

# FSAE Engine Selection: Four or One Cylinder

Kori Lutembacher, Brent Mayeaux, Jonathan Waller

Abstract (Kori Lutembacher): The engine serves as a vital component to any vehicle. For formula one style racing, the choice of engine can decide whether a team wins the race or does not finish at all. When determining the best engine for the overall design of the car, experience plays a crucial role. For the LSU FSAE team, the Suzuki GSX-R600 is the best option. It is a four-cylinder 600cc engine that provides an excellent amount of power without adding too much extra weight to the car and also by being reasonably priced. However, more options such as a one-cylinder engine can be explored for future LSU FSAE teams. Researching both four and one-cylinder engines results in both advantages and disadvantages to each option. However, more extensive engine research needs to be performed in order to confirm the team's selection. As the program expands and develops, the team can set new goals for the engine.

## **Table of Contents**

<u>INTRODUCTION</u>	<u>3</u>
<u>ANALYSIS/DISCUSSION</u>	<u>4-8</u>
<b>1 CYLINDER ENGINE</b>	<b>4-6</b>
<b>4 CYLINDER ENGINE</b>	<b>6-8</b>
<u>CONCLUSION/RECOMMENDATIONS</u>	<u>8-9</u>
<u>REFERENCES</u>	<u>10</u>
<u>APPENDIX</u>	<u>11-27</u>

## **Introduction-Kori Lutembacher**

The Formula Student competition is a world famous mini-Indy car competition. These contests are held all over the world from Germany to Australia. The LSU Formula SAE(FSAE) team competes in Michigan against 120 schools from all over the world. The teams compete in both static and dynamic events. The dynamic events include acceleration and endurance tests and the static events include an intense design competition.

Each year the organizers of the FSAE competition release a set of detailed rules, which all teams must follow closely to avoid disqualification. These rules are updated every year based on what the judges may have seen at that year's competition. The rules are mandated to ensure all the participants' safety and also to ensure that no team has an unfair advantage. The judges want the winner to be determined only based on the team's design. The main engine rules that must be followed include using a four-stroke piston engine, having a restrictor based on whether the engine is fueled by gasoline or E-85. The LSU team uses a gasoline engine so they must have a 20mm restrictor in the intake. Turbochargers and superchargers are allowed if the team designs them [2].

With these rules, there are still many options for teams when determining the best engine for their car's design. The majority of the teams similar to the LSU team use motorcycle engines, both four- and single-cylinder. Some teams (i.e. Western Washington University) are ambitious and design their own engine. Last year the team designed a V8 554cc engine. The engine block, crankshaft, transmission case, and connecting rods were made in-house out of aluminum. Kawasaki 250cc four-stroke motorcycle engine cylinder heads were used along with the transmission internals of a Honda F1 600cc. However, despite their innovation and excellent design, the team was disqualified because they did not follow the rules and used a remote starter instead of designing an on-board starter [3].

Determining which engine to use is mainly based on the overall weight of the car. Due to the restrictor on the engine, the maximum power output will not be more than 100hp. This regulation leads many teams to sacrifice the extra power and use a single-cylinder engine. These cars are typically very light and handle better as a result. Many teams have been quite successful with this strategy. Even Steven Fox, the main judge of the FSAE competition, told the LSU team during his visit that a one-cylinder engine and a lightweight car should be in the team's future goals. This year the LSU team is using a Suzuki GSX-R600 and analysis was performed in order to compare it to other to other engine options for future LSU FSAE teams.

## **Analysis/Discussion**

### **Single-Cylinder Engines – Jonathan Waller**

Beyond the obvious size/weight/simplicity boons, there are countless very real performance benefits to running a single-cylinder engine. Motocross bikes are designed for tracks with short straights and tight corners, so the power requirements are much like an FSAE track. Therefore drivability, especially out of corners, is great because of high torque and diminished emphasis on gear changes. Fuel economy is generally comparable, if not better. Handling is also improved because the engine center of gravity (CG) is dramatically lower than a wet sump four-cylinder engine. Even dry sump four-cylinder engines only lower their CG by an inch or two.

