelerate assessment and development of new technologies to meet increasingly stringent emissions and fuel economy standards. Data regarding the latest advanced technology production engines represent an important touchstone, highlighting cutting edge concepts which exist in production vehicles and may shift to the mainstream fleet within the next few years. However, publicly available fuel maps for recently introduced engines that are suitable for in-depth technical analysis and use in full-vehicle simulation models are rarely available. Published engine maps tend to be incomplete and fail to show the whole operating range of the engine. In addition, supporting detailed information describing the data collection methods and generation of the complete map from test data is seldom, if ever, provided. For example, two recent engine technology papers with excellent technical content provide only limited engine maps, and provide no information on data collection and map generation methods [1, 2].

The National Center for Advanced Technology (NCAT) located at EPA's National Vehicle and Fuel Emissions Laboratory in Ann Arbor, Michigan, has developed technical methods to assess the effectiveness of advanced low-emission and low-fuel consumption technologies for a broad range of light-duty vehicle applications. NCAT characterizes advanced technology vehicles, engines and transmissions using scientific laboratory testing and analysis methods to benchmark emissions and fuel consumption performance.

Much of this technology effectiveness is performed using vehicle simulation based upon the EPA developed tool ALPHA. ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types with different powertrain technologies, showing realistic vehicle behavior, and auditing of internal energy flows within the model [3, 4]. The engine model within ALPHA is 0-D, based primarily around a map of fuel consumption versus speed and output torque. Additional terms constrain the range of available engine torque along with time constants to limit changes in engine torque for transient operation. The final component of the engine model consists of adjustment factors to replicate observed behaviors such as additional fueling following a fuel cut off event or during aggressive transient engine operation [5]. The ALPHA engine model is intended to be generic, providing a simple relationship between fuel consumed relative to engine speed and torque both of which are informed by the simulated downstream powertrain components and the driver model.

To properly characterize a vehicle's overall fuel consumption and performance, a complete engine map that describes the engine's fuel consumption across the entire operating range of the engine including idle, wide-open-throttle, minimum motoring torque and maximum operating speed is essential. During engine benchmarking, NCAT collects both steady state and transient test data to characterize these different operating conditions, using scientific test methods and procedures. More detail on these test processes are included in previously published papers [6, 7, 8, 9, 10].

These test data must be combined to construct a complete engine map suitable for ALPHA model simulation. When creating engine maps for fleet level simulation, it is important to use a consistent process. In fleet level simulation a variety of constructed engine maps are scaled and mated to different powertrains and differing vehicle technologies for large scale simulation [11]. Consistent map construction enables the meaningful comparison of different engines and allows proper characterization of the effects of new vehicle technologies, including their interaction with different engine maps. To enable a consistent process, much of the data processing methods discussed later in the paper are incorporated into a single function for consistent application.

Moreover, there are some cases where portions of the input data are unavailable - for example, when using published engine maps where no source data are included. In these cases, a consistent process for establishing values of missing simulation inputs is also important. Some parameters such as minimum engine torque or time constants associated with engine torque are necessary for simulation, but relatively benign in comparing fuel consumption. As discussed later, employing consistent assumptions and default values to fill any undefined parameters enables more meaningful comparison when working with partial data sets.

The remainder of this paper outlines the process for constructing engine maps from full or partial data sets in a robust and consistent way. This includes working with test data, working with published maps, and establishing consistent default values for potentially missing data. This process ensures that, whether utilizing benchmarking test data or other published technical materials, the difference between engines can be estimated in full vehicle simulation engineering analyses over both standard certification cycles and real world operation.

Engine Operating Regions & Data Sources

While ALPHA uses a wide range of model parameters in its engine model, the vast majority of engine operation and fuel consumption is defined by three main parameters. The base fuel map along with the maximum and minimum torque curves, which define the basic boundaries of engine operation, are responsible for more than 95% of the total fuel consumption. The remaining fuel consumption occurs during transitions between operating points on the map, as discussed in previous EPA papers examining the effects of spark retard for torque management or extra fuel associated with deceleration fuel cut-off or other transient phenomena. [4, 5]

The processes used for collecting test data to establish the base fuel map often vary, and are constrained by available testing capabilities. A focus of the EPA engine testing program is to enable simulation within ALPHA for estimating vehicle fuel consumption, and thus the test conditions and procedures are intended to facilitate data use in simulation. The test process replicates a warm engine in normal operating

conditions, established by observing parameters such as coolant temperatures, intake and intercooler air temperatures. Details of the test configuration for engines benchmarked by EPA are available in their test reports [12]. As the testing is focused on warm engines additional adjustments are made in simulation to compensate for the additional fuel consumption associated with cold start. [11].

The following sections describe how different portions of the map pose challenges, and provide some available methods to characterize operation within each region of the map. Figure 1 illustrates the different regions of operation typically characterized for a complete engine benchmark. Although the process outlined in this section is intended to be generically applicable to any source of input data, for illustrative purposes Figure 1 shows data from a 2016 Honda Civic 1.5L engine [6]. For each region, suggested testing methods are described along with analytical techniques to process the data. The test data are then combined all together into one complete engine map suitable for use in ALPHA simulation.

Each test mode is discussed in further detail below, with an emphasis on incorporation of the individual data sets into a complete map suitable for use in a full vehicle simulation model. For a more detailed description of these test methods to characterize operation of engines in the different modes, please refer to the companion paper presenting the benchmarking results for a 2016 Honda Civic 1.5L engine and CVT transmission [6]. Data packages that go into greater detail on EPA test methods for other engines are also available on NCAT's benchmarking website [12].

FIGURE 1 Engine mapping test data points from benchmarking 2016 Honda 1.5L L15B7 using Tier 2 test fuel.

