Powertrains Problem

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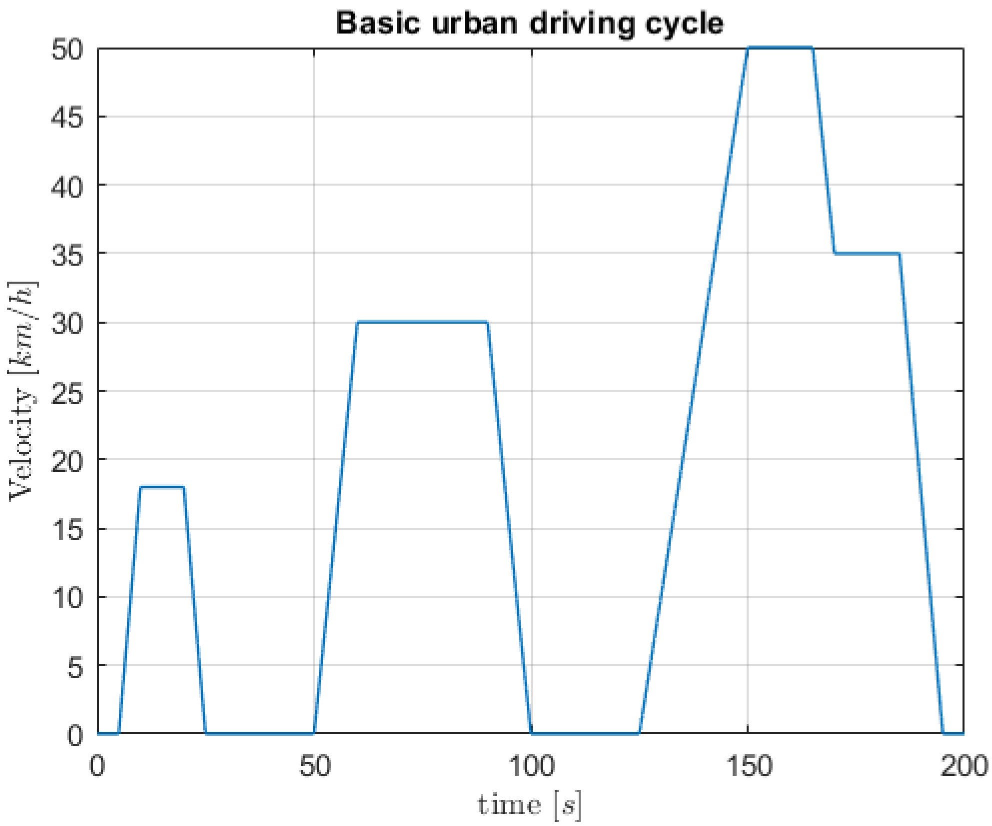
Drawing the two driving cycles

In order to perform this study, the driving cycles were ploted in matLab. Two types of driving cycles were used:

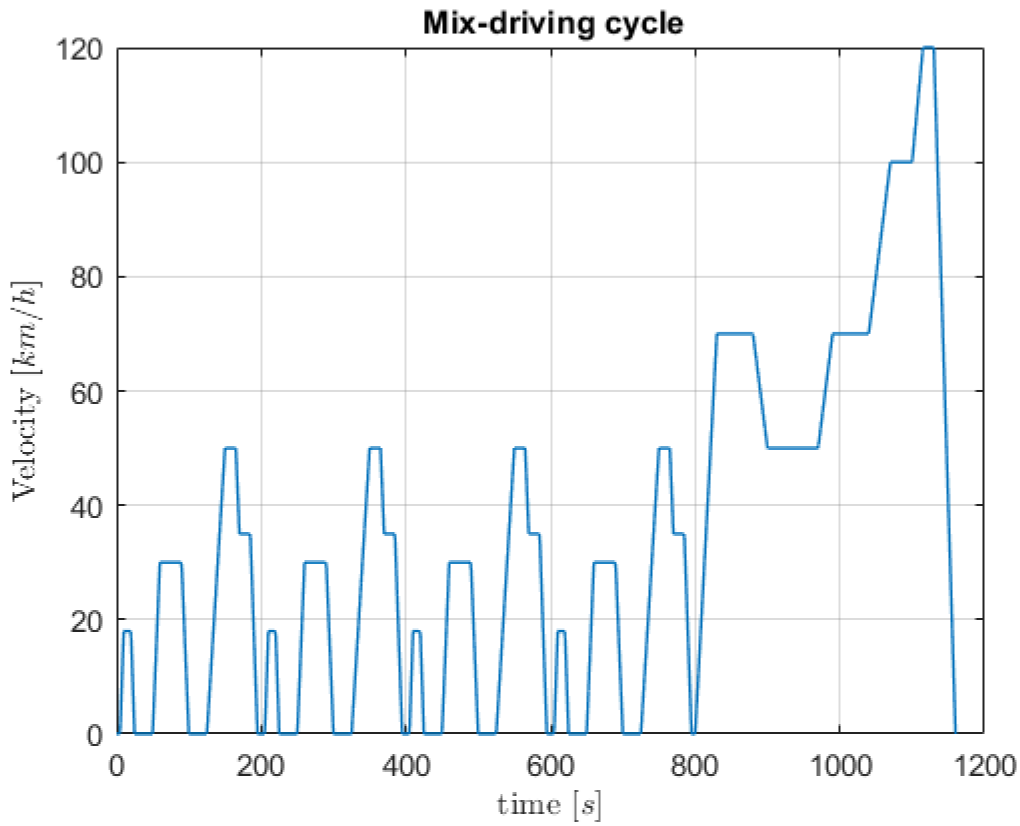
```
clear
close all
clc
```

```
[basic_time, basic_velocity] = BasicDrivingCycle();
figure();
plot(basic_time, basic_velocity, 'LineWidth', 1);
set( gca, 'FontSize', 11);
grid on;
title('Basic urban driving cycle');
xlabel('time $[s]$','Interpreter', 'latex');
ylabel('Velocity [$km/h$]','Interpreter', 'latex');
```



Note that the Mix-driving cycle is composed of urban and extra-urban driving cycles, being the first the concatenation of basic urban driving cycles.

```
[mix_time, mix_velocity] = MixDrivingCycle(basic_time,
 basic_velocity);
figure()
plot(mix_time, mix_velocity, 'LineWidth', 1);
set( gca, 'FontSize', 11);
grid on;
title(' Mix-driving cycle');
xlabel('time $[s]$','Interpreter', 'latex');
ylabel('Velocity [$km/h$]','Interpreter', 'latex');
```



Vehicles Configurations and assumptions

In the study there are 4 possible powertrain configurations of light duty urban vehicles, presented in the figures (1), (2), (3) and (4). They consist of pure eletric, pure combustion, series hybrid and paralel hybrid.

Assumptions: Pure Eletric Powertrain

In this configuration the battery in series with the eletric motor/generator in series with the transmission. There are two possible modes of functioning, the motor discharging the batteries while accelerating, and the opposite, generator charging the batteries decelerating.

Acceleration: During discharge the ciruit has an efficiency different of 100%. The overalll efficiecy $\eta_{overall}$ is given by the product of the individual effincicency of each component of the circuit

$$\eta_{overall} = \prod_{i=1} \eta_i.$$

Thus, for this powertrain, one has that [$battery \rightarrow motor \rightarrow transmission$] will translate in a overall efficiency given by:

$$\eta_{overall} = \eta_{battery}\eta_{motor}\eta_{transmission}$$

- Assuming that the batteries are made from lithium-ion, according to https://en.wikipedia.org/wiki/Lithium-ion_battery it is reasonable to assume that the discharging effincicency of the battery of around 80%;
- From https://en.wikipedia.org/wiki/Electric_car#Energy_efficiency it is reasonable to assume that the eletric motor has an efficiency of 70%;

- From https://www.nap.edu/read/21744/chapter/7 it is resonable to assume that the effinciecy of an automatic transmission is 90%; So the the overall discharging performance can be computed:

```
efficiency_battery_discharge = 0.8;
efficiency_transmission = 0.9;
efficiency_motor = 0.8;
efficiency_pure_eletric_discharging =
 efficiency_battery_discharge*efficiency_motor*efficiency_transmission;
```

Thus the eletric power in acceleration is given by:

$$P_{eletric} = \frac{P_{mecanic}}{\eta_{overall}}$$

Deceleration During deceleration, it is assumed that the motor works as a generator, recharging the battery. Although it is the same path as acceleration [$transmission \rightarrow generator \rightarrow battery], the efficiencies have different values.

