Project 2 Report
Md Nazmuzzaman Khan

Project Description:

The objective is to accelerate the vehicle as rapidly as possible without violating any physical constraints (e.g. maximum motor, generator, or engine speeds and torques, |Pbatt| < |Pbattmax| etc.).

The general control strategy is as follows. For a given vehicle speed, and a desired output power determined by the drive cycle, or driver inputs, the desired operating point of the engine can be determined based on the maximum efficiency curve of the engine. From the vehicle speed and engine speed, the desired generator speed can then be calculated. The generator speed is regulated through the inverter by controlling the output power of the generator (either as generator or motor). Motor torque is determined by looking at the difference between the total vehicle torque demand and the engine torque that is delivered to the ring gear. The battery provides power to the motors along with the electricity generated by the engine. For this project (accelerating as rapidly as possible), if desired tractive power less than 21 kW, assume all-electric launch (Teng = Tgen = 0). Otherwise, assume that

Pbatt = 21 kW, and Peng = Ptrac - Pbatt.

The top-level simulation diagram is depicted in Fig. 1. The state variables are the vehicle and engine speeds. The desired engine power and motor torque are determined based upon pedal position. The desired engine speed is then determined using a table look up (desired operation is along optimum BSFC line). Engine speed is controlled indirectly by controlling generator speed.

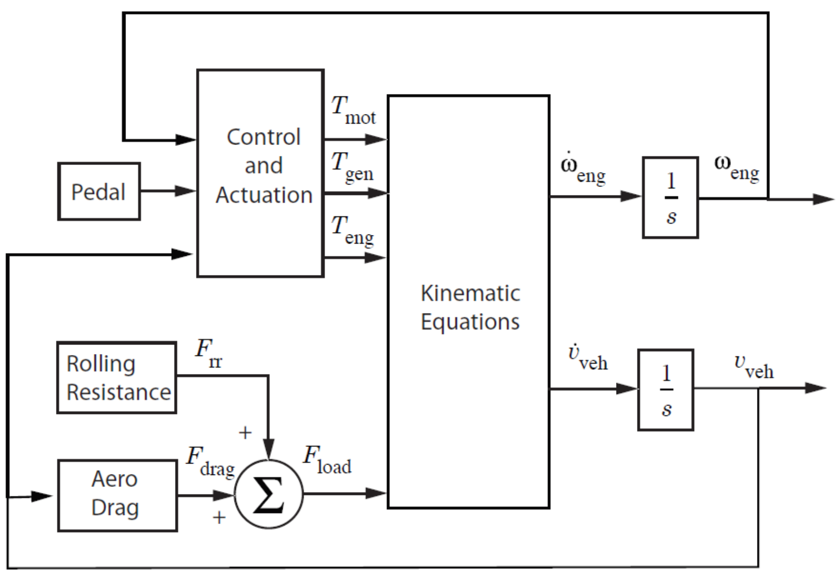

Fig 1: Top-level block diagram.

The kinematic equations can be expressed as

$$T_{\text{eng}} + T_{\text{gen}} \frac{N_s + N_r}{N_s} = \widehat{J}_{\text{eng}} \dot{\omega}_{\text{eng}} - K \dot{v}_{\text{veh}} \quad (1)$$

$$-F_{\text{load}} - T_{\text{gen}} \frac{N_r}{N_s} \frac{1}{G_{fd} r_{\text{wheel}}} + T_{\text{mot}} \frac{1}{G_{fd} r_{\text{wheel}}} = \widehat{M}_{\text{veh}} \dot{v}_{\text{veh}} - K \dot{\omega}_{\text{eng}} \quad (2)$$

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ω_{eng_dot} and v_{veh_dot} is calculated in 'Kinematic Equations' block using equation (1) and (2).

Matlab code for Kinematic Equations:

```
function [w_eng_dot, v_dot] = fcn(T_mot, T_gen, T_eng, F_load, Param)

N_s = Param.N_s; % number of sun teeth
N_r = Param.N_r; % number of ring teeth
G_fd = Param.G_fd; % gear ratio between motor and wheel speeds
r_wheel = Param.r_wheel; % wheel radius in m
Ainv = Param.Ainv; % inverse of state matrix A

% calculate generalized forces
%Slide 16
Q_1 = (T_eng + T_gen*(N_s+N_r)/N_s);
Q_2 = (-F_load - T_gen*N_r/N_s/G_fd/r_wheel + T_mot/G_fd/r_wheel);

Q = [Q_1; Q_2];

%A = [J_eng_hat -K;
 %    -K M_hat_veh];
 %Param.Ainv = inv(A);
 %from slide 16
 %Q = A * [w_eng_dot; v_dot]

y = Ainv * Q;

w_eng_dot = y(1);
v_dot = y(2);
```

Simulink block diagram for the top-level diagram is showed in Fig 2.