LEGEND

● **Core Map Steady-State Operating Points**
(Engine coupled to dyno, no transmission)

✕ **Low Speed / Near Idle Steady-State Operating Points**
(Engine coupled to CVT in drive)

＋ **Low Speed / Near Idle Steady-State Operating Points**
(Engine coupled to CVT in neutral)

▲ **High Load Transient Operating Points - Initial Value**

☐ **High Load Transient Operating Points - Final Value**

- - - The maximum torque curve from published data [2]

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Core Map (Low to Medium Torque)

The core of the steady state map contains the primary operating range of the engine, which is generally characterized by stoichiometric operation and spark timing at or near maximum brake torque (MBT), and stable engine controls (valve timing, start of injection, etc.). The stability and repeatability of engine operation in this region allows for straightforward steady state measurement using an engine dynamometer. The stability also enables the use of relatively slow response fuel flow measurement systems to determine fuel consumption. Data can be gathered by stabilizing the engine and running relatively long (10-30 second) steady state modes at pre-determined fixed speeds, with load set by the accelerator pedal position [6, 7, 8, 9].

While published engine BSFC or BTE maps normally include only positive torque data, a significant amount of operation in the negative brake torque region occurs in vehicle operation or simulation. Recording measurements in this region can significantly improve the accuracy of simulated fuel economy. The relationship between torque and fuel flow can become nonlinear due to the decreasing injection timing durations as torque is reduced. Capturing these data from production powertrains can be difficult as the accelerator pedal calibrations for many engines possess a discrete transition as shown in Figure 2 where torque output transitions from unfueled minimum to a positive value between zero and one percent accelerator pedal.

Low Speed/Near Idle

Collecting data at low speeds or near idle conditions could be accomplished using the same process as used for the core map. However, collecting data at these point poses a few challenges. Typical coupling of the engine and dynamometer using a traditional driveshaft results in a high torsional stiffness and rotational inertia at idle relative to what would be experienced in a vehicle with an open clutch or unlocked torque converter.

FIGURE 2   Contour plot displaying the non-linear relationship between accelerator pedal position and torque production from benchmarking of a 2016 Honda L15B7 engine.
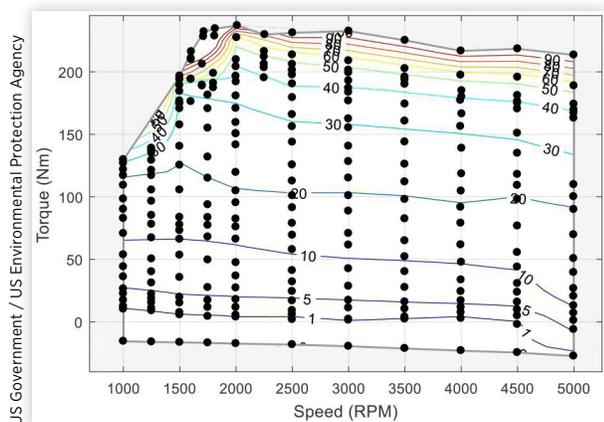
The resulting configuration tends to not replicate in-vehicle engine operation as these factors can interact with the engine control logic leading to instability within the idle speed control or false positive detection of misfire events due to issues with measuring crankshaft acceleration.

To accommodate these issues, data in the low speed and low torque areas of the engine map which are sensitive to this torsional stiffness can be gathered through a different methodology, either by incorporating a transmission (CVT or automatic) into the test setup [6, 9] or by performing in-vehicle idle fuel consumption measurements [10, 13]. For both methods, the resulting data need to be incorporated into the larger engine map (Figure 1).

The incorporation of a transmission into the test cell results in a data set that is of similar form and accuracy to the core map. However, this process requires the addition of sensors and integration of controls for the transmission and torque converter into the test cell system.

In contrast, a variety of options exist for gathering data via in-vehicle measurement. Some offer easier set up, but often with corresponding reductions in accuracy and traceability. In-vehicle measurement requires the use of alternative measurements for fuel flow, speed and torque. Installation of an in-vehicle torque sensor, necessary for accuracy similar to engine dynamometer measurements, is difficult, both in terms of packaging and sensitivity to the harsh environment [13]. Thus, estimated engine torque is often obtained via the vehicle's On-Board Diagnostic (OBD) interface, [10, 14] or by estimating torque with other parameters such as speed, manifold pressure and spark timing [15]. In-vehicle measurements also generally include the effect of accessory loads. Thus, the data measured in-vehicle should be compared with dynamometer measurements in areas of the engine map where both are available to characterize any systemic bias between the two measurement methods.

For those data sets where no low speed/idle testing has been done, engineering judgement must be exercised to fill this gap. This could be in the form of surrogate data collected on a similar engine, or estimated based on the expected trends discussed later in the QC Tools & Engineering Judgment section.

High Load

Characterization of the engine's transient behavior at high load is becoming an increasingly important area of research at EPA and in the wider automotive community. While most vehicles rarely operate under high load conditions, when they do operate at high load, emissions can be orders of magnitude higher and therefore be a significant contributor to the in-use emissions inventory.

Characterization of operation in the high load region of the engine map (blue triangles and green squares in the high load region in Figure 1) is complicated by the transient nature of engine controls which are needed to maintain acceptable combustion and exhaust temperatures and to avoid engine knock. Instead of characterizing such points based purely on torque and speed (as done for the low to medium torque portion of the map) a third axis (time) needs to be added to address the transient engine control effects.

A sample test procedure to capture transient high load operation consists of a load transient conducted at a fixed speed. The engine is first allowed to stabilize at a lower load. The accelerator pedal is then ramped to the test point in approximately one second. This operating point is maintained and data are collected until a time limit is reached or one of the thermal limits is tripped to avoid damage to the test article. Due to the transient nature of the test, measurement of the fuel consumed is often based on fuel injector pulse duration and fuel rail pressure to compensate for the slow response encountered from fuel flow meter measurements. [6]

Data from a sample transient test are shown in Figure 3. To characterize engine operation, two time windows are selected: an initial, often stoichiometric window (shown in blue), immediately after the engine achieves the desired operating point, and a final or quasi-steady state window (shown in green), which will often be enriched or exhibit a shift in spark timing. Data for each window are averaged to create the resulting test data set.