Ultimately the most important benefit is COST – both time and money. Because there are less parts to manufacture (i.e. one intake vs. four) and everything on the car being smaller means less material cost. The engine is also easy to tune because there is no need to balance the air flows to the cylinders and easy to maintain with only one spark plug to change and only five valves to shim. However, there are also drawbacks, most importantly

diminished throttle response. Four-cylinder powered cars are much faster on the course straights. Also, comparing drivetrain component sizes like gears and clutches, singles actually have the same or larger components than multi-cylinder engines.

The most common single-cylinder engines used in FSAE competitions are the Honda CRF-450X and the Yamaha WR450F. These engines are from off-road racing motorcycles and feature wide-ratio gearboxes for fully utilizing the power band.

<b>Honda CRF-450X</b>	<b>Yamaha WR-450F</b>
55hp and 37ft-lbs @ 65 pounds	45hp and 35ft-lbs @ 70 pounds
96mm bore x 62mm stroke	95mm bore x 64mm stroke
36mpg	35mpg
Higher power with reduced longevity	Better technology

**Table 1: One-Cylinder Engine Specs**

The Honda produces the most power to weight at the expense of engine life—Honda recommends changing the piston after every eight races. In contrast, the Yamaha is known for long life and cutting edge technology. Yamaha was the first single-cylinder off-road bike to feature electronic fuel injection and five titanium valves. The lightweight aluminum cylinder features a ceramic composite coating, which is applied directly to the aluminum, eliminating the need for a heavy iron sleeve. The ceramic coating insures faster, more uniform heat dissipation, reduced friction and a longer service life [1].

Another industry exclusive feature is the hand-held "YZ Power Tuner" that allows tailoring of both fuel injection settings and ignition mapping. Nine different setting points can be accessed for both the FI and ignition maps. Maps can be stored and shared with other Power Tuners if desired. The obvious benefit of this feature is to allow a race team to

tune their car to different race locations and conditions to optimize for temperature, humidity, and altitude [4].

### **Suzuki GSX R600 – Brent Mayeaux**

The LSU Formula SAE team has been using a 2007 Suzuki GSX R600 engine in its cars for the last two years. It is an in-line, four-stroke, 16-valve engine with a 12.5:1 compression ratio. The team chose this engine because it is cheap and very common. Used engines in good shape go for about \$600 and are easily found on message boards or eBay. LSU electrical engineers have also done impressive work with the GSX R600 ECU facilitating engine diagnosis and tuning [5].

Model	Suzuki GSX-R 600
Year	2007
Category	Sport
Displacement	599.00 ccm
Engine type	In-line four, four-stroke, 16-Valve
Compression	12.5:1
Bore x stroke	67.0 x 42.5 mm (2.6 x 1.7 inches)
Measured Peak Horsepower	108.4 bhp @ 13,100 rpm
Measured Peak Torque	44.3 lbs. - ft. @ 11,000 rpm
Claimed Engine Redline	15,000 rpm

**Table 2: GSX R600 Stock Specifications**

The specifications of the engine in Table 2 on a stock engine. The engine used on the FSAE vehicles has a restricted intake, so its torque and power are lower. Using matlab (see appendix), we calculated the power and indicated mean effective pressure for the engine at

full, medium, and low loads (Table 3). Mean piston speed, power/piston area, specific weight, and specific volume were also calculated at max power (Table 4). The calculated power and imep values are lower than they should be, and the matlab file may require some more work, but the actual values should fall between the stock and matlab values in Table 5 below.

GSXR600 Calculated Values				
	Pressure(kpa)	Power(kw)	Power(hp)	IMEP(kpa)
Full load	101.3	24.4	32.7	1222.91
Medium Load	90	21.67	29.06	1085.9
Low Load	80	19.26	25.83	965.54

**Table 3: Calculations for Three Loads**

Other Data @ Max Power	
Mean Piston Speed	17 m/s
Power/Piston Area	5197.37 kW/m <sup>2</sup>
Specific Weight	2.32 kg/kW
Specific Volume	24.59 cm <sup>3</sup> /kW

**Table 4: Other Data**

Future LSU teams will need to decide whether to stick with the current four-cylinder GSX R600 or to move to a single-cylinder engine. Designing around a single cylinder engine would result in a lighter and potentially smaller, more nimble, vehicle at the expense of losing some power. Table 5 compares the capabilities of the GSX R600 to those of the Honda CRF-450X and the Yamaha WR450F.

