Process for Generating Engine Fuel Consumption Map

(Future Atkinson engine with cooled EGR and cylinder deactivation)   Version: 11-28-2016

This document summarizes the process followed to utilize GT-POWER modeled engine and laboratory engine dyno test data to generate a full engine fuel consumption map which can be used by EPA's ALPHA vehicle simulations. The map generated defines the complete operating boundaries of the engine needed for ALPHA modeling, including idle, WOT, minimum torque, and maximum speed.

The GT-POWER modeled engine results are described in SAE technical paper 2016-01-0565, "Air Flow Optimization and Calibration in High-compression-ratio Naturally Aspirated SI engines with Cooled-EGR." This paper describes the two GT-POWER maps that were modeled – one map without any cylinder deactivation and another map with cylinder deactivation enabled in its operating range.

EPA tested a GM 4.3L EcoTec engine with cylinder deactivation to study the percentage of time that cylinder deactivation mode actually operates. Additional details of this testing are described in SAE technical paper 2016-01-0662, "Fuel Efficiency Mapping of a 2014 6-Cylinder GM EcoTec 4.3L Engine with Cylinder Deactivation."

Gather Engine Physical Characteristics

Note: Engine based on Mazda Skyactiv 2.0L @ 14:1 CR.

Source: http://en.wikipedia.org/wiki/SkyActiv#2.0_L

```
engine.name = 'Future High CR Atkinson Engine with Cylinder Deactivation';
engine.combustion_type = enum_engine_combustion_type.spark_ignition;
engine.displacement_L = 1.998;
engine.num_cylinders = 4;
engine.bore_mm = 83.5;
engine.stroke_mm = 91.2;
```

Source: Estimated from engine displacement

```
engine.inertia_kgm2 = 0.13;
```

Load Fuel Map Test Data from the GT-POWER Model Data

Source: SkyActiv_2L_NA_Futuring_Maps_AKI93-88-Dec16.xlsx

Two separate maps are loaded, representing engine operation with and without cylinder deactivation.

```
% Primary (non-cylinder-deac fueling map)
fuel_data{1}.speed_rpm = xlsread('SkyActiv_2L_NA_Futuring_Maps_AKI93-88-Dec16.xlsx','cEGR-
AKI93','B2:R2');
fuel_data{1}.bmep_bar = xlsread('SkyActiv_2L_NA_Futuring_Maps_AKI93-88-Dec16.xlsx','cEGR-
AKI93','A4:A29');
fuel_data{1}.bsfc_gpkWhr = xlsread('SkyActiv_2L_NA_Futuring_Maps_AKI93-88-Dec16.xlsx','cEGR-
AKI93','B4:R29');
```

```
% Load cylinder deactivation fuel map data,
deac_data.speed_rpm = xlsread('SkyActiv_2L_NA_Futuring_Maps_AKI93-88-Dec16.xlsx','cEGR+CDA-
AKI93','B2:J2');
deac_data.bmep_bar = xlsread('SkyActiv_2L_NA_Futuring_Maps_AKI93-88-Dec16.xlsx','cEGR+CDA-
AKI93','A4:A14');
deac_data.bsfc_gpkWhr = xlsread('SkyActiv_2L_NA_Futuring_Maps_AKI93-88-Dec16.xlsx','cEGR+CDA-
AKI93','B4:J14');
```

Obtain Load Low Speed / Low Torque Data

Source: 2014 Mazda 2.0L Skyactiv 13-1 Tier 2 Fuel - Core Test Data.xlsx

Note: Since no GT-POWER data below 1000 rpm was generated and we did not expect any fuel consumption improvements at low speed / light load, engine test data from a stock SkyActiv 2.0L 13:1CR engine was used for data points below 950 RPM & 50 Nm.

```
datagrabber('..\..\..\ALPHA_Validation\2014 Mazda Skyactiv\data_engine\US Engine 93 AKI\2014
Mazda 2.0L Skyactiv 13-1 Tier 2 Fuel - Core Test
Data.xlsx','structure','core_data','dataline',5,'headerline',3,'quiet')

select_points = core_data.Speed <= 950 & core_data.Torque <= 50;
fuel_data{2}.speed_rpm = core_data.Speed(select_points);
fuel_data{2}.torque_Nm = core_data.Torque(select_points);
fuel_data{2}.fuel_gps = core_data.Fuel_Flow(select_points);
```