- From it is reasonable to assume that the discharging effinciency of the battery of around 90%;
- Its is reasonable to assume that the generator has an efficiency of 80%;
- Similarly to the accelaration, it is reasonable to assume that the transmission has an efficiency of 90%; So the the overall charging performance can be computed:

```
efficiency_battery_charge = 0.9;
efficiency_transmission = 0.9;
efficiency_generator = 0.7;
efficiency_pure_eletric_charging =
 efficiency_battery_charge*efficiency_generator*efficiency_transmission;
```

Thus the eletric power in deceleration is given by:

$$P_{eletric} = P_{mecanic}\eta_{overall}$$

Asusmptions: Series Hybrid Powertrain

In the configuration, there is a series connection between the fuel, the diesel generator, the battery pack, the motor/generator, and the transmission. Knowing that combustion engines only have a good perfomance in a narrow rpm band, called power band, it is assumed that, similiar do hybrid cars in the market, the car can operate in pure eletric mode for a velocities under 50 km/h and as a hybrid for highier velocities. (Good explanation on hybrid here https://www.youtube.com/watch?v=E_xCssR8qQI) The eletric mode has the same efficiency as the pure eletric powertrain, So the efficiency of this power train can be:

- In eletrical mode, the $\eta_{overall} = \eta_{overall-eletric}$;
- According to https://en.wikipedia.org/wiki/Diesel_generator, it is reasonable to assume that the performance of the diesel generator is 65%;

Thus the overall performance is given by:

- $\eta_{overall} = \eta_{overall-eletric}$, when $v < 50km/h$
- $\eta_{overall} = \eta_{overall-eletric}\eta_{diesel-generator}$, when $v > 50km/h$

```
efficiency_diesel_generator = 0.65;
efficiency_hybrid_series_eletric_charging =
 efficiency_pure_eletric_charging;
efficiency_hybrid_series_discharging =
 efficiency_pure_eletric_discharging*efficiency_diesel_generator;
```

Assumptions: Parallel Hybrid Powertrain

The parallel power train, there are two path from the power source to the wheels:

- The series between the fuel, the engine and the transmisson;
- The series between the battery, the motor/generator and the transmission;

It is no notice that the engine can act on the generator in order to charge the battery if needed. So, with this set up, we can consider that for velocieties up to 20 km/h, the powertrain functions in pure eletric mode, for velocities greater than 450 km/h it works on pure combustion engine, for velocities in between 20 and 40 km/h it demands half the power from the bateries and half from combustion. For breaking it is assumed that regenerative breaking allways works. With this, the efficiencies considered are:

- According to https://en.wikipedia.org/wiki/Engine_efficiency, it is cosiderend that the motor is running on diesel engine, being of 30%.
- The eletric path has the same efficiency as the pure eletric powertrain.

```
efficiency_hybrid_parallel_eletric_charging =
 efficiency_pure_eletric_charging;
efficiency_hybrid_parallel_eletric_discharging =
 efficiency_pure_eletric_discharging;
efficiency_hybrid_parallel_combustion_discharging = 0.30;
```

Assumptions: Pure Combustion Powertrain

This powertrain is fairly straight forward, being it's efficiency just the efficiency of the diesel motor.

```
efficiency_pure_combustion_discharging = 0.30;
```

Power Consumption

Power Consumption: Theoretical Approach

In this section it is of interest to compare the power consumption between the different powertrains.

The objective os to calculate:

$$P_T = F_T v$$

So first one must consider the traction force F_T on each car. The forces present are:

- Motor force;

- Drag force;
- Friction force;

$F_T = f_m ma + F_{drag} + F_{friction}$

Being:

- $F_{drag} = \frac{1}{2}\rho C_d A(v - (-v_w))^2)$
- $F_{friction} = C_{rr} mg$

$f_m \rightarrow mass factor$; $\rho \rightarrow$ densidade do meio; $C_d \rightarrow$ aerodynamic drag coefficient; A $\rightarrow$ frontal surface area; $v_w \rightarrow$ wind speed; $C_{rr} \rightarrow$ rolling resistance coefficient; m and g mass a gravity;

Considering $f_m = 1.05$, $\rho = 1.225 kg/m^3$, $v_w = 25 km/h$ and using the constant values from the table(I) of the laboratory script, one can compute the values of F_T.

```
air_density = 1.225;
mass_factor = 1.05;
drag_coefficient = 0.25;
surface_area = 2.7;
wind_speed = (25/3.6);
rolling_resistance_coefficient = 0.018;
mass = 1400;
gravity = 9.8;
```

Power Consumption: Computations Function

Function used to calculate the evolution of the powers in the driving cycles:

```
function [power] = AuxPowerCalculator(mechanical_power, velocity,
 power, efficiency_breaking, efficiency_mode_1, efficiency_mode_2)
    for i=1:length(mechanical_power)
        % When the system is breaking
          if(mechanical_power(i) < 0)
              power(i) = mechanical_power(i) * efficiency_breaking;
              continue
         end
          % When the system's velocity is under 20km/h and not
 breaking
          if(velocity(i)*3.6 < 20)
              power(i) = mechanical_power(i) / efficiency_mode_1;
          end
       % When system is between 20 and 40 km/h
          if(velocity(i)*3.6 >= 20 && velocity(i)*3.6 <= 40)
              power(i) = (mechanical_power(i)/2) / (efficiency_mode_2)
 + (mechanical_power(i)/2) / (efficiency_mode_1);
          end
          if(velocity(i)*3.6 > 40)
            power(i) = mechanical_power(i) / efficiency_mode_2;
```

```
        end
    end
end
```

Power Consumption: Show Results Function

In order to more easily show the results of each system, the mechanical power and the system output power are ploted at the same time, in order to better see the effect of the different efficiencies: For that, the following function was created

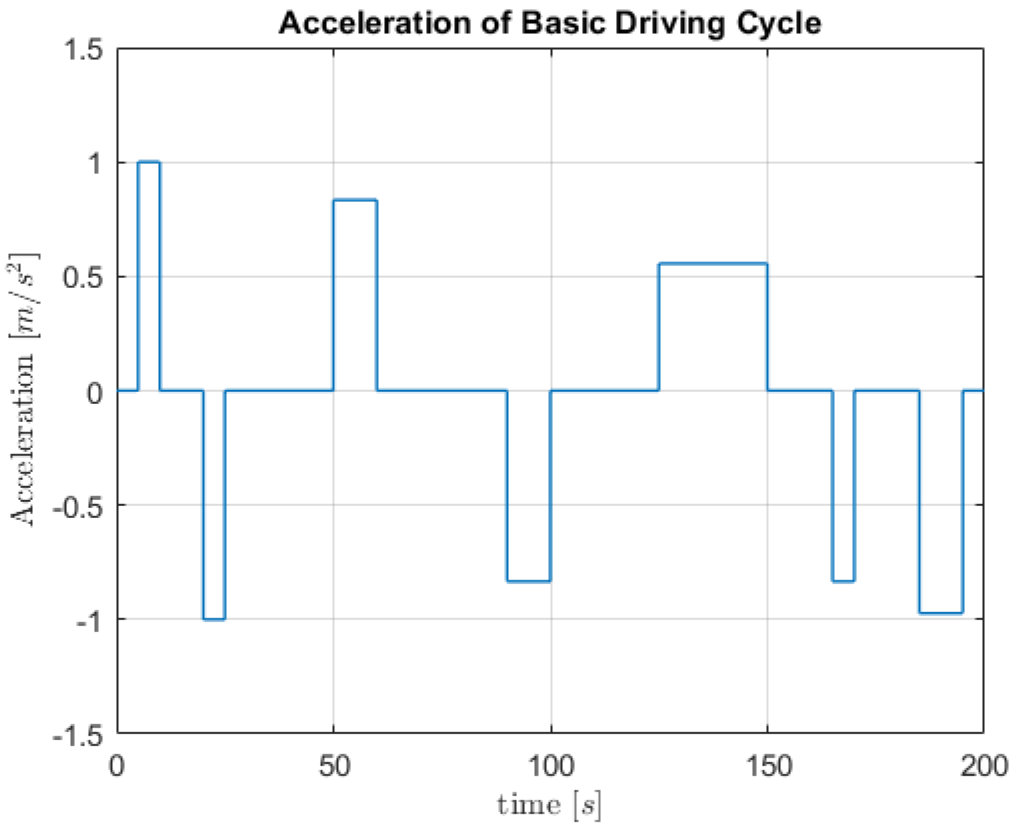
```
function [] = AuxShowPowerResults(time, power, mechanical_power,
 power_train)
  figure()
  plot(time, power/1000, time, mechanical_power/1000, 'LineWidth', 1);
  set( gca, 'FontSize', 11);
  title(sprintf('Power Consumption of %s Powertrain', power_train));
  xlabel('time $[s]$','Interpreter', 'latex');
  ylabel('Power [$kW$]','Interpreter', 'latex');
  legend( sprintf('%s Output Power', power_train), 'Mechanical
 Power');
  grid on;
end
```

Power Consumption: Basic Driving Cycle

Given the theoretical and functional approach taken above, the power consumption can be computed. First the acceleration vector is necessary in order to cumpute the force.