For most vehicle simulation, the initial measurement values are used preferentially to construct the base fuel map as this operation is most commonly encountered in the engine. Most high load operation is momentary, particularly on the regulatory driving cycles, which feature gentle accelerations and thus very little sustained high torque operation. An example of this can be seen in Figure 4, where operation over the US06 only makes a few excursions into this region, and are of relatively short duration. Recent ALPHA refinements enhance the ability to simulate more off-cycle operation and the final high load measurements provide data on the quantity of fuel enrichment as discussed later in the section on enrichment.

The measurements of maximum engine torque are consistent and points with questionable data stability can be readily identified. The procedure is also useful for examining features

FIGURE 3 Example high load test conducted on 2016 Honda L15B7 turbocharged engine showing several pertinent parameters and the windows of data selected.
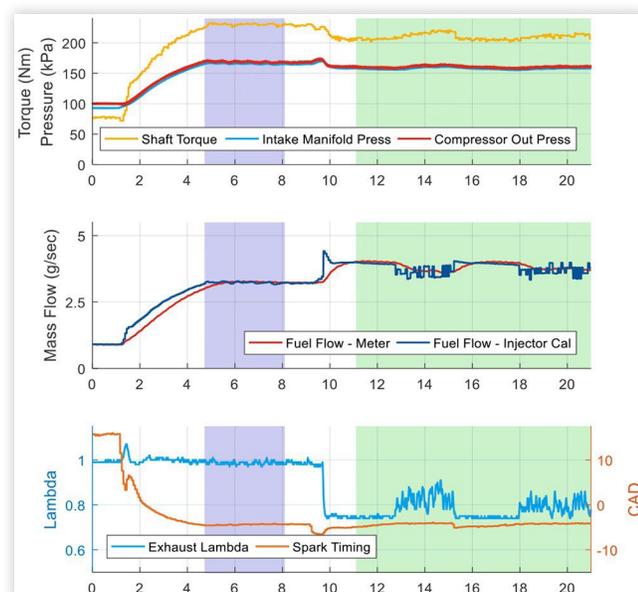
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FIGURE 4 BSFC map for 2016 Honda L15B7 turbocharged engine overlaid with US06 vehicle test data collected at 10 Hz via OBD signals.
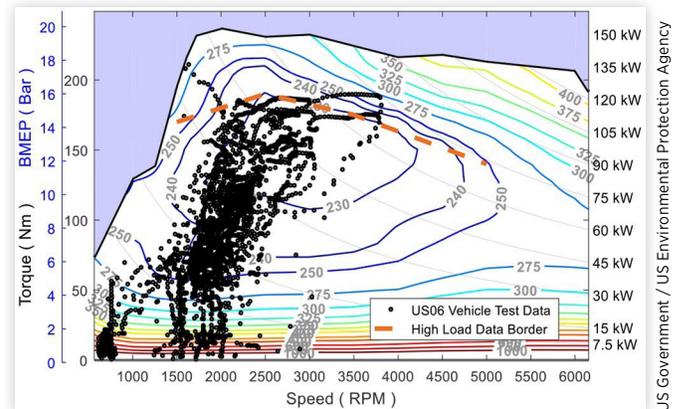
US Government / US Environmental Protection Agency

such overboost found on recent turbocharged engines [16], capturing both the maximum torque initially after the transition to high load and how the output torque decays with sustained operation.

Maximum & Minimum Torque Sweeps

In addition to characterizing engine operation at high loads, simulation runs require a definition of the maximum achievable torque. The high load transient test procedure described above is a preferred method for capturing the pertinent data maximum engine torque.

Alternatively, a sweep test, where torque measurements are recorded while speed is swept, can also be used to determine the maximum torque values. While sweep tests have been used in some previous test programs [8] to establish the maximum torque curve used for simulation, sweep tests often under-predict the maximum achievable torque of the engine. This is primarily due to the high temperatures resulting from the relatively slow speed sweep (5-10 seconds) and the subsequent enrichment or reduced torque output due to engine protection controls. Thus, when utilizing maximum torque data from a sweep test, other data such as exhaust temperatures and stoichiometry should be examined to determine if the time spent in the sweep is influencing the final results.

While some of these effects could be mitigated via a faster sweep, doing so amplifies the effect of rotational inertia in the torque measurement increasing the measurement uncertainty. For this reason, the high load transient procedure is preferred to determine maximum torque. A maximum torque sweep test is useful however to characterize the rough shape and help define the test matrix for high load transient testing or to better understand protection controls.

A sweep test at minimum engine torque or zero pedal may be used to set the lower bound on available engine torque. However, this is unnecessary if these bounds are covered via steady state testing.

Capturing Data from Published Images

Another data source that can be used to generate simulation inputs is published engine BSFC or efficiency maps. These published maps are an excellent resource for quickly incorporating the latest cutting edge technologies into ALPHA, often well before benchmark testing can be performed on the actual production engine.

However, care must be taken when creating engine maps from published images because of the lack of accompanying information specifying test procedures, fuel properties, and any post processing performed. Published maps may also reflect data from pre-production development engines. Although these maps are often representative of the production version, there can also be changes that occur after the map publication as a result of vehicle integration, such as mitigation of NVH. A sample comparing published pre-production data to benchmarking results is available in the references [6].

In addition to the cautions given above, published maps are often limited in their scope. While the publication may cover the most utilized portions of the map, details such as idle fuel consumption, maximum torque curve shape, and the efficiency roll-off beyond the bounds of the provided data can require some estimation.

One tool used by EPA to capture data from published map images is the Map Image Interpreter, a GUI built in MATLAB to quickly import data from images. After displaying the image to be captured, the user calibrates the scale of the axes to match the image. With the axes established, the points within the data can be selected either by manually clicking along each contour line or by allowing the software to attempt to follow each contour. A snapshot of the interface is shown in Figure 5.