	GSXR600(stock)	GSXR600(matlab)	WR450F	CRF 450X
Max Power(Hp)	108.4	32.7	45	55
Weight(lb)	125	125	70	65
Power-to-Weight(Hp/lb)	0.867	0.262	0.643	0.846
Displacement(cc)	600	600	450	450
Cost(\$)	600	600	n/a	2000

**Table 5: Engine Comparison**

The single-cylinder designs are almost 50% lighter than the four-cylinder GSX R600 with less power. Looking at power-to-weight though, the CRF-450X has almost the same ratio as the Suzuki. Both of these single-cylinder engines have much lower availability. There were no WR450Fs on eBay and only two CRF 450Xs listed with the latter costing around \$2000, over 300% of the cost of the GSXR600 [5].

### **Conclusion – Brent Mayeaux**

There are many options to be evaluated when selecting an engine for the Formula SAE design competition, and not one of them is necessarily the best choice always. It depends on the team’s dynamic, and they must make the right design decisions to build a successful vehicle around whatever engine they choose.

The current LSU FSAE team is fairly new to the competition, and they have a lot to learn. One thing that they have a lot of experience, testing, and work in is the Suzuki GSX R600 engine. It would be in the program’s best interest to stick with it for the next year or two and to work on improving designs on other aspects of the car. Once the team has lots of

experience putting together an excellently engineered and light car around the GSX R600, then they could possibly move to a single-cylinder platform.

Accommodating

## References

<sup>1</sup>"2008 Yamaha WR450F Review." *Top speed*. N.p., 2008. Web.

<<http://www.topspeed.com/motorcycles/motorcycle-reviews/yamaha/2008-yamaha-wr450f-ar37973.html>>.

<sup>2</sup>"2012 Formula SAE Rules." *SAE International*. N.p., 2012. Web.

<<http://students.sae.org/competitions/formulaseries/rules/2012fsaerules.pdf>>.

<sup>3</sup>"Engine and Transmission." *Western Washington University FSAE*. N.p., 2002. Web.

<<http://dot.etec.wvu.edu/fsae/viking30.htm>>.

<sup>4</sup>"FSAE Forum." *FSAE.com*. N.p., 2004. Web.

<<http://fsae.com/eve/forums/a/tpc/f/125607348/m/4006096252/p/2>>.

<sup>5</sup>Suzuki 2007 GSX R600 Manual

## Appendix

### Matlab Code

```
% ME 4633 (Spring 2012): Lecture on fuel/air cycles etc.
%
% calculations are similar to examples 4.2,4.3,4.4,6.5 & 5.2 from heywood
%
% uses mole/mass basis instead of mass of dry air basis
% will be using consistent values for xb throughout the program
% different to book, where xb=0 is used in 4.2 and xb>0 for the remainder

% I. Schoegl, March 2012

% script created to support ME4633 IC Engines @ ME/LSU.

clear
close all

% define fuel, compression ratio and initial state
n = 8;
m = 18;          % fuel is C8H18
Mf = 114.23;    % data for iso-octane
phi = 1;        % equivalence ratio
rc = 12.5;      % compression ratio
T1 = 350;       % K
P1 = 101.325;   % kPa
xb = 0.08;      % burned gas fraction

% some other parameters
```

```

T0 = 298.15; % datum

Tprop = 1740; % evaluation of mixture properties

Runiv = 8.314; % gas constant

%% MIXTURES

fprintf('\n-----\n');

fprintf('MIXTURE COMPOSITION\n\n');

% mixture

[compBB, compUU, nBB, nUU, xB, xU, fu] = burnedgas(n, m, phi, Tprop, xb);

fprintf('Including residual gas (xb=%0.4f)\n', xb);

fprintf(' Unburned: %s\n', compUU);

fprintf(' Burned: %s\n', compBB);

%% HEATING VALUES

% sanity check: calculate lower heating value (heywood lists 44.3 MJ/kg)

hB = mixprop('h', compBB, T0, 'mole');

hU = mixprop('h', compUU, T0, 'mole');

deltaHf0 = hB*nBB - hU*nUU; % per mole of O2 (we don't

LHV_fuel = -deltaHf0/fu/Mf;

fprintf('\nLHV = %2.5f MJ/kg fuel\n', LHV_fuel/1000);

% actual heating value of mixture (on a mass basis)

[hB, MwUU] = mixprop('h', compBB, T0, 'mass');

[hU, MwBB] = mixprop('h', compUU, T0, 'mass');