Obtain Maximum Torque (WOT) Curve Data

Source: engine_2014_mazda_skyactiv_US_2L0_tier2.m

Note: Duplicated from base Mazda Skyactiv 2.0L 13:1 CR US calibration.

```
WOT_data.speed_radps = [     0.00000000,        ;      95.039723,        ;       157.17760,         ;
177.96973,       ;      209.47442,       ;      235.68091,       ;      256.39794,         ;
282.73763,       ;      314.14238,       ;      356.10551,       ;      429.36596,        ;
628.31853,       ;      680.67841,          ];
WOT_data.torque_Nm = [    0.00000000, ;      134.56250,        ;       164.92581,         ;
167.81143,       ;      187.87381,       ;      188.25000,       ;      182.26000,         ;
188.21273,       ;      201.40161,       ;      197.39857,       ;      200.09762,         ;
184.00000,       ;     0.00000000,          ];
```

Obtain Minimum Torque (Motoring) Curve Data

Source: engine_2014_mazda_skyactiv_US_2L0_tier2.m

Note: Duplicated from base Mazda Skyactiv 2.0L 13:1 CR US calibration.

```
CT_data.speed_radps = [      0.00000000,        ;      3.0210242,        ;      146.55530,        ;
403.16650,        ;      424.02144,        ;      465.83686,        ;      680.67841,        ];
CT_data.torque_Nm = [     -16.013253,  ;    -16.108797,        ;    -20.648276,        ;    -
28.763975,        ;    -33.455621,        ;    -34.963536,        ;    -42.710982,        ];
```

Obtain Properties of the Fuel Used When Mapping the Engine

Source: FTAG 23945 used for *engine_2014_mazda_skyactiv_US_2L0_tier2.m* from which the GT-POWER engine model was derived.

Note: When using ALPHA to conduct specific technology assessments, the fuel properties and associated fuel consumption map for this engine definition are adjusted to suit the standard fuel being used during the specific assessment. For example, fuel rate is adjusted for LD GHG assessments to represent a suitable fuel rate with Tier 2 Certification fuel.

```
%Load from fuel database
engine.fuel = class_REVS_fuel( 'FTAG 23945' );
engine.fuel
```

```
ans = class_REVS_fuel with properties:
                        id: 'FTAG 23945'
               description: 'Tier 2 Cert'
          density_kgpL_15C: 0.743
        energy_density_MJpkg: 42.887
     carbon_weight_fraction: 0.86678
           anti_knock_index: []
     research_octane_number: 97.1
        motor_octane_number: 88.2
              cetane_number: []
            alcohol_pct_vol: 0
                   gCO2pgal: 8932.8
        energy_density_BTUplbm: 18438
           specific_gravity: 0.74371
```

Calibrate Idle Fuel Consumption and Define Idle Speed

Fuel consumption in the idle region of the map is calibrated using vehicle benchmarking data collected on a vehicle chassis dyno. Actual idle fuel consumption during an ALPHA simulation would depend on the transmission drag and accessory loads.