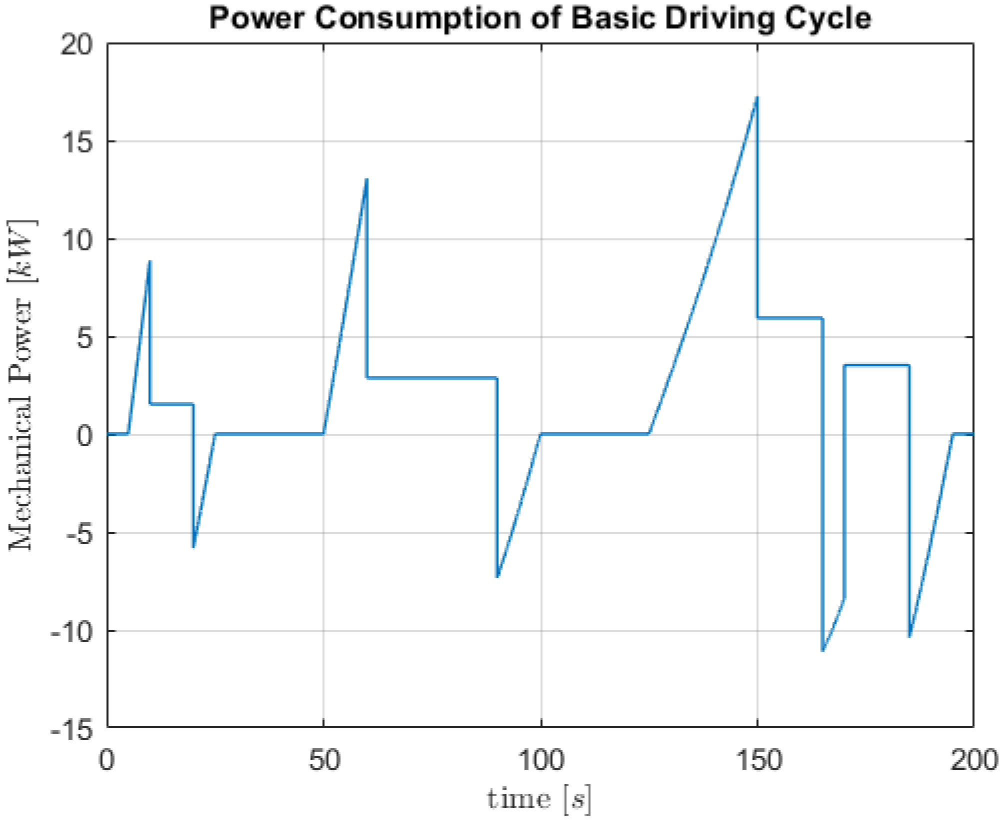
The basic velocity must be converted from km/h to m/s:

```
basic_velocity = basic_velocity/3.6;
time_step = basic_time(4) - basic_time(3);
basic_acceleration = diff(basic_velocity)/time_step;
% It is necessary to pop the last value of the time and velocity
 arrays due
% to the previous derivative:
basic_time(end) = [];
basic_velocity(end) = [];
figure();
plot(basic_time, basic_acceleration, 'LineWidth', 1);
set( gca, 'FontSize', 11);
title('Acceleration of Basic Driving Cycle');
xlabel('time $[s]$','Interpreter', 'latex');
ylabel('Acceleration [$m/s^2$]','Interpreter', 'latex');
grid on;
```



The mechanical power involved is compueted by:

```
force_motor = mass_factor * mass * basic_acceleration;
force_drag = 0.5 * air_density * drag_coefficient * surface_area *
 (basic_velocity + wind_speed).^2;
force_friction = rolling_resistance_coefficient * mass * gravity;
force_traction = force_motor + force_drag +  force_friction;
mechanical_power_basic_cycle = force_traction.*basic_velocity;
figure();
plot(basic_time, mechanical_power_basic_cycle/1000, 'LineWidth', 1);
set( gca, 'FontSize', 11);
title('Power Consumption of Basic Driving Cycle');
xlabel('time $[s]$','Interpreter', 'latex');
ylabel('Mechanical Power [$kW$]','Interpreter', 'latex');
grid on;
```



It is to notice that the negative values of power correspond to power from breaking, this power is used by the regenerative breaking (if in operation).

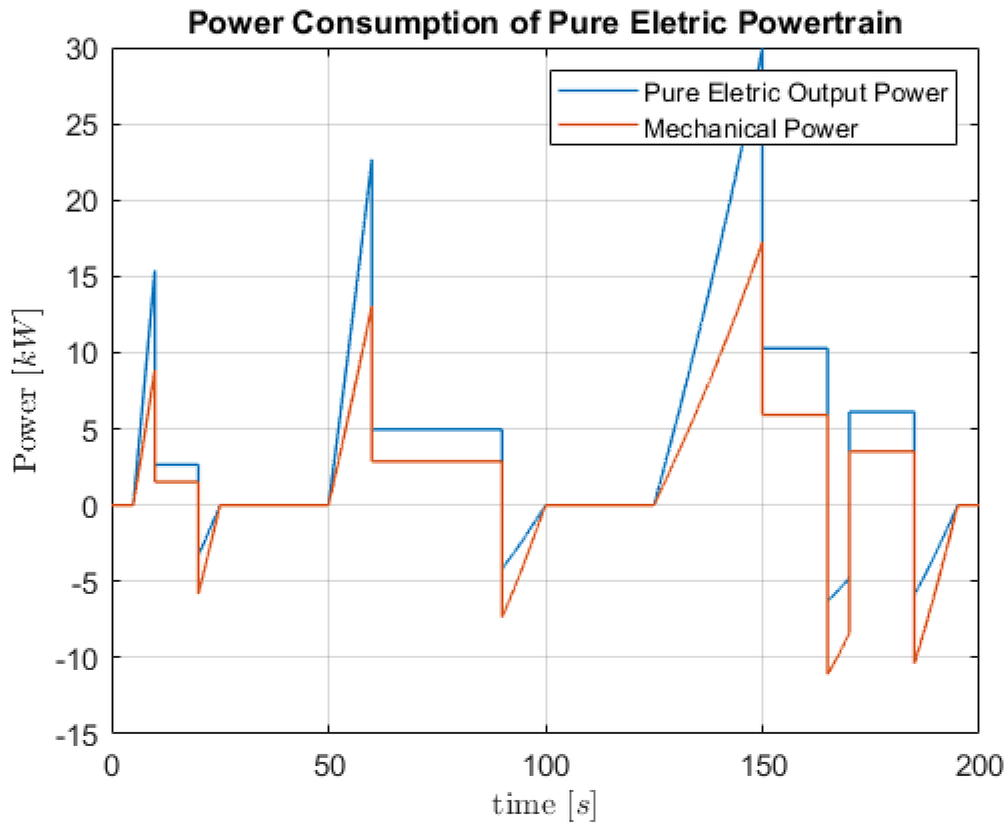
Power Consumption: Pure Eletric in Basic Driving Cycle

Now, in order to calculate the power consumption carried by the pure eletric power train. It will work in the follwing manner:

- When the car is accelerating, the efficiency of discharged is appliend in the power calculation;
- When the car is decelerating, the efficiency of the charge is apploed in the power calculation;

Thus, for the pure eletric powertrain the power is given by:

```
pure_eletric_power_basic_cycle = zeros(1,
 length(mechanical_power_basic_cycle));
pure_eletric_power_basic_cycle =
 AuxPowerCalculator(mechanical_power_basic_cycle, basic_velocity,
 pure_eletric_power_basic_cycle, efficiency_pure_eletric_charging,
 efficiency_pure_eletric_discharging,
 efficiency_pure_eletric_discharging);
AuxShowPowerResults(basic_time, pure_eletric_power_basic_cycle,
 mechanical_power_basic_cycle, 'Pure Eletric');
```



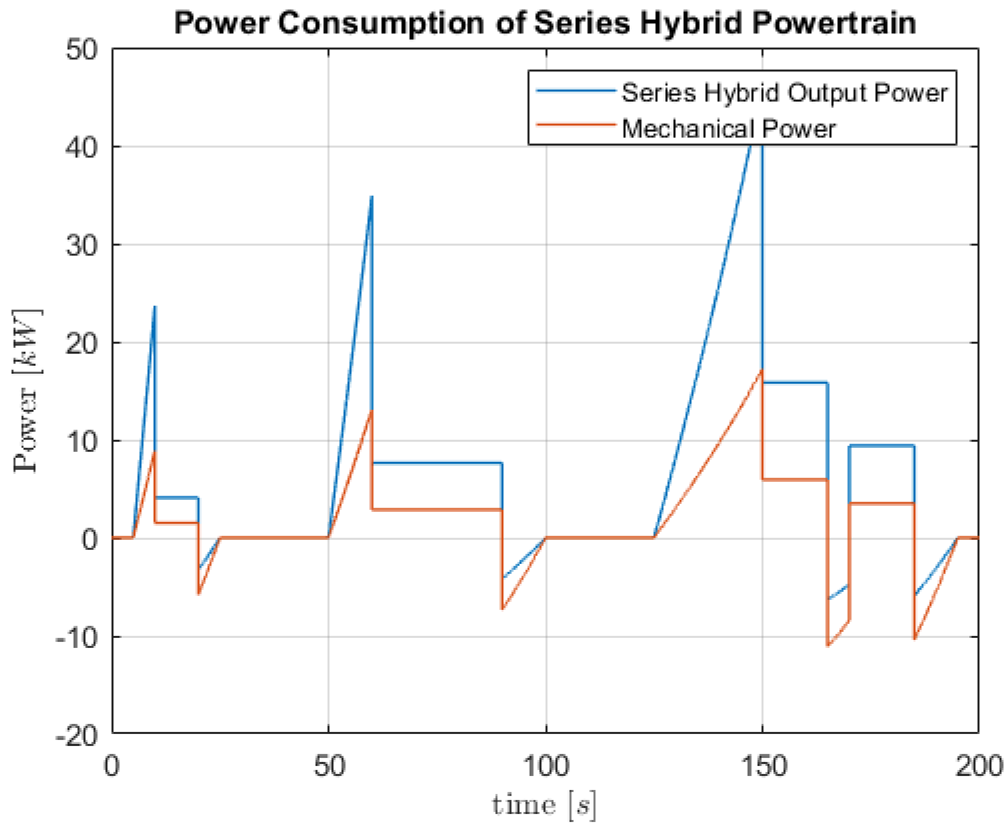
As one can see on the figure above, as expected the electrical power consuption is greater than the mechanical power consumption, and I doesn't regenerate all the power available in the regenerative-breaking periods.