```

```

deltaHf0 = hB - hU; % per mole of O2

Q = -deltaHf0;

fprintf('Q = %2.5f kJ/kg mixture\n',Q);

% gas constants

Ruu = Runiv/MwUU;
Rbb = Runiv/MwBB;

%% DO CYCLE ANALYSIS

fprintf('\n-----\n\n');

fprintf('FUEL/AIR CYCLE (constant volume combustion)\n\n');

fprintf(' (1) Initial state:      %5.1f K %7.2f kPa\n', T1, P1)

% part 1 - compression ... example 4.2

% isentropic process (on a mole basis so we can use universal gas constant)
Psi1 = mixprop('Psi',compUU,T1,'mass');
fcu = @(T) mixprop('Psi',compUU,T,'mass') - Psi1 + Ruu*log(1/rc);
T2 = fzero(fcu,600);
P2 = P1*rc*(T2/T1); % get pressure - using ideal gas law
fprintf(' (2) End of compression:  %5.1f K %7.2f kPa\n', T2, P2)

% part 3 - combustion ... example 4.5

% constant volume combustion - same internal energy on mass basis
u2 = mixprop('u',compUU,T2,'mass');

```

```

u3 = u2;

fcu = @(T) mixprop('u',compBB,T,'mass') - u2;
T3 = fzero(fcu,2500);

P3 = P2*Rbb/Ruu*T3/T2; % get pressure - using ideal gas law
fprintf(' (3) End of combustion:      %5.1f K %7.2f kPa\n', T3, P3)

%% part 4 - expansion ... example 4.3

% isentropic process
Psi3 = mixprop('Psi',compBB,T3,'mass');
fcu = @(T) mixprop('Psi',compBB,T,'mass') - Psi3 + Rbb*log(rc);
T4 = fzero(fcu,1500);

P4 = P3/rc*(T4/T3); % get pressure - using ideal gas law
fprintf(' (4) End of expansion:      %5.1f K %7.2f kPa\n', T4, P4)

%% part 5 - total work

% work (on a per kg mixture basis)
W12 = - mixprop('u',compUU,T2,'mass') + mixprop('u',compUU,T1,'mass');
W34 = - mixprop('u',compBB,T4,'mass') + mixprop('u',compBB,T3,'mass');
work = W12 + W34;
eta = work/Q;

fprintf('\nResults:\n')
fprintf(' Compression work: %7.2f kJ/kg\n',W12);
fprintf(' Expansion work:      %7.2f kJ/kg\n',W34);
fprintf(' Net work:              %7.2f kJ/kg\n',work);
fprintf(' Heat input:           %7.2f kg/kg\n',Q);
fprintf(' Efficiency:           %7.2f %%\n',eta*100);

```

```

%% PLOT fuel/air cycle and analyze air-standard cycle for comparison
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% create axes

figa = figure;
subplot(1,2,1), axP = gca; hold on, box on,
subplot(1,2,2), axT = gca; hold on, box on
col = get(gca, 'colororder');

% create some volume values
V = linspace(1,1/rc,50);

%% compression - fuel/air

% solve for temperatures / pressures between points 1 and 2
Psi1 = mixprop('Psi',compUU,T1,'mass');
T12fu = zeros(size(V)); % create empty solution array
for i=1:length(V),
    fcn = @(T) mixprop('Psi',compUU,T,'mass') - Psi1 + Ruu*log(V(i));
    T12fu(i) = fzero(fcn,600);
end
P12fu = P1./V.*T12fu/T1;

% plot pressure and temperature
hFu(1,1) = plot(axP,V,P12fu);
hFu(1,2) = plot(axT,V,T12fu);