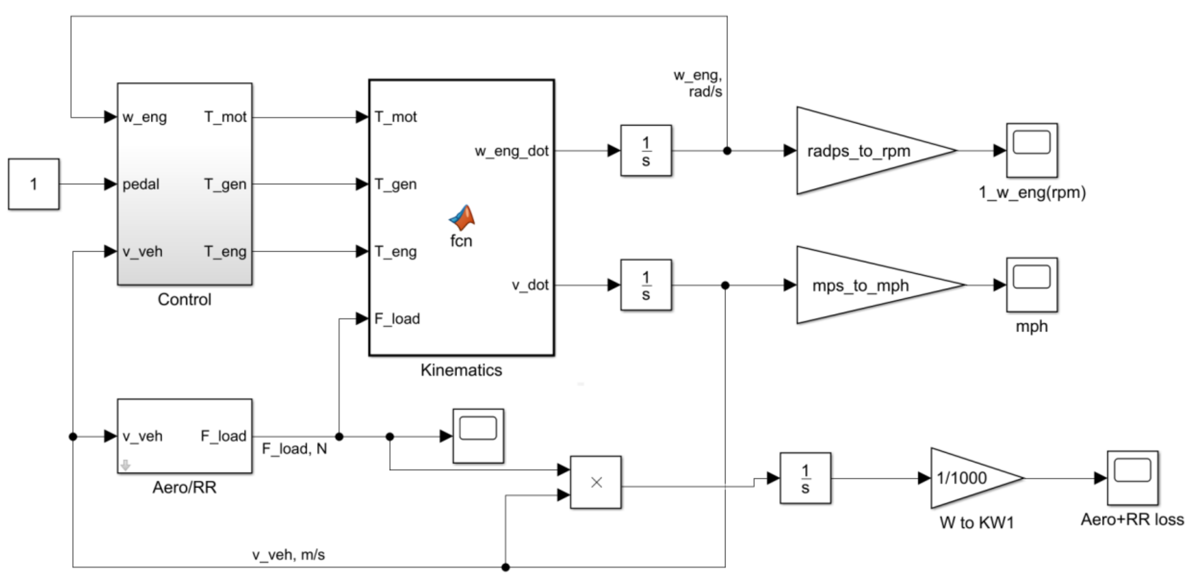


Fig 2: Simulink block for top level diagram.

Expanded view of ‘Control’ block is showed in Fig 3. Engine limit, motor limit and generator limit blocks are shown in Fig 4.

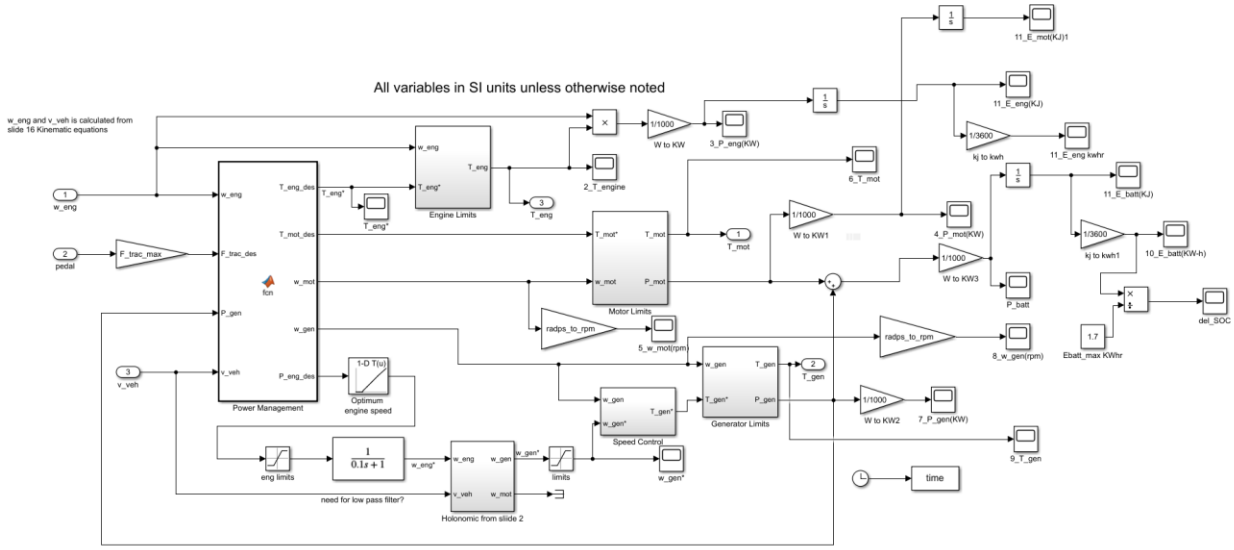
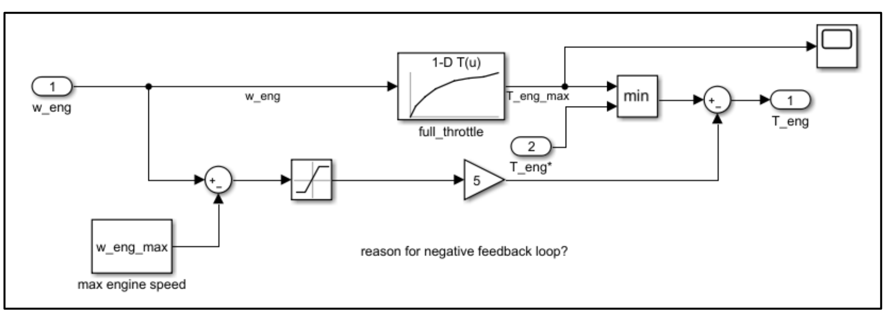
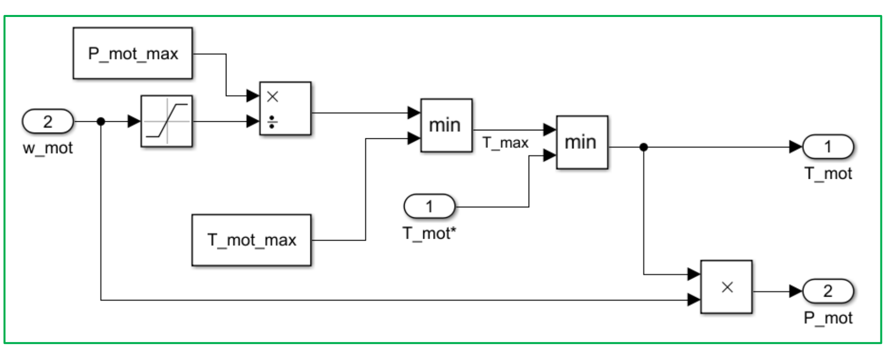


Fig 3: Simulink block for control.