Source: engine_2014_mazda_skyactiv_US_2L0_tier2.m

Note: Duplicated from base Mazda Skyactiv 2.0L 13:1 CR US Calibration

```
% Idle speed dynamic with vehicle speed > 1 m/s => 800 RPM,  stopped => 550 RPM
engine.idle_speed_radps.axis_1.signal  = 'veh_spd_mps';
engine.idle_speed_radps.axis_1.breakpoints = [  0,      1      ];
engine.idle_speed_radps.table = [ 550,    800 ] * convert.rpm2radps;
```
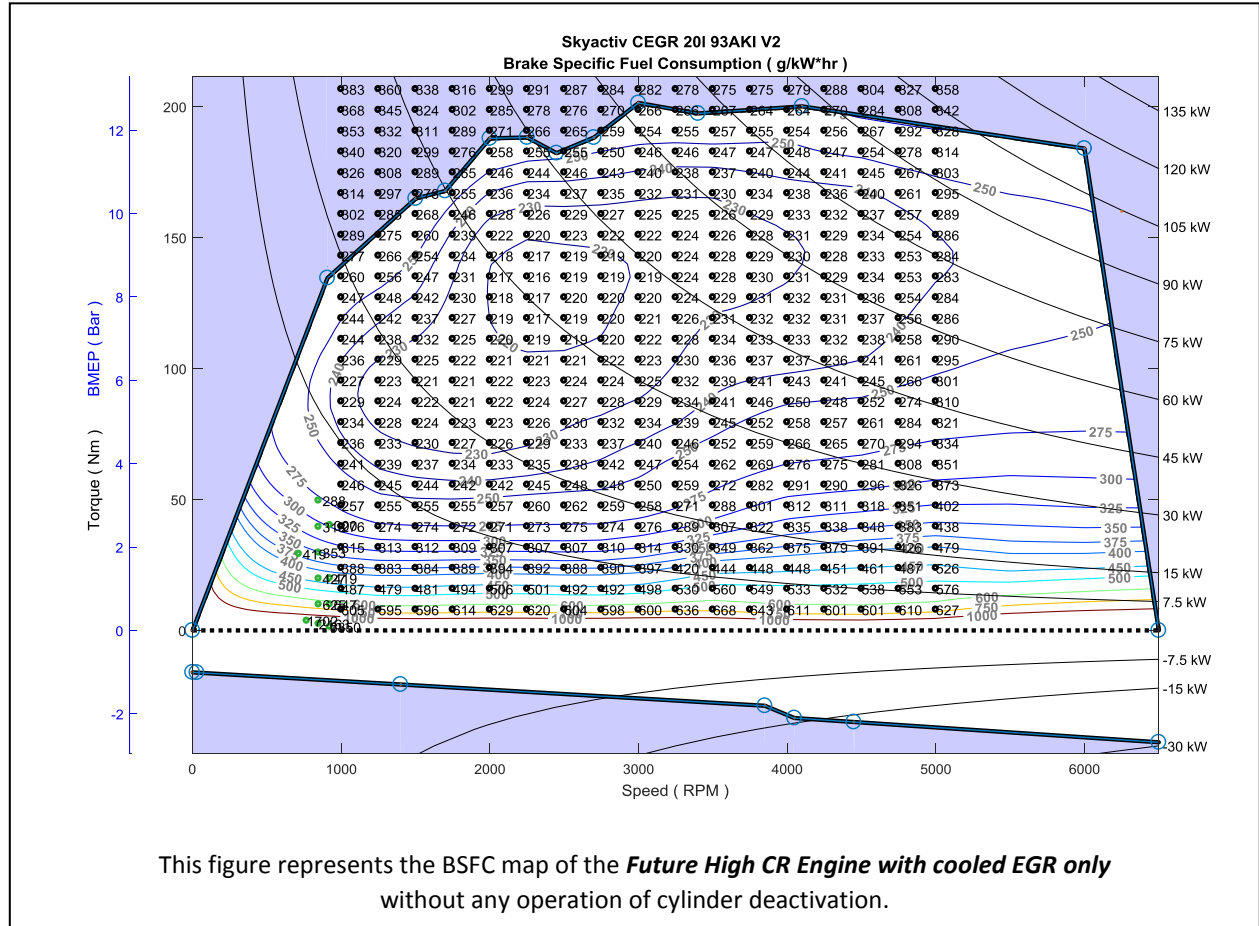
Build Fuel Consumption Maps

Notes: Generate combined WOT curves and fuel consumption map for this engine using REVS_build_engine. A single fuel consumption map is generated with a 60% weighting where CDA is available.

Like other engines with cylinder deactivation technology, this engine is capable of operating with and without cylinder deactivation. EPA's testing on a GM 4.3L EcoTec engine with cylinder deactivation revealed that cylinder deactivation mode to be active 60% of the time when possible (in the region that is capable of cylinder deactivation). Additional details of this testing are described in SAE technical paper 2016-01-0662, "Fuel Efficiency Mapping of a 2014 6-Cylinder GM EcoTec 4.3L Engine with Cylinder Deactivation." *ALPHA vehicle simulation results using this engine reflect a similar level of operation in cylinder deactivation mode.*

