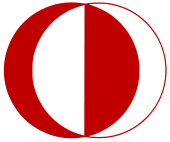
07.04.2019



**MIDDLE EAST TECHNICAL UNIVERSITY**

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

**EE 7566** Homework #1

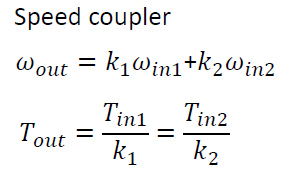
***Vehicle Dynamics and***

***Electrified Vehicle Powertrains***

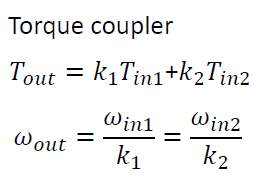
GÖKHAN ÇAKAL – **2332120**

# 1.)

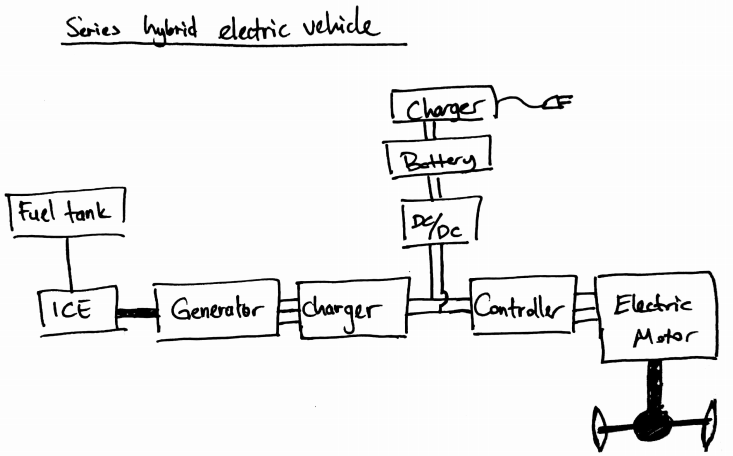
These are torque and speed couplers. These are used in order to couple the outputs of two different mechanical drive sources such as electric motor and internal combustion engine. In speed couplers, torque outputs of two drives are proportional to each other with a ratio and speeds of two drives are added as stated below. As an example of speed coupler, we can give planetary gear unit.



In torque coupler, torques of two drives are added and speeds are related with a ratio as shown below. Front and rear wheels of a car is an example of torque coupler. They have the same speeds but their torques are added.



# 2.)



**Advantages**:

* ICE speed is adjusted at its maximum efficient point, independently
* There is no complicated gear box and transmission device
* Easy design

**Disadvantages**:

* Generator adds additional weight and cost. It decreases overall efficiency.
* ICE, generator and electric motor should be same sized (not valid for range extender)
* Energy from ICE is converted twice, decreasing efficiency.

Most common application of series hybrid configuration is range extenders as we will discuss.

# 3.)

Electrical continuous variable transmission device (eVT) is fully electromagnetic transmission device. Its structure is similar to conventional electric motors. It consists of two concentric rotors and a stator. The inner rotor is wound rotor and outer rotor contains permanent magnets or it is squirrel cage rotor. Stator is as the same as in conventional electric motor stator. Since there is no direct mechanical contact in and eVT, the efficiency is higher and the system is more reliable. It has inherent overload protection. Also, it can eliminate vibrations. Thus and eVT combines several functionalities into a single useful device, making the system compact.

# 4.)

#### a)



Note: Since the equations are already written in Matlab code at the end, I didn’t write them here again.

#### b)





As can be seen above, base speed is 5233 rpm. Below base speed, we are in constant torque region. Above base speed, we are in constant power region. Maximum power and torque is 126 kW and 230 Nm, respectively. Maximum speed is 12000 rpm as found in part a.

#### c)



Here, we have followed the drive cycle with perfect match except one-two steps of lag. This lag is due to controller schematic and inevitable. Here, I used proportional constant (Kp) of 0.7. As we increase Kp, our controller gives stronger responses against speed changes. More dynamic system can be achieved. Power of the machine should be able to answer the need of faster response. With increasing Kp, our vehicle becomes more dynamic like we are in sport mode. Low Kp values results in smoother responses and power consumption may be decreased like we are in eco mode. Vehicle controllers use different Kp values in different operation modes like eco or sport mode. With increasing Kp, fuel consumption also increases.