Power Consumption: Series Hybrid in Basic Driving Cycle

This power train will behave in the following manner:

- When the velocity is less than $50km/h$, the car will run o eletric power only;
- When the car reaches the $50km/h$ mark, it will turn on the diesel generator;

```
series_hybrid_eletric_power_basic_cycle = zeros(1,
 length(basic_acceleration));
series_hybrid_eletric_power_basic_cycle =
 AuxPowerCalculator(mechanical_power_basic_cycle,
 basic_velocity,series_hybrid_eletric_power_basic_cycle,
 efficiency_hybrid_series_eletric_charging,
 efficiency_hybrid_series_discharging,
 efficiency_hybrid_series_discharging);
AuxShowPowerResults(basic_time,
 series_hybrid_eletric_power_basic_cycle,
 mechanical_power_basic_cycle, 'Series Hybrid');
```



As expected, the power consumption of the hybrid powertrain is greater than that of the pure eletric powertrain mesured earlier.

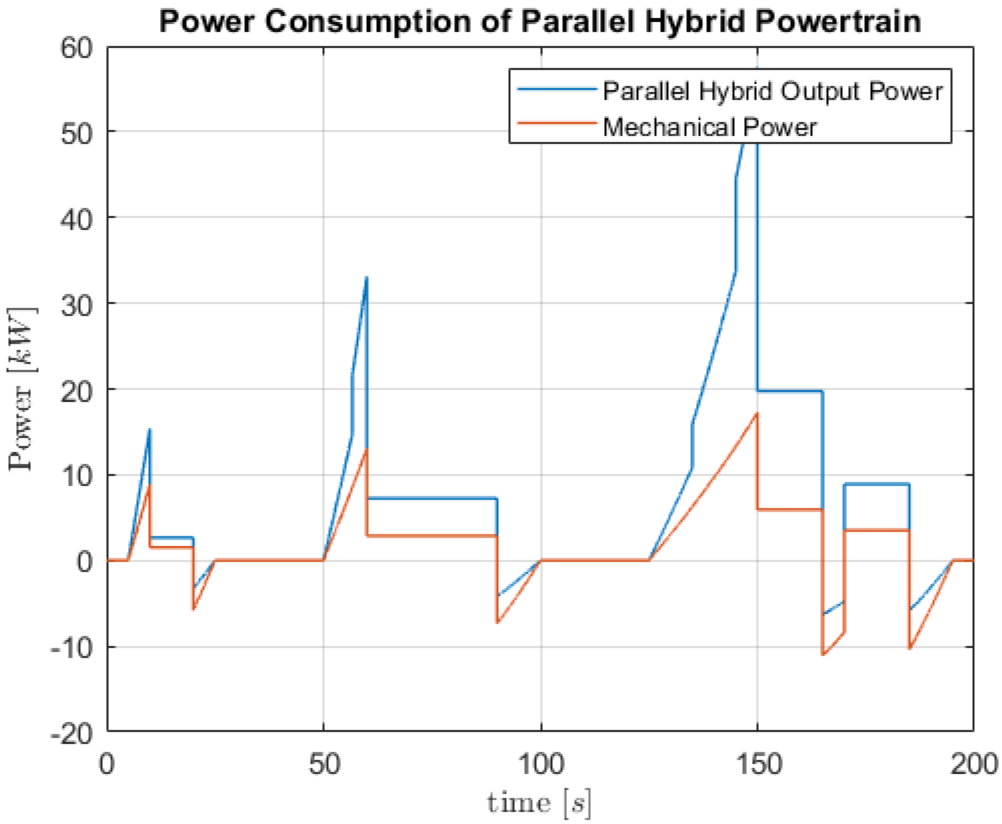
Power Consumption: Parallel Hybrid in Basic Driving Cycle

This power train will behave in the following manner:

- When the velocity is less than $20km/h$, the car will run o eletric power only;
- When the car reaches the $20km/h$ mark, it will demand half the energy from the bateries and half the energy from the combustion engine;
- Finally, the with velocities over 40 km/h, the car will run on combustion power only;

```
parallel_hybrid_eletric_power_basic_cycle = zeros(1,
 length(basic_acceleration));
parallel_hybrid_eletric_power_basic_cycle =
 AuxPowerCalculator(mechanical_power_basic_cycle,
 basic_velocity, parallel_hybrid_eletric_power_basic_cycle,
 efficiency_hybrid_parallel_eletric_charging,
 efficiency_hybrid_parallel_eletric_discharging ,
 efficiency_hybrid_parallel_combustion_discharging);
```

```
AuxShowPowerResults(basic_time,
 parallel_hybrid_eletric_power_basic_cycle,
 mechanical_power_basic_cycle, 'Parallel Hybrid');
```

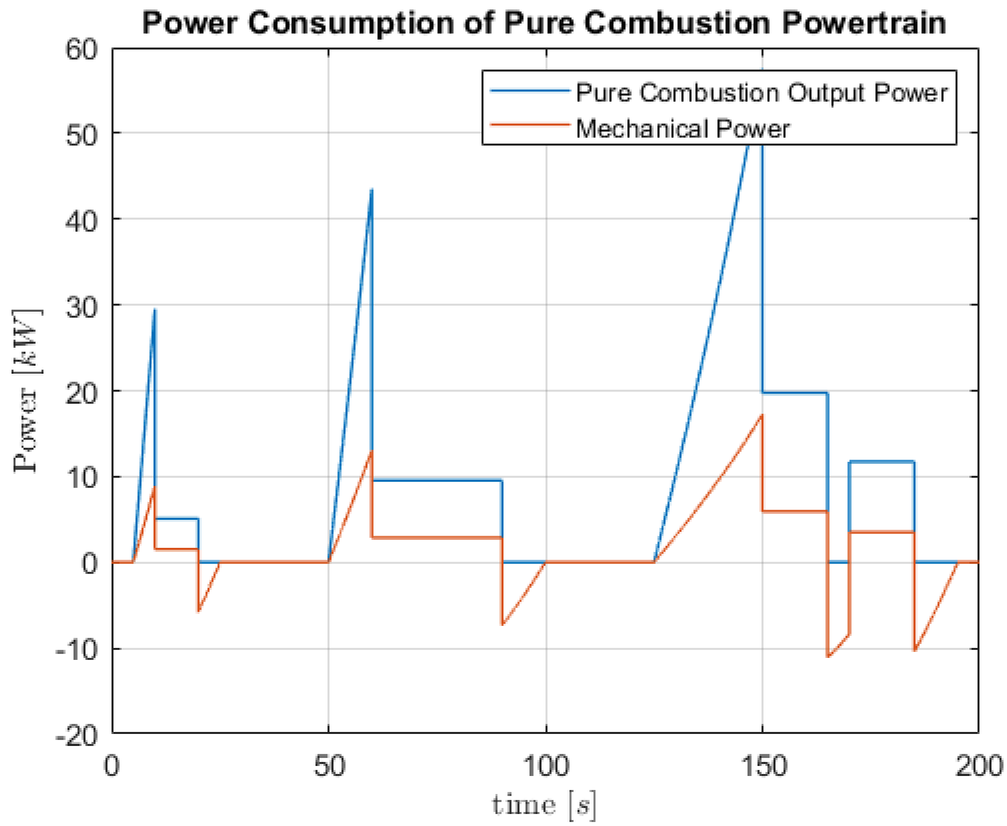


As expected, for velocities under 20 km/h, the parallel powertrain has the same consumption as the pure eletric powertrain, however, when the velocity reaches 20 km/h the performace decreases due to the combustion engine, and it decreases even more when the car reaches the velocities of 40 km/h.

Power Consumption: Pure Combustion in Basic Driving Cycle

The power combustion power will have allways the same efficiency when it is accelerating, and during breaking it will not spend or restore any energy.

```
pure_combustion_power_basic_cycle = zeros(1,
 length(mechanical_power_basic_cycle));
pure_combustion_power_basic_cycle =
 AuxPowerCalculator(mechanical_power_basic_cycle,
 basic_velocity, pure_combustion_power_basic_cycle,
 0, efficiency_pure_combustion_discharging ,
 efficiency_pure_combustion_discharging);
AuxShowPowerResults(basic_time, pure_combustion_power_basic_cycle,
 mechanical_power_basic_cycle, 'Pure Combustion');
```