```

```

%% do a standard air cycle in comparison

% evaluate gamma value
Tair = 600;
[cv,MwAir] = mixprop('cv','O2:1,N2:3.776',Tair,'mass');
Rair = Runiv/MwAir;
gamma = (cv+Rair)/cv;

% print header
fprintf('\n-----
\n');
fprintf('AIR STANDARD CYCLE (const. volume combustion,
gamma=%5.3f)\n\n',gamma);
fprintf(' (1) Initial state:          %5.1f K %7.2f kPa\n', T1, P1)

%% compression - standard air

% standard isentropic compression with gamma=const
T12air = T1*V.^(1-gamma);
P12air = P1*V.^-gamma;
T2air = T12air(end);
P2air = P12air(end);
fprintf(' (2) End of compression:    %5.1f K %7.2f kPa\n', T2air, P2air)

% plot pressure and temperature
hAir(1,1) = plot(axP,V,P12air);
hAir(1,2) = plot(axT,V,T12air);

```

```

%% combustion - fuel/air

% plot pressure and temperature
hFu(2,1) = plot(axP,V(end)*[1 1],[P2 P3]);
hFu(2,2) = plot(axT,V(end)*[1 1],[T2 T3]);

%% combustion - standard air

% add heat
T3air = T2air + Q/cv;
P3air = P2air*T3air/T2air;
fprintf(' (3) End of combustion:      %5.1f K %7.2f kPa\n', T3air, P3air)

% plot pressure and temperature
hAir(2,1) = plot(axP,V(end)*[1 1],[P2air P3air]);
hAir(2,2) = plot(axT,V(end)*[1 1],[T2air T3air]);

%% expansion - fuel/air

% solve for temperatures / pressures between points 3 and 4
Psi3 = mixprop('Psi',compBB,T3,'mass');
T34fu = zeros(size(V)); % create empty solution array
for i=1:length(V),
    fcn = @(T) mixprop('Psi',compBB,T,'mass') - Psi3 + Rbb*log(rc*V(end-
i+1));
    T34fu(i) = fzero(fcn,1600);
end
T4fu = T34fu(end);

```

```

P34fu = P3/rc./V(end:-1:1).*T34fu/T3;

P4fu = P34fu(end);

% plot pressure and temperature
hFu(3,1) = plot(axP,V(end:-1:1),P34fu);
hFu(3,2) = plot(axT,V(end:-1:1),T34fu);

%% expansion - standard air

% standard isentropic expansion with gamma=const
T34air = T3air*(rc.*V(end:-1:1)).^(1-gamma);
P34air = P3air*(rc.*V(end:-1:1)).^-gamma;
T4air = T34air(end);
P4air = P34air(end);
fprintf(' (4) End of expansion:      %5.1f K %7.2f kPa\n', T4air, P4air)

% plot pressure and temperature
hAir(3,1) = plot(axP,V(end:-1:1),P34air);
hAir(3,2) = plot(axT,V(end:-1:1),T34air);

%% close cycles

% plot pressure and temperature
hFu(4,1) = plot(axP,V(1)*[1 1],[P4fu P1]);
hFu(4,2) = plot(axT,V(1)*[1 1],[T4fu T1]);

hAir(4,1) = plot(axP,V(1)*[1 1],[P4air P1]);
hAir(4,2) = plot(axT,V(1)*[1 1],[T4air T1]);

```

```

%% analyze work

% work (on a per kg mixture basis)
W12air = -cv*(T2air-T1);
W34air = -cv*(T4air-T3air);
workAir = W12air + W34air;
etaAir = workAir/Q;

fprintf('\nResults:\n')
fprintf(' Compression work: %7.2f kJ/kg\n',W12air);
fprintf(' Expansion work:   %7.2f kJ/kg\n',W34air);
fprintf(' Net work:          %7.2f kJ/kg\n',workAir);
fprintf(' Heat input:         %7.2f kg/kg\n',Q);
fprintf(' Efficiency:         %7.2f %%\n',etaAir*100);

%% FUEL AIR cycle with adjusted gamma

% plot internal energies
T = (300:100:3000)';
Tref = 1000;

% unburned mixture
TsU = [500,1000];
polyU = polyfit(TsU,mixprop('u',compUU,TsU,'mass'),1); % linear fit
cvU = polyU(1);
gammaU = (cvU+Ruu)/cvU;
uFU = polyval(polyU,Tref); % reference value