#### d)



#### e)



#### f)



Regenerative energy is the energy retrieved during braking. Instead of losses of mechanical brakes, brake energy is used to charge back the battery. Actually, it is the one of the main advantages of electric vehicles over conventional internal combustion engines. As shown above, with regenerative braking, we restore 27.6% of the energy we used for traction in WLTP drive cycle. It is actually important amount of battery capacity. In city driving, since we have to use brakes frequently, regenerative braking provides important amount of saving. However, in highway driving, we rarely use brakes. Thus, we see advantage of regenerative braking mostly in city driving.

#### g)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Capacity of battery  In kWh | Electric machine power in kW | Electric machine torque in Nm | Mass of drivetrain in kg (incl. battery) | Cost of drivetrain in $ | Fuel consumption in kWh | Fuel economy  In TL/km | Total Regen. energy in % |
| BEV with 350 km range | 0.05g & 750 W | 38.93 | 126.02 | 230 | 460.1 | 13657 | 38.93 | 0.056 | 27.6 |
| 0.05 g & 0 W | 32.82 | 123.28 | 226 | 426.7 | 12315 | 32.82 | 0.047 | 27.2 |
| BEV with 500 km range | 0.05g & 750 W | 56.33 | 133.24 | 243 | 554.6 | 17455 | 56.33 | 0.056 | 28.5 |
| 0.05 g & 0 W | 47.52 | 129.45 | 238 | 506.6 | 15527 | 47.52 | 0.048 | 28.1 |
| BEV REX with 350+150 km range | 0.05g & 750 W | 39.10 | 127.86 | 235 | 489.2 | 14563 | 94.99 | 0.111 | 27.9 |
| 0.05 g & 0 W | 32.99 | 126.02 | 230 | 456.8 | 13259 | 80.15 | 0.094 | 27.6 |

# 5.)

When accessories are on,



When accessories are off,



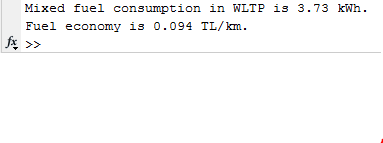
This results make sense since as we open the accessories, fuel consumption will increase and to compensate this we need to increase fuel tank capacity.

#### a)

When accessories are on,



When accessories are off,



# 6.)

#### a)

Before deciding, let’s compare these two. In REX, battery is smaller. Some of its range is supplied from internal combustion engine. Thus, charging times of the BEV will be more painful. Also, due to battery size, BEV is heavier and bulkier. However, since REX contains extra ICE and generator, initial drivetrain cost of BEV is less, which is an advantage. The bottleneck of REX is that its fuel economy is almost twice expensive compared to BEV.

If I was a rich man, I would definitely buy BEV and locate level 3 charger in my home to overcome fast charging times of BEV. Thus, my choice is BEV.

#### b)

As machine power increases, more energy is delivered in certain amount of time. This means faster acceleration and more dynamic performance. However, more power also means more fuel consumption and worse fuel economy.