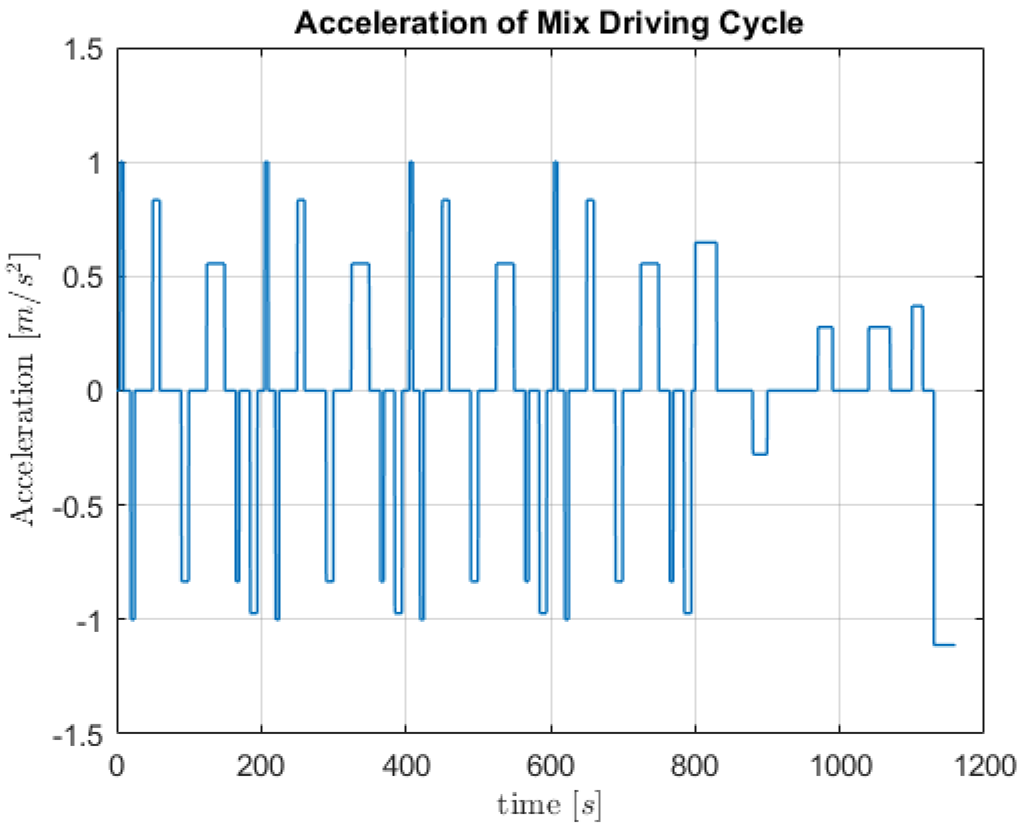


As expected when the mechanical power is zero or negative, the combustion power will be zero.

Power consumption: Mixed Driving Cycle

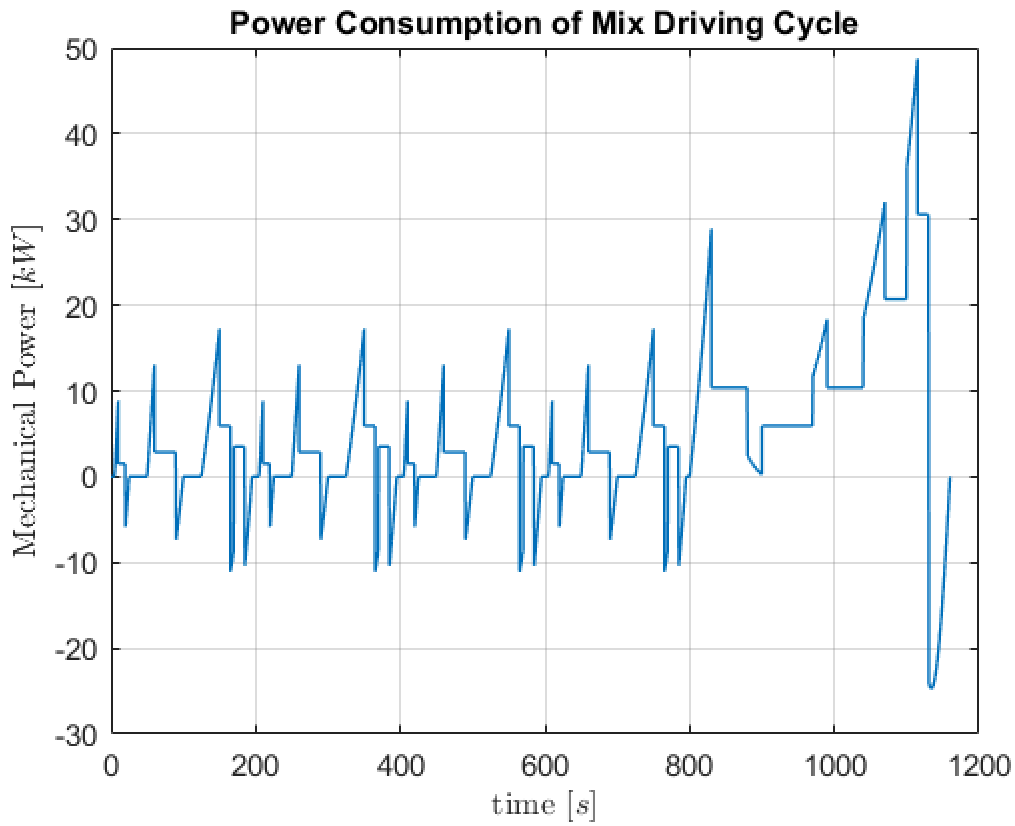
Similar to what was done for the basic driving cycle, the acceleration and the mechanical power wil be computed, and then through the AuxPowerCalculator() function, the power consumption of each power train will be studied.

```
mix_velocity = mix_velocity/3.6;
time_step = mix_time(4) - mix_time(3);
mix_acceleration = diff(mix_velocity)/time_step;
% It is necessary to pop the last value of the time and velocity
 arrays due
% to the previous derivative:
mix_time(end) = [];
mix_velocity(end) = [];
figure();
plot(mix_time, mix_acceleration, 'LineWidth', 1);
set( gca, 'FontSize', 11);
title('Acceleration of Mix Driving Cycle');
xlabel('time $[s]$','Interpreter', 'latex');
ylabel('Acceleration [$m/s^2$]','Interpreter', 'latex');
grid on;
```



The forces involved in the system remain the same, thus, the mechanical power can be computated:

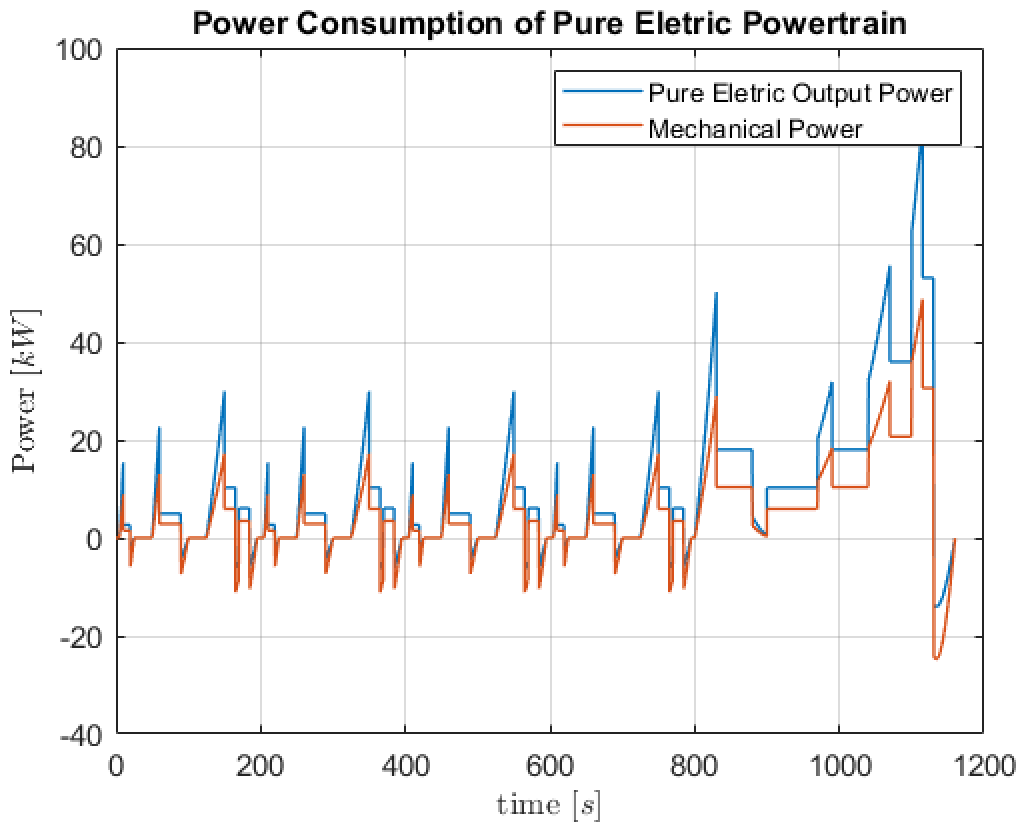
```
force_motor = mass_factor * mass * mix_acceleration;
force_drag = 0.5 * air_density * drag_coefficient * surface_area *
 (mix_velocity + wind_speed).^2;
force_friction = rolling_resistance_coefficient * mass * gravity;
force_traction = force_motor + force_drag +  force_friction;
mechanical_power_mix_cycle = force_traction.*mix_velocity;
figure();
plot(mix_time, mechanical_power_mix_cycle/1000, 'LineWidth', 1);
set( gca, 'FontSize', 11);
title('Power Consumption of Mix Driving Cycle');
xlabel('time $[s]$','Interpreter', 'latex');
ylabel('Mechanical Power [$kW$]','Interpreter', 'latex');
grid on;
```



The powertrains will mantain the same efficiencies as before, during the urban part of the cycle, but new conclusion will be drawn once the car reaches the extra-urban part of the cycle.