For clarity, we generate and display two engine fuel consumption maps to delineate each of the operational modes (one BSFC map covering operation without cylinder deactivation, and one BSFC map covering operation with cylinder deactivation mode active). These maps define the complete operating boundaries of the engine needed for ALPHA modeling, including idle, WOT, minimum torque, and maximum speed.

```
engine = REVS_build_engine(engine,  fuel_data ,WOT_data ,CT_data,'deac',  deac_data,
'deac_single_map' ,0.6)
```
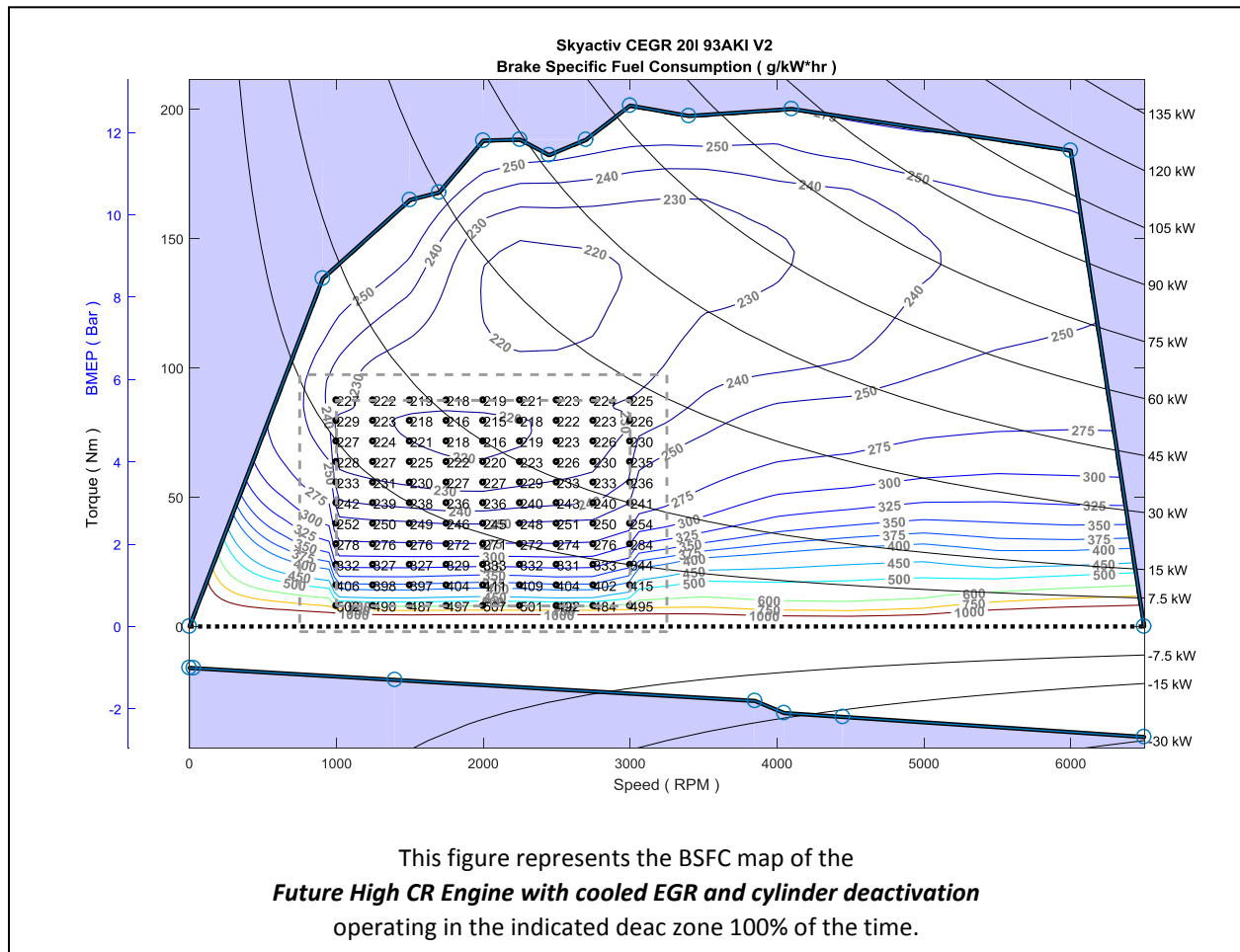
This figure represents the BSFC map of the *Future High CR Engine with cooled EGR only* without any operation of cylinder deactivation.

This figure represents the BSFC map of the
Future High CR Engine with cooled EGR and cylinder deactivation
operating in the indicated deac zone 100% of the time.