FIGURE 5 Snapshot of the Map Image Interpreter interface midway through capturing the efficiency contours from a published map for the Toyota TNGA 2.5l engine [2]
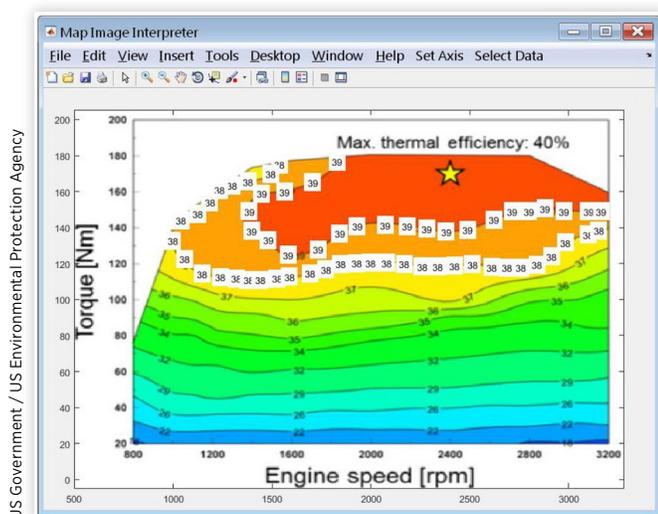
Constructing ALPHA Input Engine Maps

Much of the process for merging the various pieces of data into a format suitable for use in ALPHA is accomplished by an EPA developed function called "REVS_build_engine." The overall process within the function is as follows, which will be explained further in the following sections:

1. Define operating envelope to be covered by the map
2. Define speed and load grid for fuel map construction
3. Generate fuel map from input data
4. Examine resulting fuel map and revise data if necessary
5. Apply adjustments for transient operation

While the process is quite similar whether data are collected from engine testing or imported from a published image, there are some differences incorporated into the process which produce better final results from each source.

Defining Operating Envelope

The first step in constructing a composite fuel map is to establish the range of operation which needs to be covered. For ALPHA this is done by generating curves for maximum and minimum torque versus engine speed. Depending on the data available, different techniques are used to generate these curves.

Maximum Torque The maximum engine torque versus engine speed provides the upper bound on engine torque production during simulation. This parameter is especially important in technology assessments and fleet level simulation to establish the required scaling of engines to maintain performance metrics (e.g. 0-60 mph acceleration) when simulating the application of engine maps into larger or smaller vehicles. This is crucial to appropriately compare the effectiveness of various engine and vehicle technology packages in future fleet modeling [6].

The primary method used to generate a maximum torque curve is to utilize the hull, or outer bound, of the test data. This approach gives excellent results when done in conjunction with the high load transient test method described previously. The combination captures the peak initial values following tip-in as would be encountered in a vehicle. However, depending on the coarseness of the grid used when obtaining the fuel map, the resulting areas may either over- or under-estimate the available engine torque due to the natural fluctuation in engine output torque versus speed resulting from wave dynamics within the intake manifold. Therefore, it is important that test points are selected with sufficient resolution to capture these variations.

Maximum torque data collected by sweeping speed at maximum pedal input yield significantly more data than are required to implement appropriate bounds on engine operation in simulation. The transient nature of the test method can also result in a significant amount of dispersion in the torque measurement. Generating a curve to represent this

type of data begins by averaging the torque data over 100 RPM windows resulting in an averaged curve. This process helps remove some noise present in the data, particularly near points where a resonance between the engine and dynamometer may result in erratic torque measurement. If this filtering is omitted and only the maximum values in the raw data are used, the maximum torque output of the engine would be overstated.

Another important source of input for maximum torque is from published data such as vehicle specifications listed on manufacturer websites. Maximum engine power and torque values are usually readily available for vehicles, which is very helpful for validating or extending the maximum torque curve to cover the operational range. While maximum torque values are typically used to corroborate test results, the maximum power values help extend the curve beyond the area typically collected or available in published maps.

The data representing maximum engine torque, which are often a combination of the above types, contain more information than is necessary to represent the curve. To reduce the complexity of the resulting map while maintaining the fidelity of the original data, a reduced curve for maximum or minimum torque can be iteratively constructed, starting with the end points. The curve is then interpolated at each point of the input data and the point with the largest error is added to the curve. This process is repeated until all the torque differences between the data and constructed curve are within 1% of the maximum engine torque. An example of this process for both the hull method and sweep method is visible in Figure 6.

In addition to providing the upper limit on engine torque, the maximum torque curve also provides a bound on the speed range of the engine. In a vehicle, the rev limiter can provide this operation with a hard edge, dramatically reducing engine torque over a very narrow band of engine speed. However, in simulation a more gradual torque roll-off at speeds above the speed of maximum power is more desirable as sudden changes in maximum available torque can result in erratic simulation behavior and model instability for scenarios such as simulating zero to sixty acceleration. To provide an appropriate roll-off that will enable simulation near maximum power, two speed-load points are added to
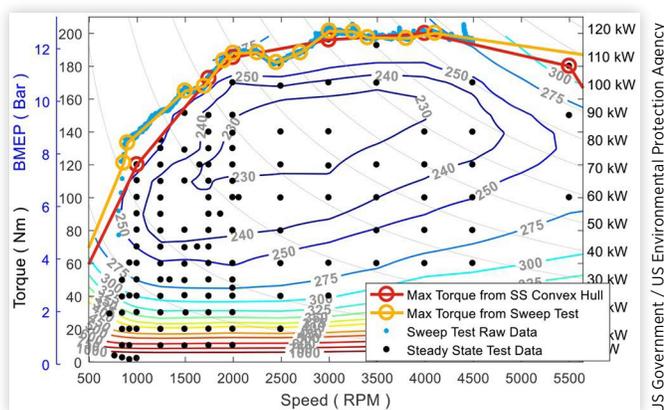
extrapolate the maximum torque curve down to zero power. The first is set at a speed five percent beyond the range of the input data, and a torque equivalent to either ninety percent of the power of the final data point or the linear extrapolation of the input data, whichever is less. The second point is set at a speed ten percent beyond the range of the input data and zero output torque or the linear extrapolation of the input data, whichever is less. While the selection of these added points may seem somewhat arbitrary, they provide a means to reliably simulate engine operation near maximum power, which is necessary to determine pertinent vehicle performance metrics without expanding the operating range in an unrealistic manner.