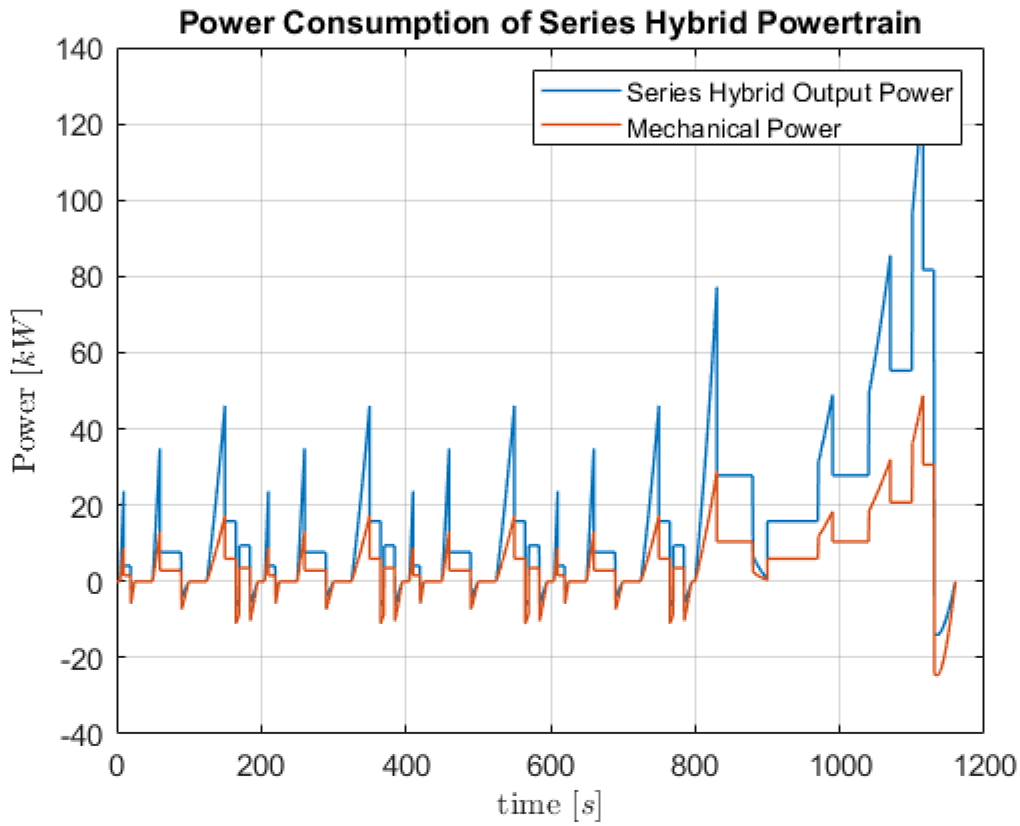
Power Consumption: Pure Eletric in Mix Driving Cycle

```
pure_eletric_power_mix_cycle = zeros(1,
 length(mechanical_power_mix_cycle));
pure_eletric_power_mix_cycle =
 AuxPowerCalculator(mechanical_power_mix_cycle, mix_velocity,
 pure_eletric_power_mix_cycle, efficiency_pure_eletric_charging,
 efficiency_pure_eletric_discharging,
 efficiency_pure_eletric_discharging);
AuxShowPowerResults(mix_time, pure_eletric_power_mix_cycle,
 mechanical_power_mix_cycle, 'Pure Eletric');
```



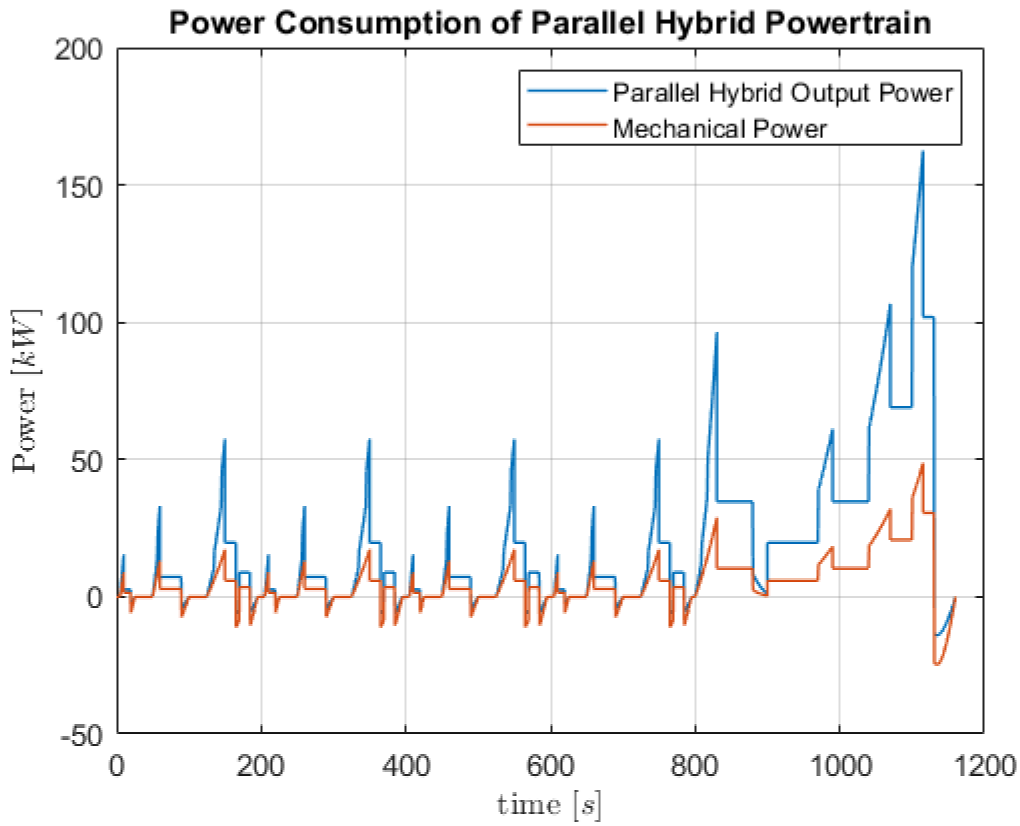
Power Consumption: Series Hybrid in Mix Driving Cycle

```
series_hybrid_eletric_power_mix_cycle = zeros(1,
 length(mix_acceleration));
series_hybrid_eletric_power_mix_cycle =
 AuxPowerCalculator(mechanical_power_mix_cycle,
 mix_velocity,series_hybrid_eletric_power_mix_cycle,
 efficiency_hybrid_series_eletric_charging,
 efficiency_hybrid_series_discharging,
 efficiency_hybrid_series_discharging);
AuxShowPowerResults(mix_time, series_hybrid_eletric_power_mix_cycle,
 mechanical_power_mix_cycle, 'Series Hybrid');
```



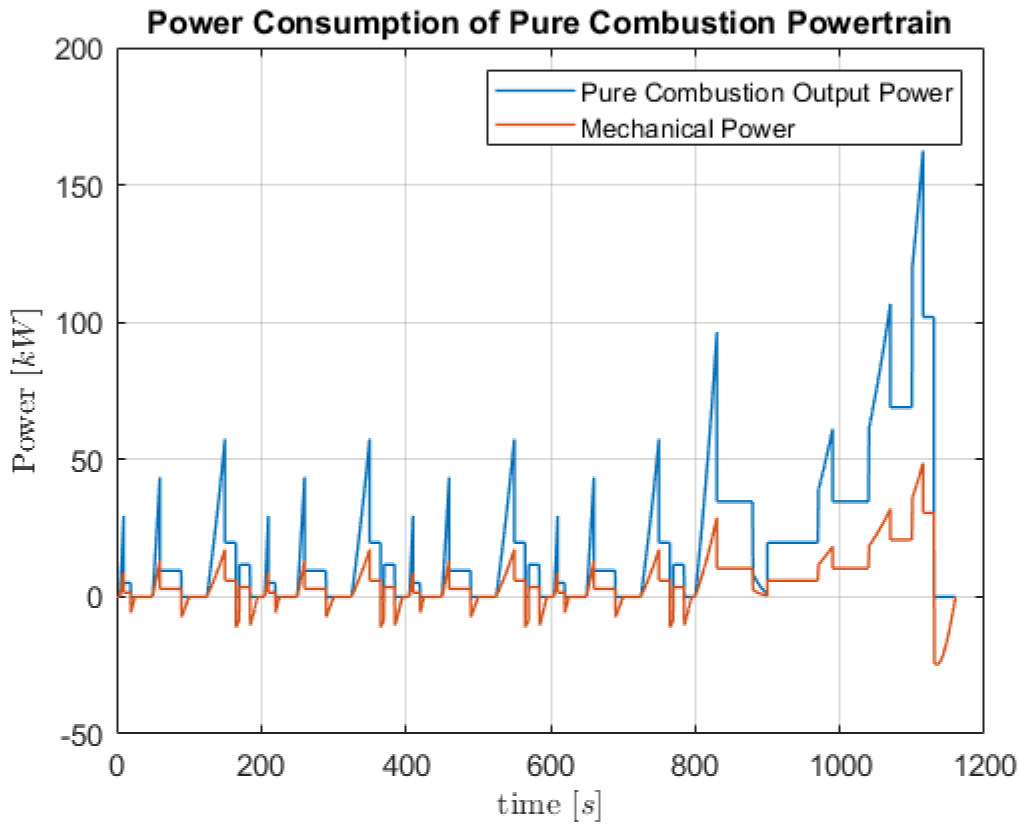
Power Consumption: Parallel Hybrid in Mix Driving Cycle

```
parallel_hybrid_eletric_power_mix_cycle = zeros(1,
 length(mix_acceleration));
parallel_hybrid_eletric_power_mix_cycle =
 AuxPowerCalculator(mechanical_power_mix_cycle,
 mix_velocity, parallel_hybrid_eletric_power_mix_cycle,
 efficiency_hybrid_parallel_eletric_charging,
 efficiency_hybrid_parallel_eletric_discharging ,
 efficiency_hybrid_parallel_combustion_discharging);
AuxShowPowerResults(mix_time, parallel_hybrid_eletric_power_mix_cycle,
 mechanical_power_mix_cycle, 'Parallel Hybrid');
```