Set Model Calibration Options

Note: These parameters influence particular behaviors within the ALPHA model. They often do not have a corresponding value with test data, but are calibrated to match observed behavior.

```
engine.pedal_map_type = enum_engine_pedal_map_type.max_engine_power;

%Post DFCO fuel adjustment - calibrated from time series test data
engine.refuel_profile_mult = [1.0, 1.3, 1.0];
engine.refuel_profile_time_secs = [0 0.1 8];
engine.refuel_limit_gps = 0.2;
engine.refuel_min_defuel_duration_secs = 1.5;

%Acceleration based fuel adjustment - calibrated from time series test data
engine.acceleration_penalty_gpradps2 = 0.007;
engine.acceleration_penalty_squelch_gps = 0.1;

%Transient Response Time Constants
```

```
engine.throttle_duration_secs =    0.2;
engine.boost_time_constant_secs =  0.2;
```

Save Engine Fuel Consumption Maps

Note: The resulting file contains data for both cylinder deactivation modes of this engine.

```
write_REVS_engine( 'engine_future_atkinson_20l_CEGR_DEAC_tier2.m', engine);
```

Display Summary of Engine Fuel Consumption Map Information

Note: The listing below shows only the engine's fuel consumption map related information contained in the ALPHA Engine Definition .m file for this engine. This information is a subset of the full engine definition .m file that adds vehicle level information related to dynamic fuel use, accessories, etc.

```
% ALPHA ENGINE DEFINITION
% Generated 8-Nov-2016 12:24:00
% Future High CR Atkinson Engine with Cylinder Deactivation

% Constructor
engine = class_REVS_engine_legacy();
engine.name = mfilename;
engine.matrix_vintage = enum_matrix_vintage.future;

% Physical Description
engine.combustion_type = enum_engine_combustion_type.spark_ignition;
engine.displacement_L = 2.0;
engine.num_cylinders = 4;
engine.inertia_kgm2 = 0.105;

% Fuel Properties
engine.fuel = class_REVS_fuel('FTAG 23945');

% Pedal Calibration
engine.pedal_map_type = enum_engine_pedal_map_type.max_engine_power;

% Idle Speed
engine.idle_speed_radps.axis_1.breakpoints = [    0.00000000,         1.0000000,    ];
engine.idle_speed_radps.axis_1.signal = 'veh_spd_mps';
engine.idle_speed_radps.table = [    57.595865,        83.775804,    ];

% Maximum Torque Curve
engine.full_throttle_speed_radps = [    0.00000000,  ;    95.039723,        ;    157.17760,
        ;    177.96973,        ;    209.47442,        ;    235.68091,        ;    256.39794,
        ;    282.73763,        ;    314.14238,        ;    356.10551,        ;    429.36596,
```

```
                ;       628.31853,            ;       680.67841,              ];
engine.full_throttle_torque_Nm = [       0.00000000,     ;       134.56250,              ;       164.92581,
        ;       167.81143,            ;       187.87381,            ;       188.25000,            ;       182.26000,
        ;       188.21273,            ;       201.40161,            ;       197.39857,            ;       200.09762,
        ;       184.00000,            ;       0.00000000,              ];

% Minimum Torque Curve
engine.closed_throttle_speed_radps = [       0.00000000,            ;       3.0210242,          ;
146.55530,       ;       403.16650,            ;       424.02144,            ;       465.83686,            ;
680.67841,         ];
engine.closed_throttle_torque_Nm = [     -16.013253,   ;     -16.108797,          ;     -20.648276,
        ;     -28.763975,          ;     -33.455621,          ;     -34.963536,          ;     -42.710982,
];

% Fuel Map
engine.fuel_map_speed_radps = [       0.00000000,            68.067841,         99.483767,        104.71976,
130.89969,            157.07963,         183.25957,         209.43951,         235.61945,         261.79939,
287.97933,            314.15927,         319.39525,         340.33920,         366.51914,         418.87902,
471.23890,            523.59878,         575.95865,         628.31853,         680.67841,         733.03829,     ];
engine.fuel_map_torque_Nm = [       -50.000000,         -45.000000,         -40.000000,         -35.000000,        -
30.000000,            -25.000000,         -20.000000,         -15.000000,         -10.000000,         -5.0000000,
0.00000000,            5.0000000,         10.000000,         15.000000,         20.000000,         25.000000,
30.000000,            35.000000,         40.000000,         45.000000,         50.000000,         55.000000,
60.000000,            65.000000,         70.000000,         75.000000,         80.000000,         85.000000,
90.000000,            95.000000,         100.00000,         105.00000,         110.00000,         115.00000,
120.00000,            125.00000,         130.00000,         135.00000,         140.00000,         145.00000,
150.00000,            155.00000,         160.00000,         165.00000,         170.00000,         175.00000,
180.00000,            185.00000,         190.00000,         195.00000,         200.00000,         205.00000,
210.00000,            215.00000,         220.00000,     ];
engine.fuel_map_gps = [
  0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,  ;
  0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,  ;