Minimum Torque Curve The minimum torque curve provides the lower bound on engine torque, which in ALPHA is intended to be the lower limit encountered during normal operation. The minimum torque curve can influence fuel consumption and estimated GHG emissions, particularly when simulating technologies like alternator regen or mild hybrids, where reduced engine drag enables more energy to be captured during braking events, reducing total fuel consumption. For SI engines, deceleration events under closed throttle are likely to include fuel cutoff.

If available, test data either from sweep tests, or from discrete closed throttle operating points, can be processed in a manner similar to the maximum torque data. However, there are times when data regarding minimum engine torque may not be available. This is particularly true when constructing a fuel map from published images. REVS_build_engine can generate a minimum torque curve when needed beginning with an initial default curve, which is then scaled based on engine displacement. Figure 7 shows the default closed throttle curve along with the minimum torque curves developed for various engines benchmarked by EPA [12]. The default curve was defined based on test data some of which is included in the figure. The default minimum torque is biased toward

FIGURE 6 Comparison of maximum torque curve constructed from sweep test data to curve constructed form the convex hull of steady state fuel map test data.

FIGURE 7 Comparison of default minimum torque curve used by REVS_build_engine compared with curves generated from EPA engine benchmarking. [12]
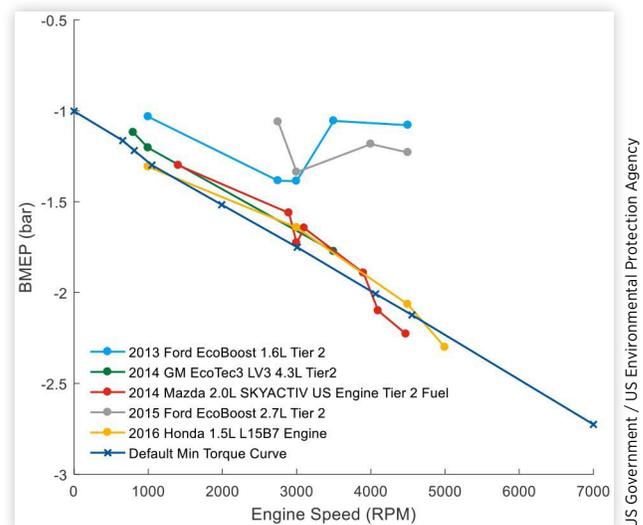
higher friction, and may be revised based on supplemental data from the fuel map itself. After generation of the fuel map, as discussed in the next section, the map is interpolated or extrapolated to estimate the torque which corresponds to zero fuel flow. If this torque is greater than the result from the default curve, that portion will be revised upward to match the zero fueling torque.

If the resulting minimum torque curve does not cover the full speed range needed for simulation. The data is extrapolated linearly using only the end points to cover the necessary range. To reduce the number of points and simplify the simulation, a process identical to what is done for the maximum torque is implemented by constructing a curve that matches the data within 1% of maximum engine torque.

Defining Fuel Map Grid

A gridded fuel map is desirable to simplify the interpolation of fuel flow for simulation. The data from engine testing tend to be gridded naturally by the test method with consistent speeds but more variable torque values. REVS_build_engine constructs the grid on which the fuel map will be built by independently looking for clusters within the speed and torque data. After sorting the values, clusters are identified by iteratively splitting the set into groups starting with the largest gap until all the variation of each group is sufficiently small relative to the scale of the input data. The mean value of each cluster is then used to establish the fuel map grid. The resulting grid is helpful in maintaining consistency between the input measurements and the resulting fuel map. Additional points are added on each axis to ensure consistent coverage over the full range from zero speed to beyond maximum power and minimum to maximum torque. The grid constructed from a sample data set is shown in Figure 8. Note the data set used to construct this and the subsequent figures in the following sections are intentionally a very simple data set to more easily demonstrate and visualize the process. The test data packages collected generally contain a larger number of test points and thus provide a more detailed fuel map. [12]

FIGURE 8 Fuel map output grid generated by REVS_ build_engine to match scattered input data. Red dots indicate test points and gray lines indicate the selected speed or torque points for the output grid.
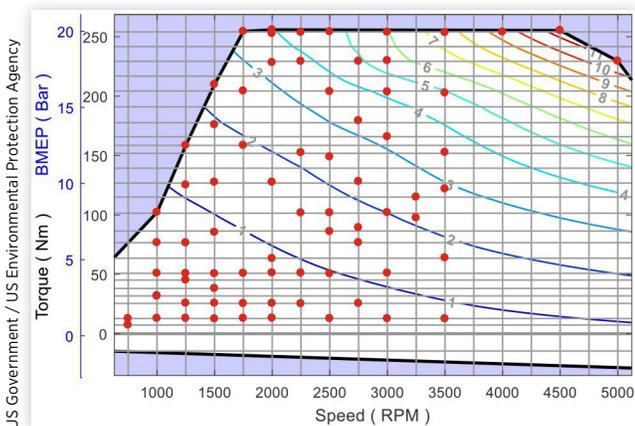
Data collected from published images are often substantially more scattered and follow the contours in the data. Without a distinct set of clusters to build the fuel map grid, a standard grid is used. The speed axis in the standard grid is composed of 250 RPM spacing for the lower half of the operating range and 500 RPM spacing for the upper half. The torque axis uses an evenly spaced set of 25 points spanning from minimum to maximum torque.

Fuel Map Surface Fitting

With the desired output grid established, the fuel flow data can then be merged together for surface fitting. Working with scattered data necessitates that the distance between speed and torque points must be of similar scale to generate satisfactory results. This is accomplished by normalizing the torque and speed data by the range of the operating envelope defined above.