Power Consumption: Pure Combustion in Mix Driving Cycle

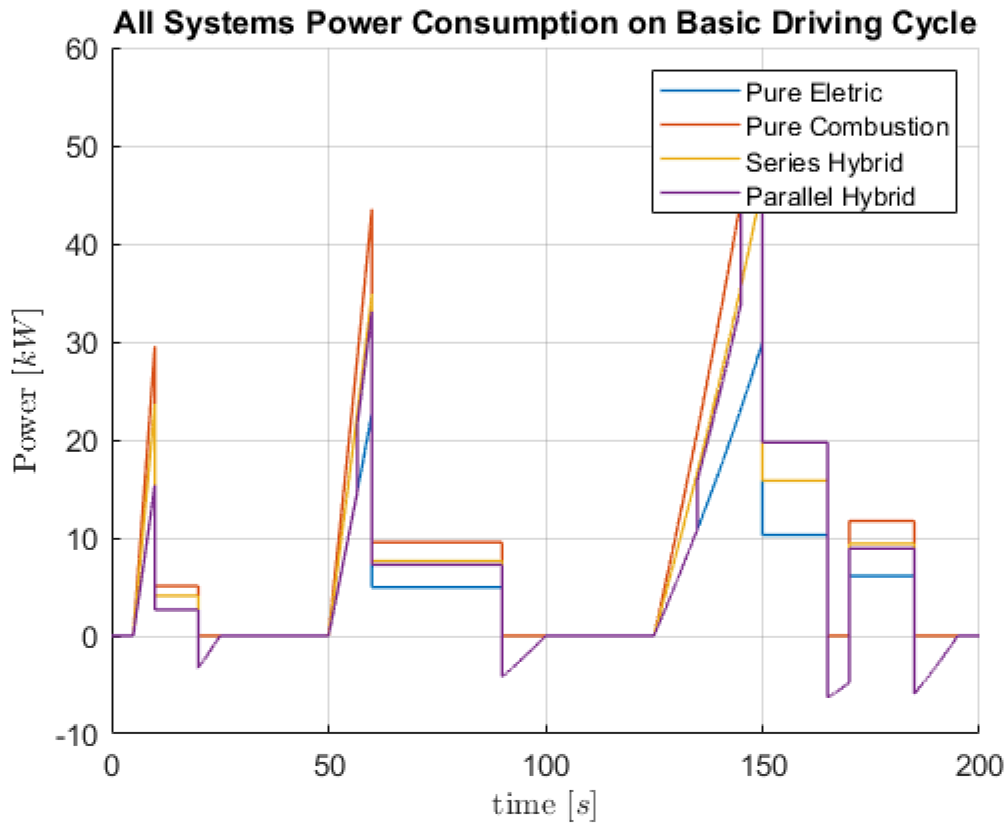
```
pure_combustion_power_mix_cycle = zeros(1, length(mix_acceleration));
pure_combustion_power_mix_cycle =
 AuxPowerCalculator(mechanical_power_mix_cycle,
 mix_velocity, pure_combustion_power_mix_cycle,
 0, efficiency_pure_combustion_discharging,
 efficiency_pure_combustion_discharging);

AuxShowPowerResults(mix_time, pure_combustion_power_mix_cycle,
 mechanical_power_mix_cycle, 'Pure Combustion');
```



Power Consumption: Comparison

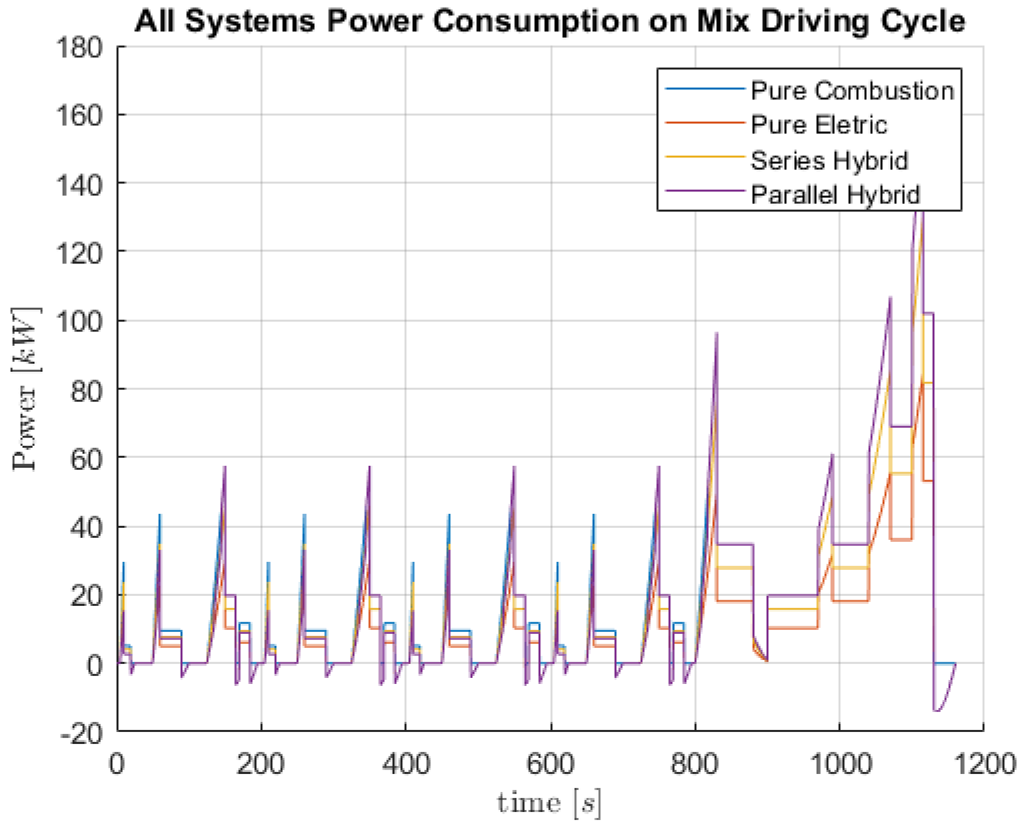
In order to better visualize the comparison of all systems, the following plot shows all power consumptions side to side:

```
figure()
hold all
plot(basic_time, pure_eletric_power_basic_cycle/1000, 'LineWidth', 1);
plot( basic_time, pure_combustion_power_basic_cycle/1000, 'LineWidth',
 1);
plot( basic_time,
 series_hybrid_eletric_power_basic_cycle/1000, 'LineWidth', 1);
plot( basic_time,
 parallel_hybrid_eletric_power_basic_cycle/1000, 'LineWidth', 1);
set( gca, 'FontSize', 11);
title('All Systems Power Consumption on Basic Driving Cycle');
xlabel('time $[s]$','Interpreter', 'latex');
ylabel('Power [$kW$]','Interpreter', 'latex');
legend('Pure Eletric', 'Pure Combustion', 'Series Hybrid', 'Parallel
 Hybrid');
grid on;
```



One can see that, for the basic driving cycle, the combustion powertrain performs worse when compared to the eletric and hybrid powertrains, due to the intrinsic low efficiency of the diesel motor. For speed under 20 km/h, the eletric and the paralel hybrid perform the same way, given that in the speed range from 0 to 20 km/h they all fuction with a pure eletric powertrain. One can see that the one the velocity reaches the 20 km/h mark, the combustion engine starts providing half the energy, therefore increasing the power consumption. Finally one the speed reaches 40 km/h the parallel hybrid work on pure combustion engine, presenting the same power consumption as a pure combustion car. The series hybrid powertrain performs allways in between the pure eletric and the pure combustion car. In comparison to the parallel hybrid, the series performs better for low speeds and worse for higher speeds, that is due to the combustion power in the eletric being more active with the increasing of the velocity.

```
figure()
hold all
plot( mix_time, pure_combustion_power_mix_cycle/1000);
plot(mix_time, pure_eletric_power_mix_cycle/1000);
plot( mix_time, series_hybrid_eletric_power_mix_cycle/1000);
plot( mix_time, parallel_hybrid_eletric_power_mix_cycle/1000);
set( gca, 'FontSize', 11);
title('All Systems Power Consumption on Mix Driving Cycle');
xlabel('time $[s]$','Interpreter', 'latex');
ylabel('Power [$kW$]','Interpreter', 'latex');
legend('Pure Combustion','Pure Eletric', 'Series Hybrid', 'Parallel
 Hybrid');
grid on;
```



Finally, in the mixed driving cycle, one can observe that for the urban part of the cycle, the same conclusions drawn as for basic driving cycle are valid here. For the extra-urban part of the cycle, one can notice that:

- As allways, the pure eletric car has the best performace of all the power trains;
- Next comes the series hybrid, that has it's efficiency diminished due presence of the disel generator, that for these speeds power the battery;
- Finally, the paralel hybrid and the pure combustion powertrains perfom the worst, due to the low efficiency of the diesel motor;

Energy Recovery

The powertrains that have an eletric motor/generator, can harnest the power of the breaking to restore the energy in the batteries. In this section, the quantity of this saved energy will be studied for each powertrains in each driving cycle.

Energy Recovery: Theorethical approach

The energy recovered will correspond to the negative part of the graphics of the powerconsumption calculated above. It is to notice that the efficiency of charging is not the same as discharging, due to, bettwen other factor related to the components, losses by heat. As it is expected, the pure combustion powertrain does not have negative power consumption, because it does not have the components to restore energy. So in order to compute the total recovered energy, one must simpli integrate the negative part of the power consumption graphs.