  0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.017623264,    0.078630319,
0.14209217,  ;
  0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,    0.00000000,    0.00000000,    0.012113603,    0.054940412,    0.12939299,    0.22626780,
0.31668435,  ;
  0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,  0.0021662131,    0.013195436,    0.048332286,    0.12950923,    0.24567021,    0.37478299,
0.49060952,  ;
  0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,    0.00000000,
0.00000000,    0.00000000,    0.00000000,    0.00000000,  0.0047347486,  0.0059716785,    0.011136033,
0.016769835,    0.024945375,    0.032316953,    0.088558303,    0.20997137,    0.36658102,    0.52460223,
```

```
0. 66357177,  ;
   0. 00000000,    0. 00000000,    0. 00000000,    0. 00000000,   0. 00050804710,  0. 0053168144,
0. 011343152,   0. 018969254,   0. 028140899,   0. 038105992,   0. 047209853,   0. 053681491,   0. 054771648,
0. 058528691,   0. 060525778,   0. 054580385,   0. 059602919,   0. 13635256,    0. 30037593,    0. 49298125,
0. 67600432,    0. 83532235,  ;
0. 00042814317,   0. 018336056,   0. 026318624,   0. 027523014,   0. 033542461,   0. 040471898,
0. 049403765,   0. 060433390,   0. 073173413,   0. 086688214,   0. 098996284,   0. 10737243,    0. 10863922,
0. 11250352,    0. 11262544,   0. 096795145,   0. 10103705,    0. 19577714,    0. 40360104,    0. 62637160,
0. 82913997,    1. 0057018,  ;
0. 0087289618,   0. 045662682,   0. 057229302,   0. 058908584,   0. 066560050,   0. 076049465,   0. 088894794,
0. 10422248,    0. 12101116,    0. 13853543,    0. 15535538,    0. 16807859,    0. 17005973,    0. 17627734,
0. 17725057,    0. 15713955,    0. 16305210,    0. 27165183,    0. 52158346,    0. 76675004,    0. 98406838,
1. 1746746,  ;
  0. 015352420,   0. 072072328,   0. 088383234,   0. 090543130,   0. 099627416,   0. 11308297,    0. 13157356,
0. 15246493,    0. 17376405,    0. 19541304,    0. 21776367,    0. 23791508,    0. 24129985,    0. 25284071,
0. 25843426,    0. 24097597,    0. 25258867,    0. 36994539,    0. 65584406,    0. 91395053,    1. 1408082,
1. 3423511,  ;
  0. 020839434,   0. 096349358,   0. 11964308,    0. 12172421,    0. 13314573,    0. 15294773,    0. 17924292,
0. 20727650,    0. 23367067,    0. 25939059,    0. 28774785,    0. 31865841,    0. 32424423,    0. 34474033,
0. 36012126,    0. 35354327,    0. 37702806,    0. 49831570,    0. 80697524,    1. 0675297,    1. 2993939,
1. 5089945,  ;
  0. 025897824,   0. 11720728,    0. 14747368,    0. 15072266,    0. 16872871,    0. 19749987,    0. 23361893,
0. 27051776,    0. 30292507,    0. 33305064,    0. 36748225,    0. 41146534,    0. 42035953,    0. 45370797,
0. 48622113,    0. 50007107,    0. 54399007,    0. 66674343,    0. 97398225,    1. 2268046,    1. 4599220,
1. 6750099,  ;
  0. 030885138,   0. 13537498,    0. 17583465,    0. 15590306,    0. 18639072,    0. 22270242,    0. 26397030,
0. 30511213,    0. 34030335,    0. 37239662,    0. 41229367,    0. 48067530,    0. 53356258,    0. 58465023,
0. 64598825,    0. 69329755,    0. 76967744,    0. 89802117,    1. 1539125,    1. 3910389,    1. 6225671,
1. 8409195,  ;
  0. 035857472,   0. 15334000,    0. 20561073,    0. 18944964,    0. 23200264,    0. 27846481,    0. 32976006,
0. 38088705,    0. 42517263,    0. 46561966,    0. 51434131,    0. 59539788,    0. 65641286,    0. 72800808,
0. 82539516,    0. 91807153,    1. 0372236,    1. 1796872,    1. 3422923,    1. 5596491,    1. 7875566,
2. 0073254,  ;
  0. 040643574,   0. 17215268,    0. 23404781,    0. 21968579,    0. 27176199,    0. 32653720,    0. 38498153,
0. 44323312,    0. 49552586,    0. 54452537,    0. 60256365,    0. 69570895,    0. 76060006,    0. 84546295,
0. 96525484,    1. 1083200,    1. 2696394,    1. 4341098,    1. 5344931,    1. 7321326,    1. 9551073,
2. 1748672,  ;
  0. 045072010,   0. 19256236,    0. 26014673,    0. 24627747,    0. 30447860,    0. 36519879,    0. 42806552,
0. 49093376,    0. 54988571,    0. 60693595,    0. 67364089,    0. 77551433,    0. 84119485,    0. 93302086,
1. 0629966,    1. 2545264,    1. 4530339,    1. 6441614,    1. 7249787,    1. 9077249,    2. 1253502,
2. 3441781,  ;
  0. 049038937,   0. 21298452,    0. 28338374,    0. 26898788,    0. 33071134,    0. 39545188,    0. 46059659,
0. 52602397,    0. 59058496,    0. 65472212,    0. 72834458,    0. 83665992,    0. 90013431,    0. 99318319,
1. 1240803,    1. 3606415,    1. 5874910,    1. 8047146,    1. 9096686,    2. 0852962,    2. 2982668,
2. 5158419,  ;
  0. 052373252,   0. 23152372,    0. 30464973,    0. 29088336,    0. 35550468,    0. 42384073,    0. 49211812,
0. 56139555,    0. 63213974,    0. 70292269,    0. 78137280,    0. 89291761,    0. 95364744,    1. 0486891,
1. 1836636,    1. 4569645,    1. 7026798,    1. 9423034,    2. 0860661,    2. 2634807,    2. 4736685,
2. 6903545,  ;
  0. 055148979,   0. 24910837,    0. 32732746,    0. 31321006,    0. 38129212,    0. 45400453,    0. 52684815,
0. 60171242,    0. 67977453,    0. 75734806,    0. 83885624,    0. 95159228,    1. 0110285,    1. 1098859,
1. 2543911,    1. 5554923,    1. 8117799,    2. 0699001,    2. 2540277,    2. 4409933,    2. 6512254,
2. 8680956,  ;
```