To show the outcome of the normalization process, a Voronoi diagram can be used to display the region of influence for each of the input data points over the resulting fuel map. Figure 9 shows these regions before and after normalization. The dots represent input data points and the lines are equidistant from each point. In the surface fitting this would correspond to equal weighting of the points. Correspondingly,

FIGURE 9 Comparison of the Voronoi diagrams resulting from the use of un-normalized (upper) and normalized (lower) data.
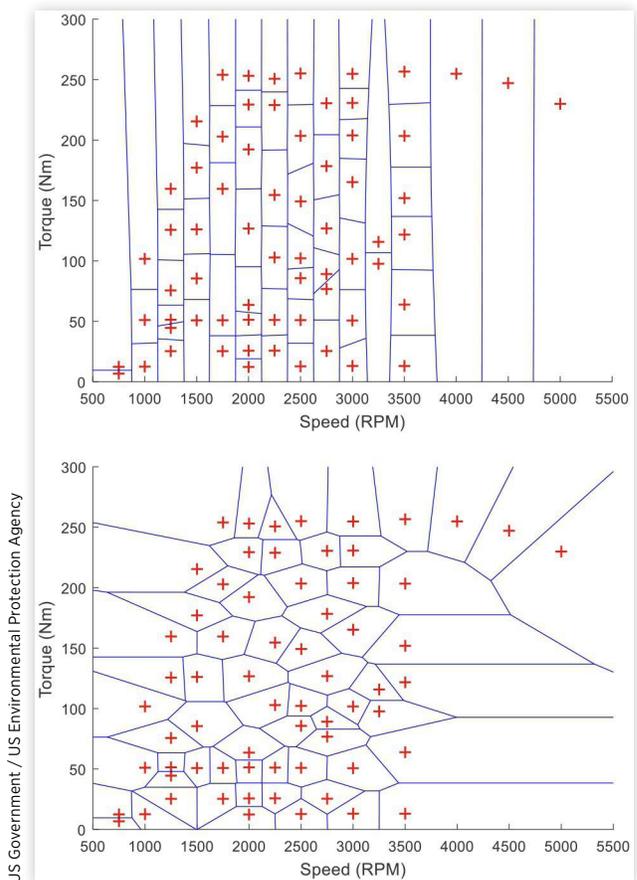
the region surrounding each point will represent the area where that data point has the greatest influence in determining the resulting fuel map.

Figure 9 also shows the error that can occur if this normalization is neglected. In the upper graph the un-normalized data contain speeds values, in RPM, which are an order of magnitude greater than torque measurements in Nm. This results in the points like the two around 3250 RPM which, with the lack of normalization, will be the dominant factor in calculating fuel consumption from zero to maximum torque. The lower diagram, constructed using the normalized data, results in regions that more appropriately balance the influence of neighboring points. The two 3250 RPM points are the dominant factor over a much more logical area.

The surface fitting when creating a fuel map is conducted in the speed, torque, and fuel flow domain. While possible to fit a surface to BSFC or BTE, both represent challenges at low or negative torques. The surface fitting is accomplished using GRIDFIT, an algorithm that attempts to fit a surface to the input data by balancing the stiffness of the resulting surface and the goodness of fit with regard to the input data. This approach possesses many advantages over the more direct interpolation of the test data. [17]

Interpolation of scattered data, as implemented by the *Scattered-Interpolant* class in MATLAB for example is done by generating a Delaunay triangulation of the data. The value for a given point in the output grid would be interpolated by constructing a plane from the vertices of the triangle surrounding the point in question. Thus, each point in the output map will depend upon up to three of the test data points. This method of interpolation could result in unintentionally omitting some of the input data. If the output grid is significantly coarser than the input data, it is possible that output points could be selected that would not utilize one or more of the input data points.

When using GRIDFIT, the entire data set factors into the calculation. Each data point is connected to the surrounding four grid points based on their distance. The grid points are also connected to each other based on the specified stiffness, or level of smoothing, which constrains changes in gradient between points in the grid. This results in an even weighting of the data and a better match of the general shape of the data especially when extrapolating or to fill portions of the map where large voids exist. GRIDFIT is not an interpolant in that the resulting output will not necessarily match the input if evaluated at one specific input data point. GRIDFIT provides some smoothing of the input data, the effect of which can be seen in Figure 10. The level of smoothing can be adjusted to match quality if the input data, smoothing out a noisy dataset or minimizing the residuals between measurements and the resulting surface for high fidelity data.

The smoothing provided by GRIDFIT has ancillary benefits in the ALPHA simulation environment. For larger fleet analysis work done in ALPHA the ALPHAshift algorithm is the primary method used for transmission gear selection. ALPHAshift attempts to select the minimum fuel consumption gear that provides appropriate torque reserve to meet driver demand. [18] The engine fuel map is one of the primary inputs for the gear selection process. A smooth fuel map ensures more consistent gear selection behavior. By reducing