```

```

% burned mixture

TsB = [1500,3000];

polyB = polyfit(TsB,mixprop('u',compBB,TsB,'mass'),1); % linear fit
cvB = polyB(1);
gammaB = (cvB+Rbb)/cvB;
uFB = polyval(polyB,Tref); % reference value

% show results in a figure (corresponds to Heywood Fig. 4-2)

figb = figure;
hold on, ax2 = gca; box on
h = plot(ax2,T, [mixprop('u',compBB,T,'mass'), polyval(polyB,T), ...
    mixprop('u',compUU,T,'mass'), polyval(polyU,T)]);
h(5) = plot(Tref*[1 1],get(gca,'ylim'),'k:');

%% run cycle analysis

fprintf('\n-----\n\n');
fprintf('FUEL/AIR CYCLE (const. vol. comb., gammaU=%5.3f,
gammaB=%5.3f)\n\n',gammaU,gammaB);
fprintf(' (1) Initial state:          %5.1f K %7.2f kPa\n', T1, P1)

%% compression - standard air

% standard isentropic compression
T12fu2 = T1*V.^(1-gammaU);
P12fu2 = P1*V.^-gammaU;

```

```

T2fu2 = T12fu2(end);
P2fu2 = P12fu2(end);
fprintf(' (2) End of compression:      %5.1f K %7.2f kPa\n', T2fu2, P2fu2)

hFu2(1,1) = plot(axP,V,P12fu2);
hFu2(1,2) = plot(axT,V,T12fu2);

% combustion - standard air

% equate internal energies (see Eq. 4.21a/4.22a, in book)
T3fu2 = T2fu2*cvU/cvB + (uFU-uFB);
P3fu2 = P2fu2*Rbb/Ruu*T3fu2/T2fu2;
fprintf(' (3) End of combustion:      %5.1f K %7.2f kPa\n', T3fu2, P3fu2)

hFu2(2,1) = plot(axP,V(end)*[1 1],[P2fu2 P3fu2]);
hFu2(2,2) = plot(axT,V(end)*[1 1],[T2fu2 T3fu2]);

% expansion - standard air

T34fu2 = T3fu2*(rc.*V(end:-1:1)).^(1-gammaB);
P34fu2 = P3fu2*(rc.*V(end:-1:1)).^-gammaB;
T4fu2 = T34fu2(end);
P4fu2 = P34fu2(end);
fprintf(' (4) End of expansion:        %5.1f K %7.2f kPa\n', T4fu2, P4fu2)

hFu2(3,1) = plot(axP,V(end:-1:1),P34fu2);
hFu2(3,2) = plot(axT,V(end:-1:1),T34fu2);

```

```

%% close cycles

hFu2(4,1) = plot(axP,V(1)*[1 1],[P4fu2 P1]);
hFu2(4,2) = plot(axT,V(1)*[1 1],[T4fu2 T1]);

%% analyze work

% work (on a per kg mixture basis)
W12fu2 = -cvU*(T2fu2-T1);
W34fu2 = -cvB*(T4fu2-T3fu2);
workFu2 = W12fu2 + W34fu2;
etaFu2 = workFu2/Q;

fprintf('\nResults:\n')
fprintf(' Compression work: %7.2f kJ/kg\n',W12fu2);
fprintf(' Expansion work:    %7.2f kJ/kg\n',W34fu2);
fprintf(' Net work:             %7.2f kJ/kg\n',workFu2);
fprintf(' Heat input:           %7.2f kg/kg\n',Q);
fprintf(' Efficiency:           %7.2f %%\n',etaFu2*100);

%% adjust line styles etc - P-v / T-v diagrams

% add labels (P-v)
title(axP,'Pressure vs. Volume')
hl(1) = xlabel(axP,'V/V_{max} [-]');
hl(2) = ylabel(axP,'P [kPa]');

% add labels (T-v)