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```
 0. 057469010,    0. 26599596,    0. 35018972,    0. 33760287,    0. 41028700,    0. 48826716,    0. 56722079,
0. 64914255,    0. 73493551,    0. 81950860,    0. 90523749,    1. 0210999,     1. 0791851,     1. 1842180,
1. 3400551,     1. 6589563,     1. 9207643,     2. 1948195,     2. 4147008,     2. 6168814,     2. 8305343,
3. 0493152,   ;
 0. 059496075,   0. 28244594,    0. 37298615,    0. 36272854,    0. 44161053,    0. 52540650,    0. 61025763,
0. 69867697,    0. 79190661,    0. 88442180,    0. 97717614,    1. 0987010,     1. 1567750,     1. 2678729,
1. 4322307,     1. 7617217,     2. 0291923,     2. 3187514,     2. 5699147,     2. 7906360,     3. 0112023,
3. 2341360,   ;
 0. 061411469,   0. 29897653,    0. 39570672,    0. 38892921,    0. 47483798,    0. 56451976,    0. 65452562,
0. 74827909,    0. 84823529,    0. 94966085,    1. 0531107,     1. 1832341,     1. 2418784,     1. 3582831,
1. 5264411,     1. 8618420,     2. 1377957,     2. 4432337,     2. 7214336,     2. 9621722,     3. 1929193,
3. 4225727,   ;
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Published with MATLAB® R2014a

Revision History

Version 06-20-2016: Initial release

Version 11-28-2016: (a) Added transient fuel adjustments characteristics to the calibrations options; (b) modifed maximum and minimum speed and torque characteristics; and (c) regenerated fuel map grid points and recalculated fuel consumption.