FIGURE 10   BSFC map for identical test data processed via Scattered-Interpolant (upper) and surface fitting via GRIDFIT (lower).
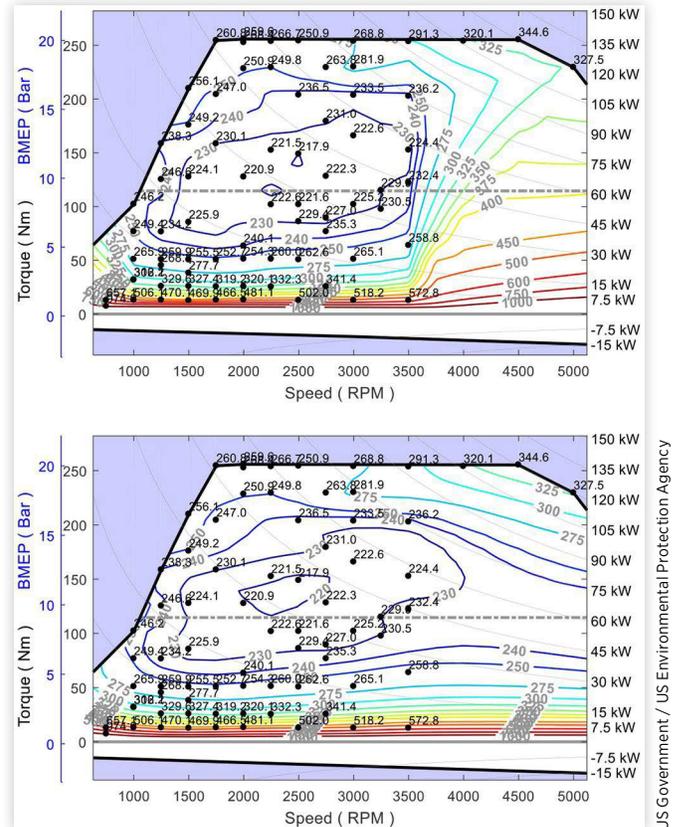
some of the variability within gear selection the effect of different engines on fuel consumption can be more accurately examined.

A second benefit of the surface provided by GRIDFIT for fleet analysis involves the engine scaling process. One of the adjustments applied when scaling engine cylinder volume involves the increased tendency for engine knock. [11] The scale of this adjustment is based upon the trends present within the fuel map of the engine being scaled. A smooth input fuel map assists in generating a more regular knock sensitivity adjustment, and more consistent simulation results.

QC Tools & Engineering Judgment

To confirm the veracity of the resulting fuel map, the input data are compared with the resulting BSFC or efficiency contour plots. These plots provide an opportunity to verify that the trends within any areas of the map which are extrapolated from test data sets match expectations. An example is shown in Figure 11, where both the high torque and high speed portions of the map, as captured originally from a published image, are missing data. For many data sets and intended uses, extrapolation into this area would not be necessary, as

FIGURE 11 An example of adding estimated data points to create more appropriate fuel map. At high speed and load the upper map resulting from the input data alone [2] exhibits poor extrapolation behavior. The lower map includes additional estimated points creating a more appropriate result.

FIGURE 12 First fuel linearity plot for 2016 Honda L15B7 turbocharged engine constructed from EPA benchmarking data for examining the trends in fuel per stroke versus speed and torque.

If the lines in this fuel linearity plot are excessively wavy, this may point to high variability in the input data, which could be offset by increasing the stiffness coefficients used by GRIDFIT when fitting the fuel surface.

The second fuel map linearity plot, shown in Figure 13, examines the trends in fuel per cylinder per engine cycle versus torque. Lines are drawn for the various speeds in the constructed fuel map from minimum to maximum torque. The expectation is that these plots would contain a stack of parallel lines in approximately the lower 2/3 of the torque range, with the high speed lines reflecting higher fuel consumption due to increased frictional losses. The lines are expected to curve upward at higher torque as additional fuel is required due to injection timing changes to combat low speed pre-ignition, or power enrichment at high speed. More information and analysis regarding these trends are described in the provided reference. [19]

This step is an iterative point in the overall map creation process. If issues or concerns regarding the input data are

operation over standard EPA GHG cycles (the FTP and HWFET cycle) are typically confined to regions with lower torque and speed. However, in cases where the original data set is truncated or the intended simulations require aggressive, high power driving cycles, the REVS_build_engine function provides the ability to extrapolate, using best engineering judgment, from the original data.

An illustration of this function is included in Figure 11. In the top map, the data are extrapolated mechanically, and the resulting extrapolation yields abnormally high efficiency in unexpected areas. By applying some reasonable judgment and adding a collection of estimated data points, the lower plot is obtained, where the contours match the expected shape.

Another tool used to examine the trends of fuel flow within the map is a pair of fuel linearity plots. The first, shown in Figure 12, is a contour plot of the amount of fuel consumed per cylinder per engine cycle over the operating range of the engine. The expectation is that this plot contains relatively parallel lines having a downward slope similar to the minimum torque curve. A slight bend in the contours at low speeds is expected, reflecting the reduction in efficiency associated with the spark timing used for idle speed control and a resulting uptick in fuel consumption. Some distortion of the trends is expected in regions where fuel enrichment is active.

FIGURE 13 Second fuel linearity plot for 2016 Honda L15B7 examining core map consistency and additional fueling due to enrichment and knock mitigation.
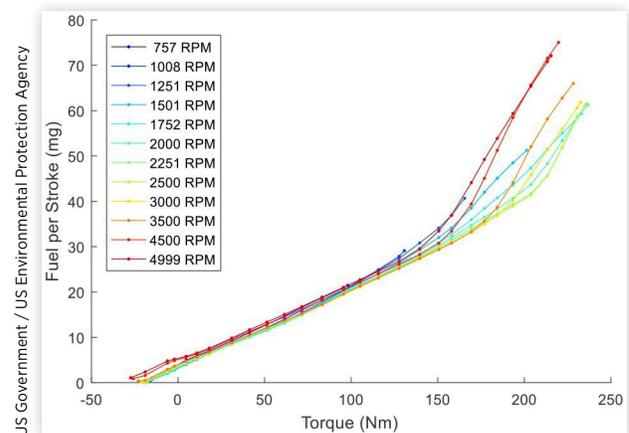
found the source data may be revisited, or individual points omitted. If deficiencies are found with extrapolation additional estimated data can be added. Then the preceding steps are rerun to produce a new map for examination.

One other quality control aspect conducted before including a constructed engine in fleet level simulation involves comparison of available vehicle test data with a matching vehicle simulation in an ALPHA validation. This includes comparisons of time series data and drive cycle fuel consumption to ensure the generated engine maps accurately represent in vehicle operation. [4, 5]

Transient Behavior

A steady state fuel map provides an excellent foundation for quantifying fuel consumption via simulation. Traditional dynamometer test cycles such as the federal test procedure (FTP) or highway fuel economy test (HWFET) can be accurately estimated via a steady state map alone. To simulate more aggressive driving cycles or off-cycle behavior, additional aspects of the engine's performance are needed to more accurately simulate engine operation. The values of the following adjustments are related to their implementation in ALPHA, which may or may not be analogous to different simulation platforms.