#### c)



# Matlab Code

|  |
| --- |
| clc; clear all; close all;    % This is Homework 1 of EE 7566 Electrical Vehicles course  % Prepared by Gökhan ÇAKAL - 2332120    %% Definitions    range = 350; %km, required range of EV  accesories\_state = 0; % state of accessories, 1 or 0  rex\_mode = 1; % range extender mode on off, 1 or 0  range\_rex = 150; %km, range extension with range extender    Kp = 0.7; % Kp constant for acceleration  g = 9.8; %m/s2, gravitional acceleration  vel\_maxspeed\_veh = 150/3.6; %m/s, max vehicle speed  vel\_wind = 0; %m/s, wind speed  acc\_maxspeed = 0.05\*g; %m/s2, acceleration at maximum speed  gear\_ratio = 9.0478; % gear ratio of electric motor to wheels  r\_wheel = 0.3; %m, radius of wheels  d\_air = 1.25; %kg/m3, density of air  area\_fr = 2.57; %m2, frontal area  cd = 0.26; % aerodynamic drag coefficient  m\_body = 1000; %kg, mass of the body only  m\_power\_pre = 0; %kg, predicted mass of the power train  c\_mass = 1.05; % increase in the mass due to rotating masses  fr = 0.006; % coefficient of rolling resistance  Pow\_accesories = 750; %W, power consumed by accesories  k\_adh = 0.9; % Adhesive coefficient of tires to ground surface  k\_load\_acc = 0.5; % load distribution during acceleration  k\_load\_dec = 0.65; % load distribution during decelearation  time\_0\_100 = 7.5; %sec, 0-100 km/h time    eff\_mc\_inv = 0.92; % efficiency of electric machine and inverter  eff\_gear\_diff = 0.97; % efficiency of gearbox + differential  eff\_batt = 0.95; % efficiency of battery pack  eff\_charger = 0.98; % efficiency of charger  eff\_ice = 0.35; % efficiency of internal combustion engine    m\_spec\_mc\_inv = 1.1e3; %W/kg, specific mass of electric machine and inverter  m\_spec\_ice = 0.55e3; %W/kg, specific mass of internal combustion engine  vol\_spec\_mc\_inv = 2.6e3; %W/l, specific volume of electric machine + inverter  cost\_spec\_ice = 50; %$/kW, specific cost of internal combustion engine  cost\_charger = 300; %$, charger cost  cost\_spec\_mc\_inv = 30; % $/kW, specific cost of electric machine and inverter  cost\_fueltank = 150; % $, cost of fuel tank  m\_charger = 10; %kg, charger mass  m\_fuel\_tank = 5; %kg, fuel tank mass  m\_emine = 70; %kg, mass of the driver  price\_electric = 0.5; %TL/kwh, electric price  price\_gas = 6.25; %TL/l, gasoline price  dens\_gas = 9.7; % kWh/l, gasoline energy density    delta\_mass = 10; % initiate loop    while delta\_mass > 5 % difference in predicted and actual mass is less than 5 kg, stop the loop    %% Part 1    circ\_wheel = 2 \* pi \* r\_wheel; %m, circumferential of wheels  n\_maxspeed\_wheel = 60 \* vel\_maxspeed\_veh / circ\_wheel ; %rpm, max speed of the wheel  n\_mc\_maxspeed = n\_maxspeed\_wheel \* gear\_ratio; %rpm, max speed of the machine  m\_total = m\_body + m\_power\_pre + m\_emine; %kg, mass of the vehicle    Fw\_maxspeed = 0.5 \* d\_air \* area\_fr \* cd \* (vel\_maxspeed\_veh+vel\_wind)^2; %N, aerodynamic drag force at max speed  Fr = fr \* m\_total \* g; %N, rolling resistance  Fg = 0; %N, grading force    Ft\_maxspeed = c\_mass \* m\_total \* acc\_maxspeed + (Fw\_maxspeed + Fr + Fg); %N, traction force at max speed  Tw\_maxspeed = Ft\_maxspeed \* r\_wheel; %Nm, torque at wheels    T\_mc\_maxspeed = Tw\_maxspeed / gear\_ratio / eff\_gear\_diff; %N, motor torque at max speed  W\_mc\_maxspeed = n\_mc\_maxspeed \* pi/30; %rad/s, motor speed at max speed    Pow\_mc\_part1 = T\_mc\_maxspeed \* W\_mc\_maxspeed; %W, plant traction power  Pow\_batt\_part1 = Pow\_mc\_part1 + Pow\_accesories; %W, power capacity of the battery      %% Part 2    Ft\_max\_acc = k\_adh \* m\_total \* g \* k\_load\_acc; %N, Maximum traction afford of tires during