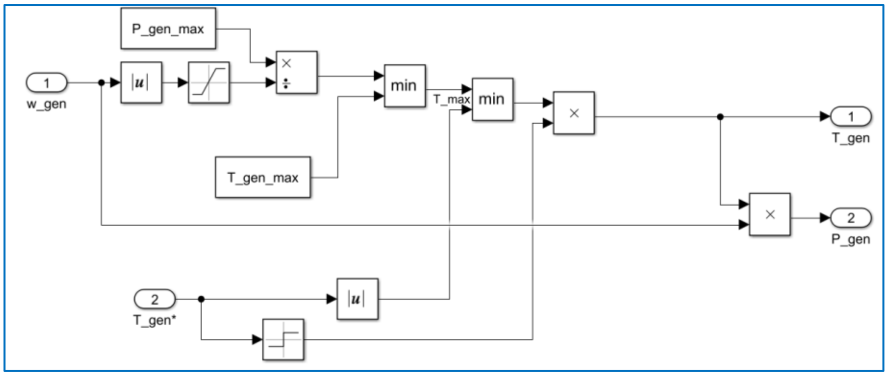
In ‘engine limit block’, maximum torque is first calculated from full throttle speed vs. torque curve. Then the minimum value between the ‘full throttle torque’ and ‘desired engine torque’ is given as output. A tuned negative feedback is used to control sudden increase in torque output. The philosophy is “we are going to use what is needed and not more”. And this philosophy is also true for motor and generator limit block. The generator speed controller (‘speed control’ block) implements a proportional + integral feedback controller where, if the speed error (difference between desired and measured speeds) is negative, a positive torque is commanded and vice versa.



(a)Engine limit block



(b)motor limit block



(c)Generator limit block

Fig 4: Engine, motor and generator limit blocks.

Generator and motor speed are calculated using the following two holonomic relations:

$\omega_{motor} = V_{veh}/(r_{wheel}*G_{fd})$ (3)

$\omega_{generator} = (N_r+Ns)*\omega_{eng}/N_s - N_r*\omega_{mot}/N_s$ (4)

Power management block assumes P_batt = P_batt_max for maximum acceleration. When traction power desired is lower than maximum battery power, all power is provided by battery. If desired power is greater than battery power, then engine power supplements for the remaining power. Calculation and equations used in this block are explained in the comments.

Power management block code:

```
function [T_eng_des, T_mot_des, w_mot, w_gen, P_eng_des]  = fcn(w_eng,
F_trac_des,  P_gen, v_veh, Param)
%#codegen

N_s = Param.N_s;              % number of sun teeth
N_r = Param.N_r;              % number of ring teeth
G_fd = Param.G_fd;
r_wheel = Param.r_wheel;
P_batt_max = Param.P_batt_max;
P_eng_max = Param.P_eng_max;
w_eng_min = Param.w_eng_min;

% Assume P_batt = P_batt_max for maximum acceleration
%EQN 1 & 2 FROM SLIDE 2 AND 3
w_gen = w_eng*(N_r+N_s)/N_s - v_veh*N_r/(N_s*G_fd*r_wheel);
w_mot = v_veh/(G_fd*r_wheel);

P_trac_des = F_trac_des*v_veh;

if(P_trac_des < P_batt_max) % electric launch
    T_eng_des = 0;
    P_eng_des = 0;
    T_mot_des = F_trac_des * G_fd * r_wheel;
    P_mot_des = T_mot_des*w_mot;
```

```
    P_batt_des = P_mot_des + P_gen;

    if(P_batt_des > P_batt_max)
       P_mot_des = P_batt_max - P_gen;
       T_mot_des = P_mot_des/w_mot;
    end

   return
end
%WHEN BATTERY CAN'T PROVIDE ACCELERATION POWER P_trac_des > P_batt_max
P_eng_des = P_trac_des - P_batt_max;
T_eng_des = P_eng_des/max([w_eng w_eng_min]);

if(P_eng_des > P_eng_max)
    P_eng_des = P_eng_max;
    T_eng_des = P_eng_des/max([w_eng w_eng_min]);
end

% calculate T_mot_des given P_batt and F_trac
%SLIDE 17

A = [w_gen w_mot; -N_r/(N_s*G_fd*r_wheel) 1/(G_fd*r_wheel)];
b = [P_batt_max; F_trac_des];
x = A\b;
T_mot_des = x(2);
%T_gen = x(1);

%check to see that P_batt will be less than P_batt_max

P_mot_des = T_mot_des * w_mot;
P_batt_des = P_mot_des + P_gen;

if(P_batt_des > P_batt_max)
   P_mot_des = P_batt_max - P_gen;
   T_mot_des = P_mot_des/w_mot;
end

return
```

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Table 1: Contains all the vehicle parameters used.

Parameter	Symbol	Value
vehicle mass	M_{veh}	1361 kg
generator inertia	J_{gen}	0.02 kg·m^2
motor inertia	J_{mot}	0.05 kg·m^2
engine inertia	J_{eng}	0.1598 kg·m^2
wheel radius	r_{wheel}	0.3107 m
rolling resistance coefficient	C_0	0.00475
aerodynamic drag coefficient	C_D	0.26
frontal area	A_F	2.33 m^2
battery capacity in kW-hr	E_{batt}	1.7 kW-hr
minimum engine power	$P_{\text{eng,min}}$	5 kW
maximum engine power	$P_{\text{eng,max}}$	57 kW
initial SOC	SOC_{init}	0.6
target SOC	SOC^*	0.6
maximum SOC	SOC_{max}	0.82
minimum SOC	SOC_{min}	0.38
maximum battery power	$\lvert P_{\text{batt,max}}\rvert$	21 kW
maximum motor power	$\lvert P_{\text{mot,max}}\rvert$	50 kW
maximum generator power	$\lvert P_{\text{gen,max}}\rvert$	30 kW
maximum engine speed	$\omega_{\text{eng,max}}$	5,000 rpm
minimum engine speed	$\omega_{\text{eng,min}}$	1,000 rpm
maximum motor speed	$\lvert\omega_{\text{mot,max}}\rvert$	6,500 rpm
maximum generator speed	$\lvert\omega_{\text{gen,max}}\rvert$	10,000 rpm
maximum motor torque	$\lvert T_{\text{mot,max}}\rvert$	400 N-m
maximum generator torque	$\lvert T_{\text{gen,max}}\rvert$	240 N-m

Init.m file contains all the necessary parameters and conversions. It also loads the full throttle speed torque relation and optimum bsfc plot to Matlab workspace.