Energy Recovery: Computations function

The function used to compute the power recovery is the following:

```
function [energy_recovered, energy_spent] =
 AuxEnergyRecoveryCalculator(time, power_consumption)
    % Filter only the negative values of the plot and pass them to
 positive
    % value
    power_recovered = power_consumption;
    power_spent = power_consumption;
    % Energy recovered
    for i=1:length(power_consumption)
        if(power_recovered(i) > 0)
            power_recovered(i) = 0;
        else
            power_recovered(i) = -power_recovered(i);
        end
    end
    energy_recovered  = trapz(time, power_recovered);
    % Energy spent
    for i=1:length(power_consumption)
        if(power_spent(i) < 0)
            power_spent(i) = 0;
        end
    end
    energy_spent  = trapz(time, power_spent);
end
```

Energy Recovery: Pure Eletric Powertrain Basic Driving Cycle

```
[energy_recovered_basic_cycle, energy_spent_basic_cycle] =
 AuxEnergyCalculator(basic_time, pure_eletric_power_basic_cycle);
```

For the basic driving cycle, the energy spent, in kWh equal to:

```
display(energy_spent_basic_cycle/(1000*3600));
```

```
    0.2570
```

And the energy recovered, in kWh is equal to:

```
display(energy_recovered_basic_cycle/(1000*3600));
```

```
    0.0245
```

One can conclude that the percentage of the energy recovered by this powertrain is:

```
display((energy_recovered_basic_cycle/energy_spent_basic_cycle)*100);
```

```
    9.5238
```

Energy Recovery: Series Hybrid Powertrain Basic Driving Cycle

```
[energy_recovered_basic_cycle, energy_spent_basic_cycle] =
 AuxEnergyCalculator(basic_time,
 series_hybrid_eletric_power_basic_cycle);
```

For the basic driving cycle, the energy spent, in kWh equal to:

```
display(energy_spent_basic_cycle/(1000*3600));
```

    0.3955

And the energy recovered, in kWh is equal to:

```
display(energy_recovered_basic_cycle/(1000*3600));
```

    0.0245

One can conclude that the percentage of the energy recovered by this powertrain is:

```
display((energy_recovered_basic_cycle/energy_spent_basic_cycle)*100);
```

    6.1904

Energy Recovery: Parallel Hybrid Powertrain Basic Driving Cycle

```
[energy_recovered_basic_cycle, energy_spent_basic_cycle] =
 AuxEnergyCalculator(basic_time,
 parallel_hybrid_eletric_power_basic_cycle);
```

For the basic driving cycle, the energy spent, in kWh equal to:

```
display(energy_spent_basic_cycle/(1000*3600));
```

    0.3905

And the energy recovered, in kWh is equal to:

```
display(energy_recovered_basic_cycle/(1000*3600));
```

    0.0245

One can conclude that the percentage of the energy recovered by this powertrain is:

```
display((energy_recovered_basic_cycle/energy_spent_basic_cycle)*100);
```

```
6.2682
```

Energy Recovered: Conclusion Basic Cyle

For this driving cycle, pure eletric powertrain perfomed better, with ~9.5% of energy recovery, followed by the series hybrid which recovered ~6.2%, followed by the parallel hybrid which recovered ~6.3% and lastly the pure combustion which can't recover any energy. Even though the hybrids and the eletric recover energy the same way, the reason that they show a different value in the percentage of energy recovered is because they spend a different amounts.

Energy Recovery: Pure Eletric Powertrain Mix Driving Cycle

```
[energy_recovered_mix_cycle, energy_spent_mix_cycle] =
 AuxEnergyCalculator(mix_time, pure_eletric_power_mix_cycle);
```

For the mix driving cycle, the energy spent, in kWh equal to:

```
display(energy_spent_mix_cycle/(1000*3600));
```

```
3.2611
```

And the energy recovered, in kWh is equal to:

```
display(energy_recovered_mix_cycle/(1000*3600));
```

```
0.1774
```

One can conclude that the percentage of the energy recovered by this powertrain is:

```
display((energy_recovered_mix_cycle/energy_spent_mix_cycle)*100);
```

```
5.4396
```

Energy Recovery: Series Hybrid Powertrain Mix Driving Cycle

```
[energy_recovered_mix_cycle, energy_spent_mix_cycle] =
 AuxEnergyCalculator(mix_time, series_hybrid_eletric_power_mix_cycle);
```

For the mix driving cycle, the energy spent, in kWh equal to:

```
display(energy_spent_mix_cycle/(1000*3600));
```

```
5.0171
```

And the energy recovered, in kWh is equal to:

```
display(energy_recovered_mix_cycle/(1000*3600));
```

0.1774

One can conclude that the percentage of the energy recovered by this powertrain is:

```
display((energy_recovered_mix_cycle/energy_spent_mix_cycle)*100);
```

3.5358

Energy Recovery: Parallel Hybrid Powertrain Mix Driving Cycle

```
[energy_recovered_mix_cycle, energy_spent_mix_cycle] =
 AuxEnergyCalculator(mix_time,
 parallel_hybrid_eletric_power_mix_cycle);
```

For the mix driving cycle, the energy spent, in kWh equal to:

```
display(energy_spent_mix_cycle/(1000*3600));
```

5.8156

And the energy recovered, in kWh is equal to:

```
display(energy_recovered_mix_cycle/(1000*3600));
```

0.1774

One can conclude that the percentage of the energy recovered by this powertrain is:

```
display((energy_recovered_mix_cycle/energy_spent_mix_cycle)*100);
```

3.0503

Energy Recovered: Conclusion Mix Cyle

As expected, the powertrains that spend less energy have a greater percentage of the energy recovered. The pure eletric vehicle recovers ~5.4%, followed by the serie hybrid which recovers ~3.5%, followed by the parallel hybrid that recovers ~3.0% of the energy. Thus, I is noticible that for the extra-urban cycle, the energy recovery does not have such great reasult as the urban cycle. It is also to notice that in a real life cenario, not all breakings correspond to a regenerative break, because if it is needed do break faster, mechanical breaking is necessary.

Economic Comparison

Here it is usefull to compare the economical viability of each powertrain. The costs are compared in a spam of one year, in which the avarage car runs about 15000 km.

To calculate what is the distance convered by the car in the mix driving cycle, one must only integrate the velocity:

```
distance_mix_cycle = trapz(mix_time, mix_velocity);
display(distance_mix_cycle/1000);
```

```
   11.0500
```

So, the number of **complete** mix driving cycles per year is given by:

```
number_of_mix_cycles_per_year = 15000/(distance_mix_cycle/1000);
number_of_mix_cycles_per_year = floor(number_of_mix_cycles_per_year);
display(number_of_mix_cycles_per_year);
```

```
number_of_mix_cycles_per_year =

        1357
```

Having access to the power consumption for each powertrain, one can compute the cost in fuel per year:

The yearly cost of the pure eletric powertrain is given by:

```
total_cost_eletric = AuxFuelCalculator(mix_time, mix_velocity,
 pure_eletric_power_mix_cycle, number_of_mix_cycles_per_year, 'Pure
 Eletric');
display(total_cost_eletric);
```

```
total_cost_eletric =

  627.6865
```

The yearly cost of the hybrid-series powertrain is given by:

```
total_cost_series_hybrid = AuxFuelCalculator(mix_time,
 mix_velocity, series_hybrid_eletric_power_mix_cycle,
 number_of_mix_cycles_per_year, 'Series Hybrid');
display(total_cost_series_hybrid);
```

```
total_cost_series_hybrid =

  919.4401
```

The yearly cost of the pure combustion powertrain is given by:

```
total_parallel_hybrid = AuxFuelCalculator(mix_time,
 mix_velocity, parallel_hybrid_eletric_power_mix_cycle,
 number_of_mix_cycles_per_year, 'Parallel Hybrid');
display(total_parallel_hybrid);
```

```
total_parallel_hybrid =

   1.1493e+03
```

The yearly cost of the pure combustion powertrain is given by:

```
total_cost_combustion = AuxFuelCalculator(mix_time, mix_velocity,
 pure_combustion_power_mix_cycle, number_of_mix_cycles_per_year, 'Pure
 Combustion');
display(total_cost_combustion);
```

```
total_cost_combustion =

   1.1895e+03
```

Economic comparison: Conclusions

Thus, the conclusions are that the cost of fuel/charge for a year follow the powerconsumptions of the powertrains, having the pore combustion powertrain spending approximely twice as much as the pure eletric, and the parallel hybrid spendind more than the series hybrid. Given the fact that the great majority of the population drives pure combustion cars, it is interesting to note the time that would take for the extra money paid for the other powertrains to be worth it: The cost of the pure combustion car is 20k euros.

- The cost of the parallel hybrid is 25k, so, according to this simulation, the parallel hybrid spends minus 40 euros per year in fuel, so it would take 125 years for for it to be worth it. However, if the costumer have the majority of his driving time in a urban area (a Uber driver for instants), it will spend less money due to the better perfomance in this regime;
- The cost of the series hybrid is 30k, so, according to the same analysis, it would take 37 years for the saved money saved be equal to the value of the car, but once again, if the solo urban driving is practice the extra money would be paid off more quickly;
- Finally, the pure eletric powertrain costs 35k, and according to the same analysis, it would take 25 years for the money saved to be paid off, but once again, and even more so now, if a more urban driving profile is taken into practice, it would take less time to pay of the investment;

```
close all
```

Published with MATLAB® R2019b