acceleration  Ft\_max\_dec = k\_adh \* m\_total \* g \* k\_load\_dec; %N, Maximum traction afford of tires during decelaration    Tmax\_mc\_max = Ft\_max\_acc \* r\_wheel / gear\_ratio / eff\_gear\_diff; %Nm, maximum allowed traction torque by machine before slipping  Tmax\_mc\_init = Fr \* r\_wheel / gear\_ratio / eff\_gear\_diff; %Nm, initial maximum torque assumption for machine      dT = 0.1; %sec, time resolution  time\_elements = time\_0\_100 / dT; %elements, number of time elements determining resolution  % dT = time\_0\_100 / time\_elements; %sec, time resolution    time\_act = zeros(1,time\_elements); % defining time array    Pow\_mc = Pow\_mc\_part1; %W, initial power assumption of the machine  vel\_endtime = 0; %m/s, start while loop    while vel\_endtime < 100/3.6 %m/s, loop until velocity speed reaches 100 km/h    for Tmax\_mc = Tmax\_mc\_init:1:Tmax\_mc\_max %Nm, machine maximum torque finder    W\_mc\_base = Pow\_mc / Tmax\_mc; %rad/s, base speed of the machine  vel\_veh\_base = W\_mc\_base / gear\_ratio \* r\_wheel; %m/s, base vehicle speed    vel\_veh = zeros(1,time\_elements); %m/s, initializing vehicle speed array  Fw = zeros(1,time\_elements); %N, initializing aerodynamic drag force array  Ft = zeros(1,time\_elements); %N, initializing traction force array  T\_mc = zeros(1,time\_elements); %Nm, initializing machine torque array  W\_mc = zeros(1,time\_elements); %Nm, initializing machine speed array    for t = 1:1:time\_elements  time\_act(t) = t \* dT; %sec, actual time array  W\_mc(t) = vel\_veh(t) / r\_wheel \* gear\_ratio; %rad/s, machine speed      % determine machine torque  if vel\_veh(t) < vel\_veh\_base; % find torque of the machine at velocity of the vehicle  T\_mc(t) = Tmax\_mc; %Nm, if vehicle is below base speed, maximum torque is achieved  else  T\_mc(t) = Pow\_mc / W\_mc(t); %Nm, if base speed is exceeded, constant power region is valid  end  % machine torque is found at that specific speed    Ft(t) = T\_mc (t) \* gear\_ratio \* eff\_gear\_diff / r\_wheel; %N, traction force  Fw(t) = 0.5 \* d\_air \* area\_fr \* cd \* (vel\_veh(t)+vel\_wind)^2; %N, aerodynamic drag force    vel\_veh(t+1) = vel\_veh(t) + ( Ft(t) - Fw(t) - Fr ) \* dT / (c\_mass \* m\_total); %m/s, vehicle speed at next time instant    end    vel\_endtime = vel\_veh(end); %m/s, achieved velocity at the end of time    if vel\_endtime > 100/3.6  break;  end    end    Pow\_mc = Pow\_mc + 100; %W, if enough speed is now achieved, increase the power of the machine  % plot(T\_mc); hold on;  end    a=1;        %% part 3    load('C:\Users\DELL\Documents\Dersler\EE 7566 Electric Vehicles\HW 1\drive cycles\cycles\_wltp.mat'); % loading WLTP drive cycle  vel\_ref = WLTP\_class\_3.Data / 3.6; %m/s, reference speed of drive cycle  vel\_act = zeros(1,numel(vel\_ref)); %m/s, actual vehicle velocity  vel\_err = zeros(1,numel(vel\_ref)); %m/s, error in velocity  Fw\_3 = zeros(1,numel(vel\_ref)); %N, drag force array in part 3  Ft\_req = zeros(1,numel(vel\_ref)); %N, required traction force  Ft\_act = zeros(1,numel(vel\_ref)); %N, actual applied traction force  W\_mc\_act = zeros(1,numel(vel\_ref)); %rad/s, actual machine speed  T\_limit\_mc = zeros(1,numel(vel\_ref)); %Nm, maximum torque that machine can supply for that specific speed  Ft\_limit\_mc = zeros(1,numel(vel\_ref)); %N, maximum force that machine can supply for specific speed    % Define maximum traction force limits due to tire adhesion    Ft\_max\_tires = k\_adh \* m\_total \* g \* k\_load\_acc; %N, Maximum traction force that tires can apply  Ft\_min\_tires = - k\_adh \* m\_total \* g; %N, Minimum traction force that tires can apply (consider mechanical brakes)    dT3 = 1; %sec, time resolution