Initialization Matlab code:

```
M_veh = 1361 +100; % vehicle and driver mass in kg
C_D = 0.26;  % drag coefficient
C_0 = 0.00475;  % rolling resistance coefficient
A_F = 2.33;   % frontal area
eta_batt = 0.7; % battery efficiency
r_wheel = 0.3107; % wheel radius in m

% rotating inertias
J_eng = 0.1598; % engine inertia in kg-m^2 from SAE 2000-01-3096
J_mg1 = 0.02; % mg1 (generator) inertia in kg-m^2
J_mg2 = 0.05; % mg2 (motor) inertia in kg-m^2

N_s = 30; % number of sun teeth
```

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```
N_r = 78; % number of ring teeth
G_fd = 0.2431; % ratio of wheel speed to motor speed

rho = 1.225; % density if air in
g = 9.8; % acceeration due to gravity in m/s^s

m_to_mi = 1/1609; % meters to miles
g_hr_to_gal_s = 44.4/32.4 * 0.264 /1000/3600; % grams per hout to gal
per s
mph_to_mps = 0.44704; % miles per hour to meters per s
mps_to_mph = 1/0.44704; % other way around
radps_to_rpm = 3600/377; %radians per sec to rev per min

w_eng_min = 1000 * 2*pi/60; % min engine speed
w_eng_max = 5000 * 2*pi/60; % max engine speed

w_gen_min = -10000 * 2*pi/60;  % min generator speed
w_gen_max = 9000 * 2*pi/60;   % max generator speed

Emax = 1.7*3.6e6; % in J -- 1kW-h = 3.6e6 J

P_mot_max = 50000;  % maximum motor power in W
P_gen_max = 30000;  % maximum generator power in W

T_mot_max = 400; %  maximum motor torque  in N-m
T_gen_max = 240; %  maximum generator torque  in N-m

P_eng_max = 57000.0;

% evaluate kinematic state matrix SLIDE 14
M_hat_veh = M_veh + J_mg1*(N_r/(N_s*G_fd*r_wheel))^2 ;
J_eng_hat = J_eng + J_mg1*((N_r+N_s)/N_s)^2;
K = J_mg1 * ((N_r+N_s)/N_s) * N_r/(N_s*G_fd*r_wheel);

A = [J_eng_hat -K;
    -K M_hat_veh];

% form parameter data structure
Param.Ainv = inv(A);
Param.G_fd = G_fd;
Param.N_r = N_r;
Param.N_s = N_s;
Param.r_wheel = r_wheel;
Param.P_batt_max = 21000;
Param.P_eng_max = P_eng_max;
Param.w_eng_min = w_eng_min;