Boost / Torque Response

The traditional emissions and fuel economy test cycles such as the Urban Dynamometer Driving Schedule (UDDS) do not feature aggressive accelerations. As a result, the torque response of the simulated engine often does not need to be constrained. For more accurate simulation of aggressive driving, appropriate time constants restricting increases in engine torque must be incorporated. The testing methodology used by EPA to populate these parameters has been discussed in a prior publication [5].

Test data to establish these parameters may be unavailable, particularly for engines generated from published images. To properly compare the engines a representative torque response behavior is necessary. The default value of the torque response time constant for naturally aspirated engines or the low load (throttled) portion of turbocharged engines within ALPHA is 0.2 seconds. The default time constant utilized in the boosted region of turbocharged engines is 0.7 seconds [5]. The boundary between these regions may be specified if throttle, intake manifold pressure or other data are available. If no data are available, the boundary is set at 9 bar BMEP.

Transient Fuel

In addition to the limitations in transient operation by the boost and torque response time constants, there is a fuel consumption adjustment necessary to account for highly aggressive transient operation. [5] This adjustment can be calculated from the same test data used to produce the torque response time constants, and similarly, is often unavailable.

Enrichment

Fuel enrichment experienced during sustained high load operation does not occur during certification drive cycles as this would quickly result in emissions beyond the regulatory limits. However, high load operation is more prevalent in real world operation especially during situations such as towing up a grade or very aggressive driving. To simulate these effects, and more accurately represent real world fuel consumption within ALPHA, enrichment must be quantified both in the amount of additional fueling and timing associated with the application of high load operation. The magnitude of enrichment is characterized by constructing a second fuel map where the final or quasi steady state fueling rates from the high load tests are utilized instead of the initial values. The resulting enrichment fuel map uses all the same processes as previously discussed with the exception that the output grid for the base map is reused rather than constructing a new one.

The second aspect of simulating enrichment within ALPHA is the timing of the transition to enriched operation. This is represented as two durations. A delay, where stoichiometric operation continues after achieving the operating point, followed by a transition duration specifying the time from the start of enrichment to achieving the final steady state value. These points are identified in Figure 14, where t_0 is the time when the operating condition is achieved, t_{start} is the start of enriched operation and $t_{complete}$ is when enrichment has achieved its quasi steady state value. For points near maximum engine power, the transition to enriched operation may occur before the engine has achieved its operating point. In this condition both delays are set to zero, indicating an immediate transition to enriched operation.

FIGURE 14 Same high load transient plot from Figure 3 with the additional enrichment timing points included.
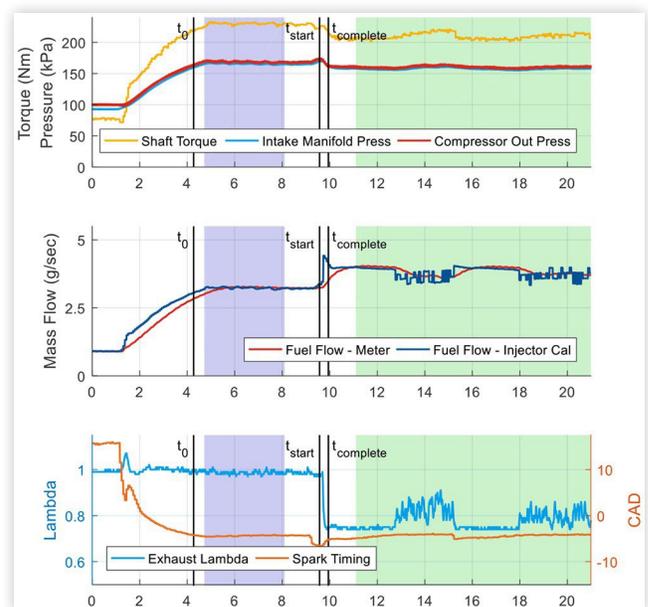
Summary

An objective comparison of various engines and their corresponding technologies in simulation necessitates consistent methodologies for developing simulation inputs. NCAT has developed technical methods to assess the effectiveness of advanced low-emission and low-fuel consumption technologies for a broad range of light-duty vehicle applications.

To properly characterize a vehicle's overall fuel consumption and performance, a complete engine map that describes the engine's fuel consumption across the entire operating range is essential. Gathering the required data may require different test methods which are matched to the different regions of the maps. These include (a) standard steady state testing in the core operating zone where operation is stable, (b) testing near idle incorporating the transmission in the test setup to more properly simulate in vehicle behavior, and (c) high load transient testing to capture engine operation immediately after a transition to high load as well as subsequent quasi-steady state operation. These test methods when combined together yield test data sets that accurately represent the overall engine performance. However, to accurately represent the engine performance during simulation, data from these disparate sources must be brought together into a complete engine map.

A consistent process was developed and incorporated into a function called "REVS_build_engine," for using the steady state and transient test data, along with external data sources, to construct a complete engine map for ALPHA or other full vehicle simulation models. This consistent process is an important consideration to create complete engine maps that enable meaningful comparison and allow proper characterization of how new vehicle technologies interact with individual engines over the entire operating range of the engine. This process also ensures that, whether the original data come from benchmarking testing or other published technical materials, the difference between engines can be accurately estimated. Examples comparing the simulations utilizing the maps resulting from this process to available test data is available in the references. [4, 5, 10]

Creating a set of complete and consistent ALPHA engine inputs enables more accurate fleet level vehicle simulation for properly evaluating future engine and vehicle technology. Expanding the availability of complete, well documented engine data is essential for the broad technical community to accelerate assessment and development of new technologies to meet increasingly stringent emissions and fuel economy standards. These improved data sets and processing also provide useful operational details to evaluating differences between certification and in-use operation.

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