of drive cycle      for t = 1:1:numel(vel\_ref)    vel\_err(t) = vel\_ref(t) - vel\_act(t); %m/s, error in velocity  acc\_req = Kp \* vel\_err(t); %m/s^2, acceleration required by loop    Fw\_3(t) = 0.5 \* d\_air \* area\_fr \* cd \* (vel\_act(t)+vel\_wind)^2; %N, aerodynamic drag force  Ft\_req(t) = c\_mass \* m\_total \* acc\_req + Fr + Fw\_3(t); %N, required traction force by loop    % define traction force limits that you machine can supply    W\_mc\_act(t) = vel\_act(t) / r\_wheel \* gear\_ratio; %rad/s, actual machine speed  if vel\_act(t) < vel\_veh\_base  T\_limit\_mc(t) = Tmax\_mc; %Nm, maximum torque that machine can supply for that specific speed  else T\_limit\_mc(t) = Pow\_mc / W\_mc\_act(t); % in field weakening region  end    Ft\_limit\_mc(t) = T\_limit\_mc(t) \* gear\_ratio / r\_wheel \* eff\_gear\_diff; %N, maximum force that machine can supply for specific speed    Ft\_act(t) = max( Ft\_min\_tires ,min( min(Ft\_req(t), Ft\_max\_tires), Ft\_limit\_mc(t)) ); %N, actually applied traction force considering limits    vel\_act(t+1) = vel\_act(t) + ( Ft\_act(t) - Fw\_3(t) - Fr ) \* dT3 / (c\_mass \* m\_total); %m/s, vehicle speed at next time instant    end      dist\_wltp = sum(vel\_act) / 1e3; %km, total distance travelled with wltp drive cycle    % battery energy calculation    Ft\_min\_mc = - k\_adh \* m\_total \* g \* k\_load\_dec; %N, minimum force that is applied by rear wheels (thus machine)    Ft\_mc\_act = max(Ft\_min\_mc,Ft\_act); %N, traction force applied by machine.  Ft\_brakes = Ft\_act - Ft\_mc\_act; %N, traction force applied by mechanical brakes. It is on stage during acceleration regenerative braking is not enough.    T\_mc\_act = Ft\_mc\_act\*r\_wheel / gear\_ratio / eff\_gear\_diff; %Nm, actual machine torque  Pow\_mc\_act = T\_mc\_act .\* W\_mc\_act; %W, machine output power applied to the vehicle at every instant    E\_batt\_wltp = sum(Pow\_mc\_act \* dT3 / eff\_batt / eff\_mc\_inv + accesories\_state\*Pow\_accesories \* dT3 / eff\_batt) / 36e5; %kWh, battery capacity for one WLTP drive cycle    E\_batt\_final = E\_batt\_wltp \* range / dist\_wltp; %kWh, battery capacity required for given range of WLTP drive cycle    Pow\_regenerated\_wltp = -min(0,Pow\_mc\_act); %W, instantaneous regenerated energy in wltp  Pow\_tractive\_wltp = max(0,Pow\_mc\_act); %W, instantaneous tractive power in wltp    E\_regenerated\_wltp = sum(Pow\_regenerated\_wltp \* dT3 \* eff\_mc\_inv \* eff\_batt) / 36e5; %kWh, regenerated energy in wltp  E\_tractive\_wltp = sum(Pow\_tractive\_wltp \* dT3 / eff\_mc\_inv / eff\_batt) / 36e5; %kWh, energy used for tractive efford in wltp      % range extender mode    Pow\_mc\_avg = mean(Pow\_mc\_act); %W, average power of electric machine  Pow\_ice = Pow\_mc\_avg / eff\_charger / eff\_mc\_inv; %W, power output of internal combustion engine  Pow\_gen = Pow\_mc\_avg / eff\_charger; %W, power output of generator  E\_batt\_rex = E\_batt\_wltp \* range\_rex / dist\_wltp; %kWh, battery energy required for range extension  E\_fueltank\_rex = E\_batt\_rex / (eff\_ice\*eff\_mc\_inv\*eff\_batt\*eff\_charger); %kWh, energy stored in fuel tank for rex  vol\_fueltank = E\_fueltank\_rex / dens\_gas; % l , volume of fuel tank for rex      % mass calculations    Pow\_batt = Pow\_mc / eff\_mc\_inv + Pow\_accesories; %W, battery power    m\_batt = E\_batt\_final\*1000 / (200 - 3\*Pow\_batt/E\_batt\_final/1000) + 120; %kg, battery mass  m\_mc\_inv = Pow\_mc / eff\_mc\_inv/ m\_spec\_mc\_inv ; %kg, mass of the machine and inverter  m\_ice = Pow\_ice / m\_spec\_ice; %kg, mass of ice  m\_gen = Pow\_gen / m\_spec\_mc\_inv; %kg, mass of generator    m\_power\_act = m\_batt + m\_mc\_inv + m\_charger + rex\_mode\*( m\_fuel\_tank + m\_ice + m\_gen + m\_charger); %kg, mass of drivetrain  m\_total\_final = m\_body + m\_power\_act + m\_emine; %kg, total mass of the vehicle including    delta\_mass = abs( m\_total - m\_total\_final ); %kg, error in actual and predicted mass    m\_power\_pre = m\_power\_pre + 10; %kg, increase predicted power mass    end      %% machine characteristics    for W\_mc = 1:1:W\_mc\_maxspeed    if W\_mc < W\_mc\_base; % check base speed  T\_mc(W\_mc) = Tmax\_mc; %Nm, if machine is below base speed, maximum torque is achieved  Pow\_mc\_char(W\_mc) = T\_mc(W\_mc) \* W\_mc; %W, machine power characteristics  else  T\_mc(W\_mc) = Pow\_mc / W\_mc; %Nm, if base speed is exceeded, constant power region is valid  Pow\_mc\_char(W\_mc) = Pow\_mc; %W, machine power characteristics    end    end  W\_mc = 1:1:W\_mc\_maxspeed;    figure;  stem(W\_mc\_act\*30/pi,T\_mc\_act,'\*','linestyle','none');  hold on;  plot(W\_mc\*30/pi,T\_mc,'b',W\_mc\*30/pi,-T\_mc,'b','linewidth',2);  % plot(W\_mc\*30/pi,T\_mc,'b','linewidth',2);    title('Torque Speed Characteristics')  xlabel('Speed (rpm)')  ylabel('Torque (Nm)')    figure;  plot(W\_mc\*30/pi,Pow\_mc\_char/1e3,'b','linewidth',2);  title('Power Speed Characteristics')  xlabel('Speed (rpm)')  ylabel('Power (kW)')      %% speed traction    figure;  time = 1:1:numel(vel\_ref); %sec, time array  plot(time,vel\_act(1:end-1)\*3.6,time,vel\_ref\*3.6); % plot reference and actual speed    title('Drive Cycle Performance')  xlabel('Time (sec)')  ylabel('Velocity (km/h)')  legend('Actual velocity','Reference velocity')    %% results    cost\_mc\_inv = Pow\_mc/1e3 \* cost\_spec\_mc\_inv; % $, cost of mc and inv  cost\_batt = E\_batt\_final \* (200 + 13 \* Pow\_batt/E\_batt\_final/1000); % $, cost of batt  cost\_ice = cost\_spec\_ice \* Pow\_ice/1e3; % $, cost of ice  cost\_gen = Pow\_ice/1e3 \* cost\_spec\_mc\_inv; % $, cost of generator    cost\_power = cost\_mc\_inv + cost\_batt + cost\_charger + rex\_mode\*( cost\_fueltank + cost\_ice + cost\_gen + cost\_charger ); % $, cost of powertrain    elect\_cost = price\_electric \* E\_batt\_final; %TL, electric cost for full range  fuel\_ec = (elect\_cost + rex\_mode \* vol\_fueltank \* price\_gas ) / ( range + rex\_mode\*range\_rex) ; %TL/km, fuel economy    fuel\_cons = E\_batt\_final + rex\_mode\*E\_fueltank\_rex; %kWh, fuel consumption for a given range  percent\_regen = E\_regenerated\_wltp / E\_tractive\_wltp \* 100; % percent of energy regenerated      fprintf('Capacity of battery is %.2f kWh.\n', E\_batt\_final);  fprintf('Electric machine power is %.2f kWh.\n', Pow\_mc/1e3);  fprintf('Electric machine torque is %.0f Nm.\n', Tmax\_mc);  fprintf('Mass of drivetrain is %.1f kg.\n', m\_power\_act);  fprintf('Cost of drivetrain is %.0f $.\n', cost\_power);  fprintf('Fuel consumption is %.2f kWh.\n', fuel\_cons);  fprintf('Fuel economy is %.3f TL/km.\n', fuel\_ec);  fprintf('Total regenerated energy is %.1f%%.\n', percent\_regen);    fprintf('Maximum machine speed is %.0f rpm. \n', n\_mc\_maxspeed);  fprintf('Fuel consumption is %.3f kWh/km. \n', fuel\_cons / ( range + rex\_mode\*range\_rex));  fprintf('Fuel economy is %.3f TL/km.\n', fuel\_ec);  fprintf('ICE power output is %.2f kW.\n', rex\_mode\*Pow\_ice/1e3);  fprintf('Capacity of fuel tank is %.2f liters.\n', vol\_fueltank\*rex\_mode);  fprintf('Mixed fuel consumption in WLTP is %.2f kWh.\n', fuel\_cons/(range+range\_rex)\*dist\_wltp);  fprintf('Fuel economy is %.3f TL/km.\n', fuel\_ec);  fprintf('Charging time with level 1 charger is %.2f hours.\n', E\_batt\_final/eff\_batt/eff\_charger/1.8);  fprintf('Charging time with level 2 charger is %.2f hours.\n', E\_batt\_final/eff\_batt/eff\_charger/19.2); |