load full_throttle.mat

load optimum_bsfc.mat

F_trac_max = T_mot_max/(G_fd*r_wheel);
```

Optimum bsfc line and full throttle torque limit given in Fig 5.

Engine data along optimum bsfc line

Speed (rpm)	Torque (N-m)	bsfc (g/kw-hr)	power (W)
1178	14	500	1727
1172	18	400	2209
1160	24	350	2915
1166	34	300	4152
1178	43	280	5305
1166	48	270	5861
1172	54	260	6628
1184	63	250	7811
1172	67	245	8223
1184	74	242	9175
1281	76	240	10195
1688	80	235	14142
2210	86	230	19904
2830	91	225	26969
3510	97	230	35655

Full-throttle torque limit

speed (rpm)	Torque(N-m)
1000	76
1198	84
1502	91
1888	97
2502	103
3000	105
3500	107
4000	110

Fig 5: Engine torque, speed and power along optimum bsfc line on the left table. Full throttle torque limit with speed on the right table.

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Desired variables plotted (indicated in table 2):

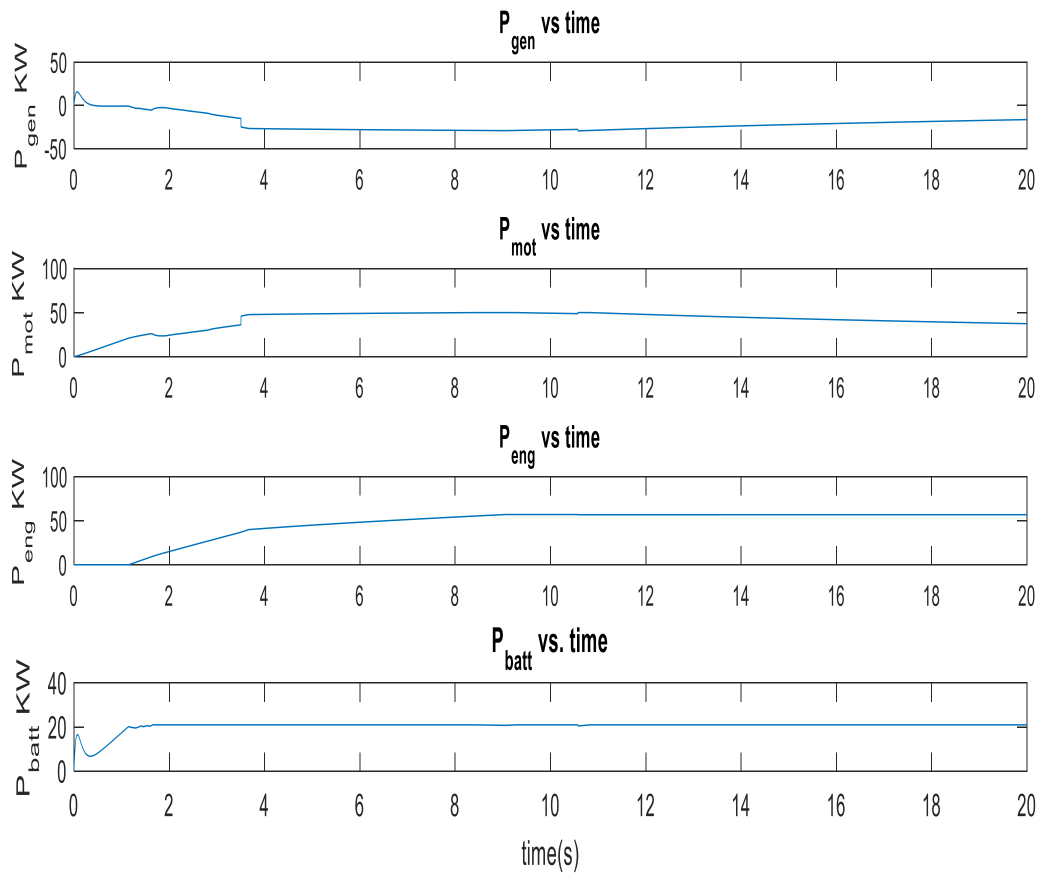

Fig 6: Battery, engine, generator and motor power plotted together. At t1=1.145 s, battery (supplying to motor) hits power limit of 21 KW. Engine kicks in. As of this moment power going out of generator and Pgen turns negative. At t2=1.645 s, ω_eng goes beyond 1200 rpm (starts to increase), which results in a slight dip into Pmot (Peng has lower slope than Pbatt). At t3= 3.504s, ω_gen hits max limit of 9000 rpm. Which decreases Pgen and Pmot increases to max limit. That results into further decrease in Peng slope. At t4=9.06, Peng also hits the limit. At t5=10.6s, ω_eng hits limit (5000rpm), which results into Pgen going up and Pmot going down.

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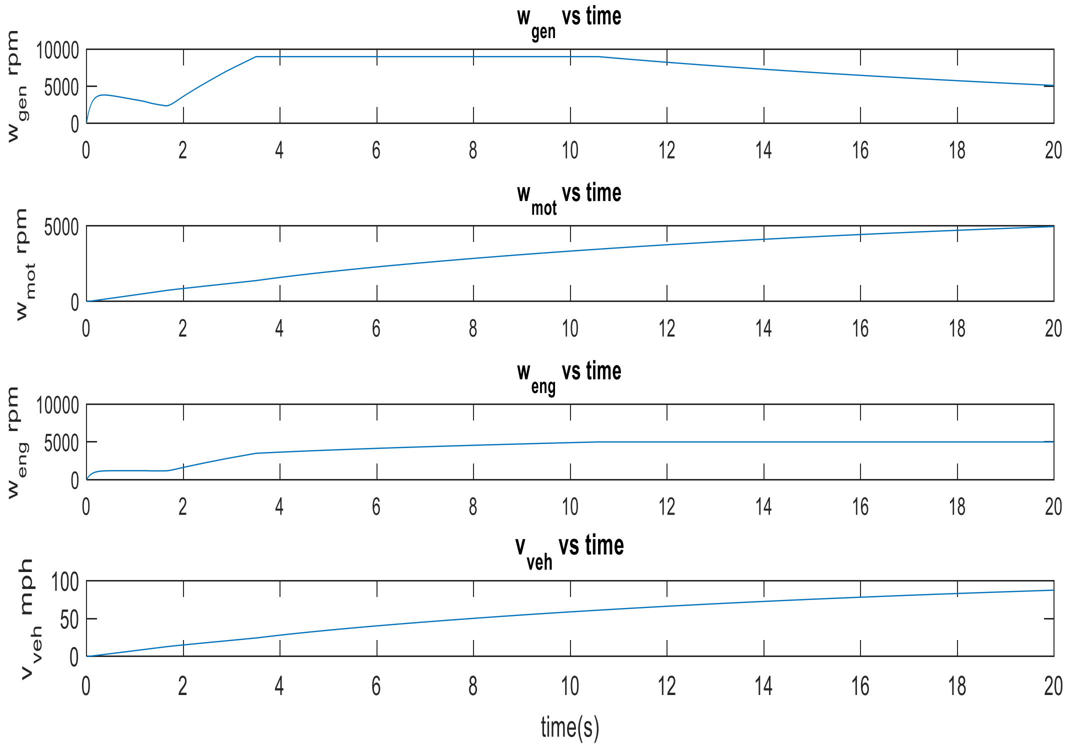