```

```

title(axT, 'Temperature vs. Volume')
hl(3) = xlabel(axT, 'V/V_{max} [-]');
hl(4) = ylabel(axT, 'T [K]');
hl(5) = legend(axT, [hFu(2), hAir(2), hFu2(2)], ...
    {'Fuel/Air - thermo data', 'Air - standard', 'Fuel/Air - approx.'}, ...
    'location', 'northeast');

% adjust font & line styles
set(axP, 'fontsize', 14)
set(axT, 'fontsize', 14)
set(hl, 'fontsize', 12);
set([hFu, hAir, hFu2], 'linewidth', 2)
set(hFu, 'color', col(1, :));
set(hAir, 'color', col(2, :), 'linestyle', '--')
set(hFu2, 'color', col(3, :), 'linestyle', '-.')

% adjust line styles etc - u vs. T diagram

% add labels
title(ax2, 'Simple Analytic Ideal Gas Model');
hl1(1) = legend(ax2, h, {'burned - exact', 'burned - fit', ...
    'unburned - exact', 'unburned - fit', 'T_{ref}'}, 'location', 'southeast');
hl1(2) = xlabel(ax2, 'Temperature [K]');
hl1(3) = ylabel(ax2, 'Internal Energy [kJ/kg]');

% adjust font & line styles
set(ax2, 'fontsize', 14)
set(hl1, 'fontsize', 12);
set(h(1:2), 'color', col(1, :))

```

```
set(h(3:4), 'color', col(2,:))  
set(h(2:2:end), 'linestyle', '--')  
set(h(1:4), 'linewidth', 2)  
  
%% save figures  
  
print( figa, '-dpng', 'ex5_2a')  
print( figb, '-dpng', 'ex5_2b')
```

**Printed Matlab Solutions**

>> ME4633\_Proj\_Part2

-----  
**MIXTURE COMPOSITION**

Including residual gas (xb=0.0800)

Unburned: C8H18:0.0736,O2:0.92,N2:3.773,CO2:0.0512,H2O:0.0576,

Burned: N2:3.773,CO2:0.64,H2O:0.72,

LHV = 44.64844 MJ/kg fuel

Q = 2556.64650 kJ/kg mixture

-----  
**FUEL/AIR CYCLE (constant volume combustion)**

(1) Initial state: 350.0 K 101.33 kPa

(2) End of compression: 809.1 K 2928.09 kPa

(3) End of combustion: 3099.2 K 10652.56 kPa

(4) End of expansion: 1709.7 K 470.11 kPa

Results:

Compression work: -408.10 kJ/kg

Expansion work: 1635.26 kJ/kg

Net work: 1227.16 kJ/kg

Heat input: 2556.65 kJ/kg

Efficiency: 48.00 %

-----

AIR STANDARD CYCLE (const. volume combustion,  $\gamma=1.375$ )

(1) Initial state: 350.0 K 101.33 kPa

(2) End of compression: 901.7 K 3263.11 kPa

(3) End of combustion: 4225.4 K 15290.53 kPa

Exiting fzero: aborting search for an interval containing a sign change

because complex function value encountered during search.

(Function value at -448 is -2.5338+2.1071i.)

Check function or try again with a different starting value.

(4) End of expansion: 1640.1 K 474.80 kPa

Results:

Compression work: -424.40 kJ/kg

Expansion work: 1988.70 kJ/kg

Net work: 1564.30 kJ/kg

Heat input: 2556.65 kJ/kg

Efficiency: 61.19 %

-----

FUEL/AIR CYCLE (const. vol. comb.,  $\gamma_U=1.304$ ,  $\gamma_B=1.237$ )

- (1) Initial state: 350.0 K 101.33 kPa
- (2) End of compression: 754.4 K 2729.91 kPa
- (3) End of combustion: 3262.3 K 11213.32 kPa
- (4) End of expansion: 1792.6 K 492.91 kPa

Results:

Compression work: -386.57 kJ/kg

Expansion work: 1711.56 kJ/kg

Net work: 1324.99 kJ/kg

Heat input: 2556.65 kJ/kg

Efficiency: 51.83 %

>>