Fig 7: Engine, generator, motor and vehicle speed plotted together. At the very beginning, ω_gen increasing very rapidly. That is controlled by the PID, so that ω_eng doesn't increase that rapidly. This results in the sudden dip in Pbatt. At t2=1.645 s, ω_eng goes beyond 1200 rpm (starts to increase) due to increase in traction power (which results in increase in engine torque beyond 80Nm at 1200 rpm). At t3= 3.504s, ω_gen hits max limit of 9000 rpm. That also decreases the slope of ω_eng. At t5=10.6s, ω_eng hits limit (5000rpm). ω_gen = constant1*ω_eng – constant2*ω_mot. If ω_eng remains constant and ω_motor increases (didn't hit limit, increasing Ptractive), ω_gen will decrease. This result to ω_gen decrease.

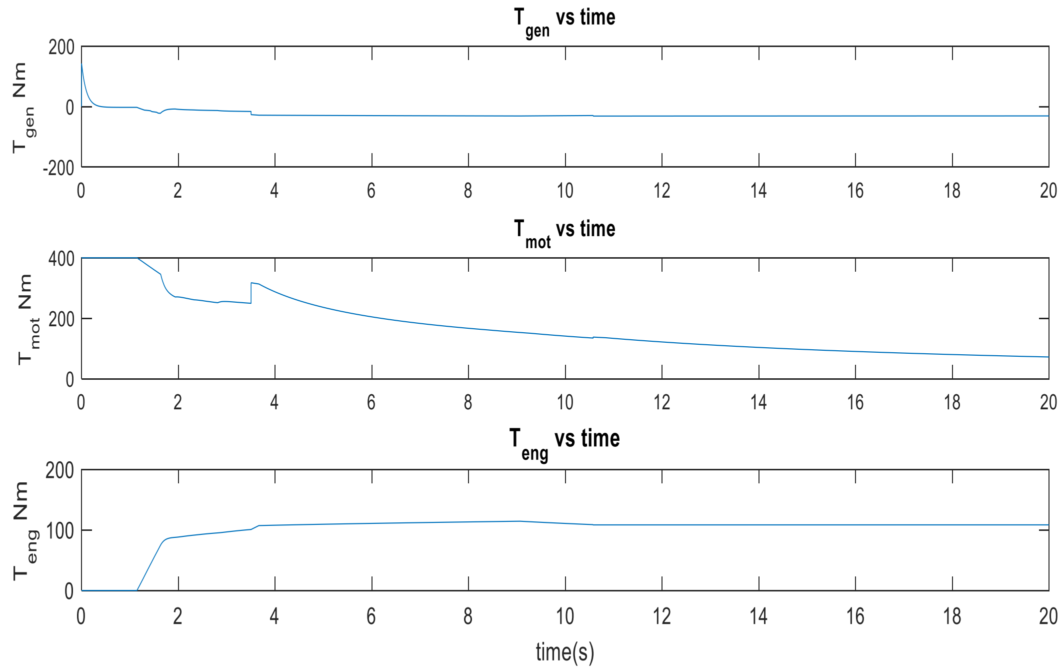

Fig 8: Engine, generator and motor torque plotted together. Battery supplies torque instantly, which results in Tmot hitting limit at the very beginning. At t1=1.145 s, battery (supplying to motor) hits power limit of 21 KW. This results to decrease in Tmotor (as Teng starts to increase). When Teng>0, Tgen<0 and remains there. At t3= 3.504s, ω_gen hits max limit of 9000 rpm and Tgen goes down. This results in sudden increase in Tmot (Tgen*ω_gen+Tmot*ω_mot=Pbatt (constant)). But Tmot goes down quickly, as extra torque is supplied by engine directly to differential.

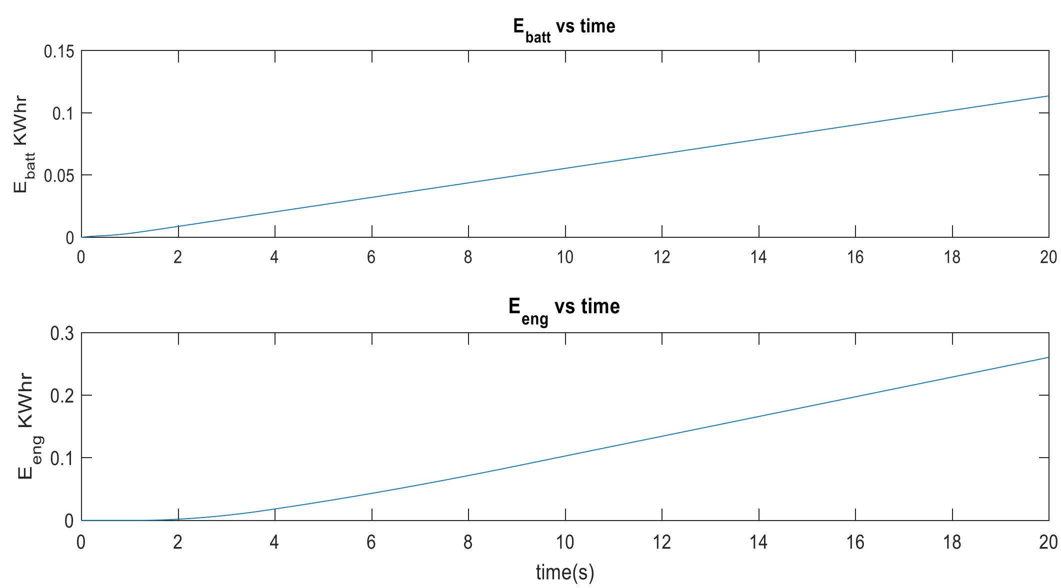

Fig 9: Battery and engine energy plotted together. Battery energy generating early as engine starts when Pbatt reaches limit. Because engine supplies more than double power to battery, engine supplies more energy to reach 60mph.

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Ques. 1: Were any limits violated? If so, which ones and by how much?

Generator speed reached 9003 rpm (limit 9000 rpm), engine speed reached 5001 rpm (limit 5000) but these values can be considered within limit. So, no limits were violated. Certain variables reached their limits at certain times (as stated earlier). But those variables were contained within limits by the model.

Ques. 2: What is the total time needed to accelerate the vehicle from 0 to 60 mph?

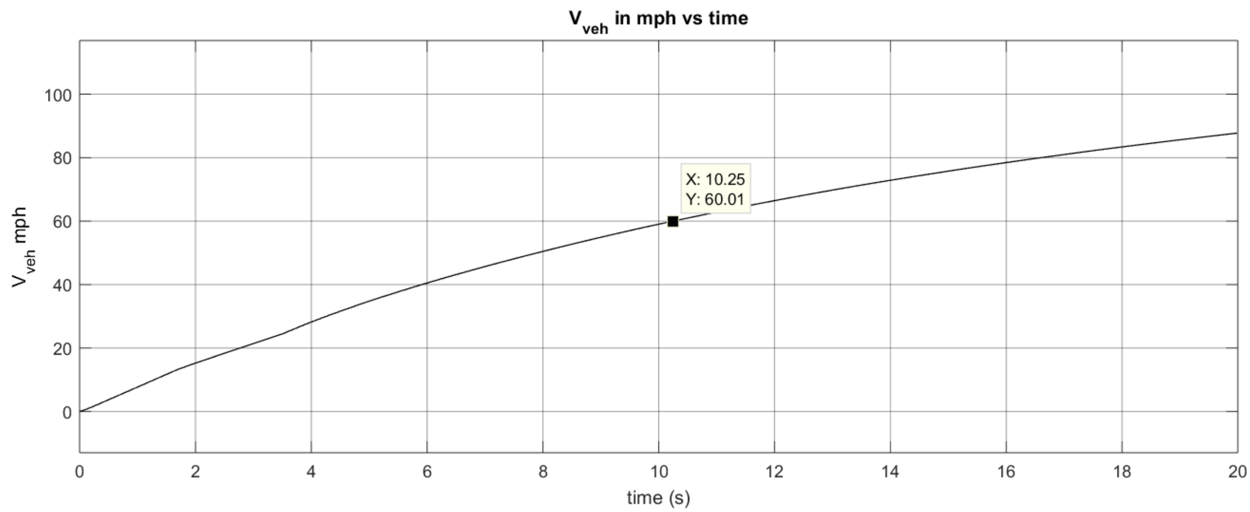

Fig 10: Vehicle speed in mph vs. time. It took 10.25 seconds to reach 60 mph.

Ques. 3: How much energy (in kW-hr) was supplied by the battery in doing so? What was the corresponding change in SOC, neglecting battery losses?

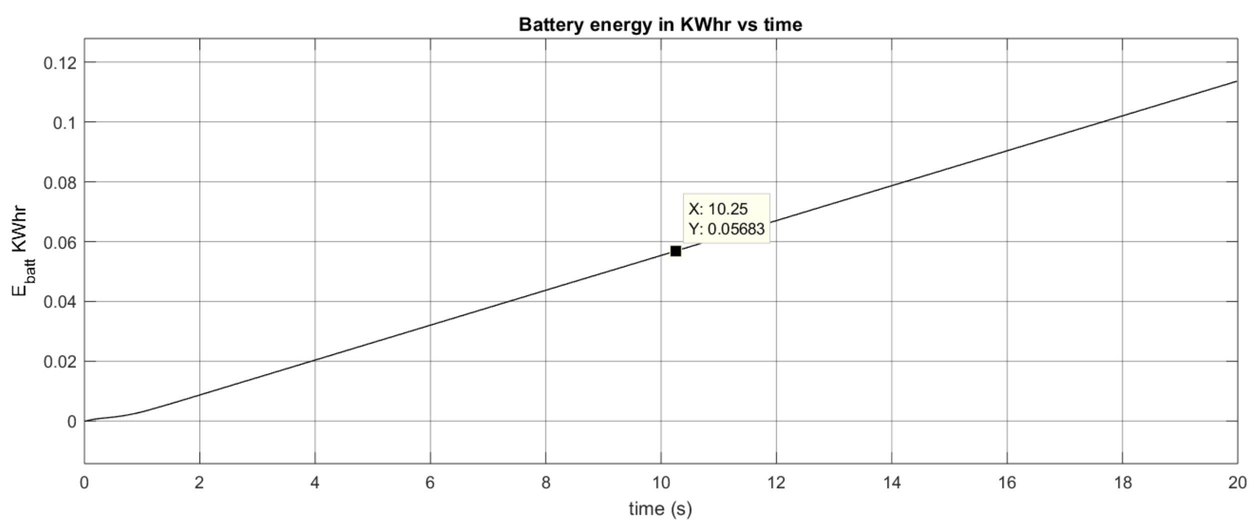

Fig 11: Battery energy in KWhr vs. time. 0.0568 KWhr is supplied by the battery to reach 60 mph. Battery capacity 1.7 KW hr. (1.7/.0568) = 29 times Prius can go 0-60 mph before it completely drains the battery from 100% SOC to 0.

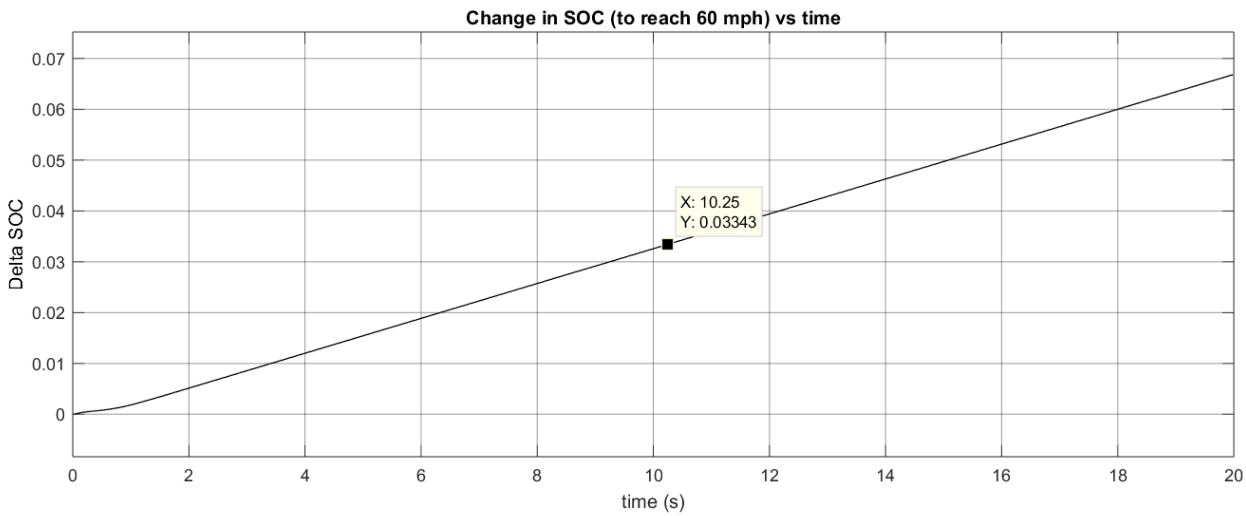

Fig 12: Change in SOC vs. time. Change in SOC is calculated by dividing battery energy by maximum energy of battery. Delta SOC is 0.033 to reach 60 mph.

Ques. 4: How much mechanical energy was supplied by the engine (also in kW-hr)?

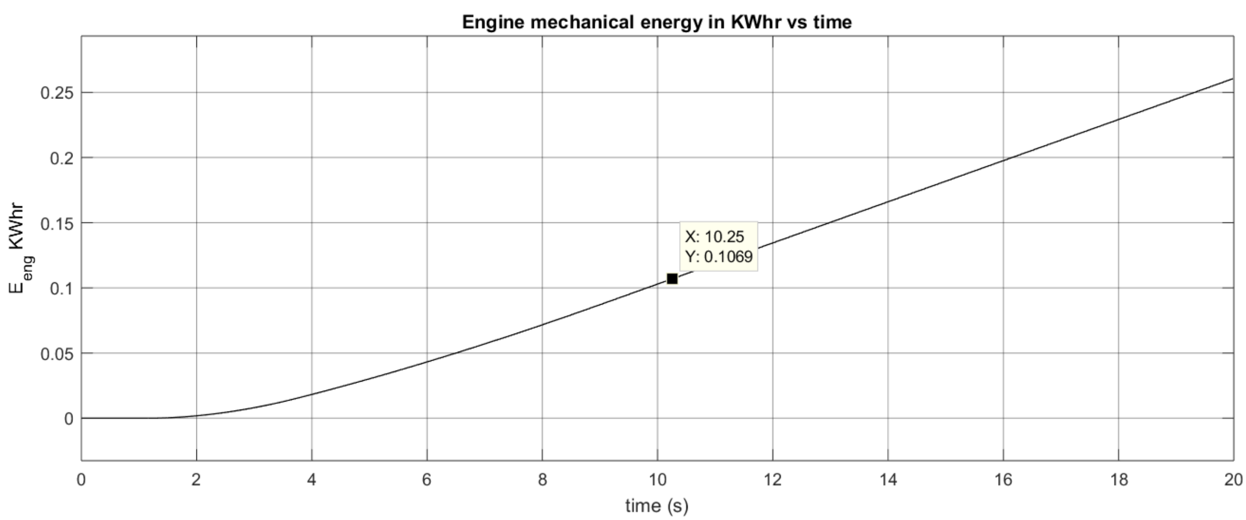

Fig 13: Mechanical energy is supplied by engine. 0.1069 KWhr is supplied by the engine to reach 60 mph. It is almost twice the energy supplied by battery. This trend is also observed in power plot where engine supplied more (almost twice) power.

Ques. 5: What is the kinetic energy of the vehicle (in kW-hr) at 60 mph? Include kinetic energy of translational and rotational motions.

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```
%rotation
M_veh = 1361 +100; % vehicle and driver mass in kg
% rotating inertias
J_eng = 0.1598; % engine inertia in kg-m^2 from SAE 2000-01-3096
J_mg1 = 0.02; % mg1 (generator) inertia in kg-m^2
J_mg2 = 0.05; % mg2 (motor) inertia in kg-m^2
N_s = 30; % number of sun teeth
N_r = 78; % number of ring teeth
G_fd = 0.2431; % ratio of wheel speed to motor speed
r_wheel = 0.3107; % wheel radius in m

% evaluate kinematic state matrix SLIDE 14
M_hat_veh = M_veh + J_mg1*(N_r/(N_s*G_fd*r_wheel))^2 ;
J_eng_hat = J_eng + J_mg1*((N_r+N_s)/N_s)^2;
K = J_mg1 * ((N_r+N_s)/N_s) * N_r/(N_s*G_fd*r_wheel);


%Energy calculated from simulink block simulation at 60mph
E_aero = 33.19; %in KJ, P_aero=F_aero*v_veh, then integrate and divide
by 1000
E_eng = 384.8;  %in KJ, P_eng integrated and divide by 1000
E_batt = 204.6; %in KJ, P_batt integrated and divide by 1000


%at 60 mph
v_veh = 26.82; %m/s
w_gen = 942.69; %9002 rpm converted to rad/s
w_mot = 355.21; %3392 rpm converted to rad/s
w_eng = 518.36; %4950 rpm converted to rad/s

%from slide 16
KE = (0.5*J_eng_hat*w_eng^2 + .5*M_hat_veh*v_veh^2 -
K*w_eng*v_veh)/1000 + E_aero %in KJ
%Kinetic_energy = 0.5*(M_veh*v_veh^2 + J_eng*w_eng^2 + J_mg1*w_gen^2 +
J_mg2*w_mot^2)/1000 + E_aero %KE in KJ

Vehicle_energy = E_eng + E_batt
```

Kinetic energy = 589.007 KJ

Vehicle energy = 589.4000 KJ

The difference in energy is mainly due to numerical error.