



Electrical Drives and Electrical Vehicles

POTENTIAL OF ELECTRIC/HYBRID
PROPULSION SYSTEMS
TO REDUCE PETROLEUM USE AND
GREENHOUSE GAS EMISSIONS

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Powertrains Problem

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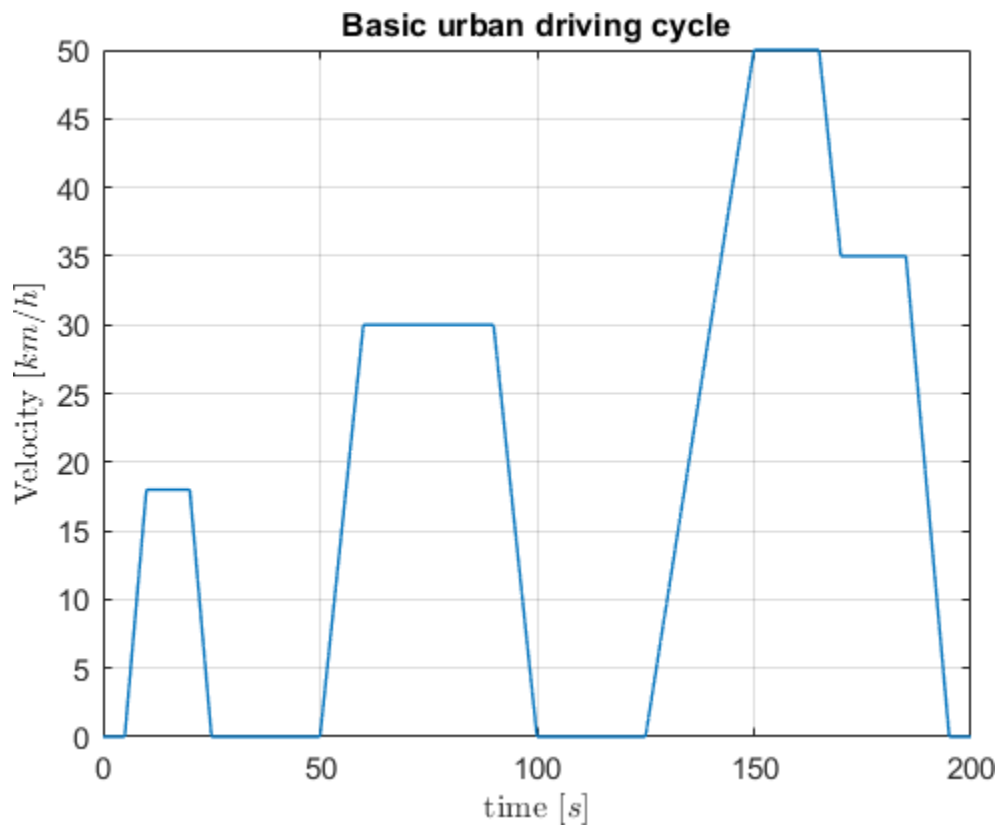
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Drawing the two driving cycles

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

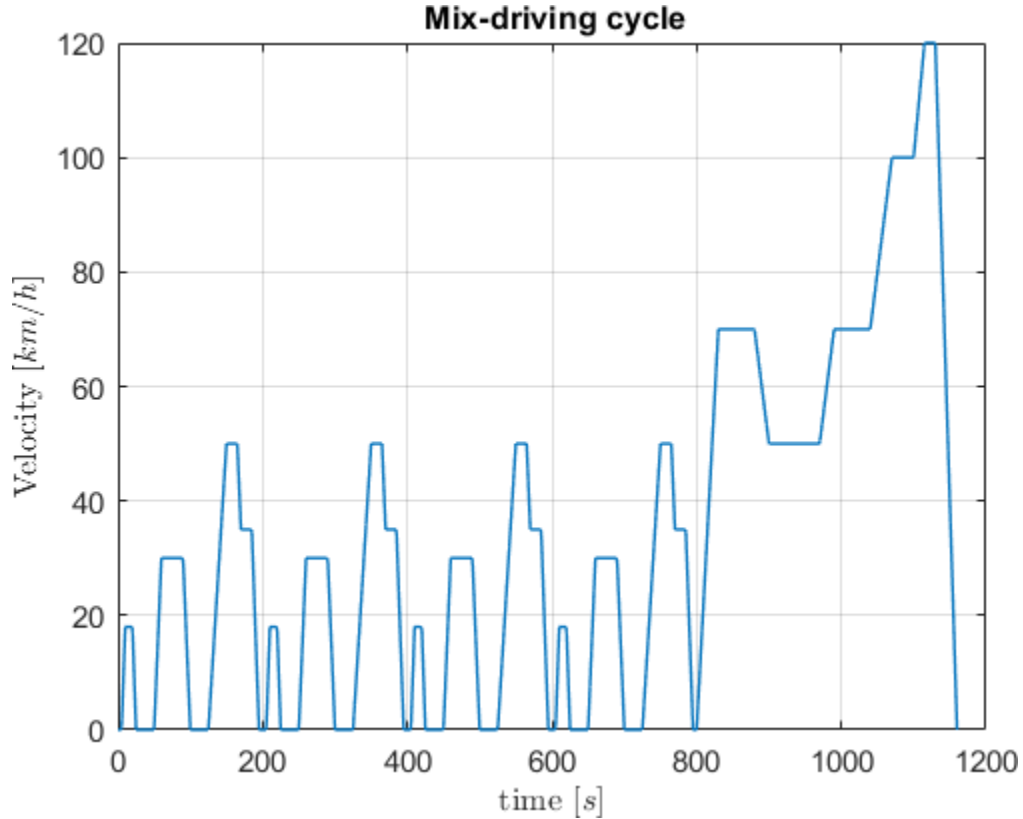
```
clear
close all
```

```
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 electric, pure combustion, series hybrid and parallel hybrid.

Assumptions: Pure Electric Powertrain

In this configuration the battery is in series with the electric motor/generator in series with the transmission.

There are two possible modes of functioning, the motor discharging the velocities while accelerating, and the opposite, generator charging the velocities decelerating.

Acceleration: During discharge the circuit has an efficiency different from 100%. The overall efficiency $\eta_{overall}$ is given by the product of the individual efficiency 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 velocities are made from lithium-ion, according to https://en.wikipedia.org/wiki/Lithium-ion_battery it is reasonable to assume that the discharging efficiency of the battery of around 80%;

- From https://en.wikipedia.org/wiki/Electric_car#Energy_efficiency it is reasonable to assume that the electric motor has an efficiency of 70%;
- From <https://www.nap.edu/read/21744/chapter/7> it is reasonable to assume that the efficiency 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_electric_discharging =
    efficiency_battery_discharge*efficiency_motor*efficiency_transmission;

```

Thus the electric power in acceleration is given by:

$$P_{electric} = \frac{P_{meccanic}}{\eta_{overall}}$$

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* → *generator* → *battery*], the efficiencies have different values.

- From it is reasonable to assume that the discharging efficiency of the battery of around 90%;
- Its is reasonable to assume that the generator has an efficiency of 80%;
- Similarly to the acceleration, 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_electric_charging =
    efficiency_battery_charge*efficiency_generator*efficiency_transmission;

```

Thus the electric power in deceleration is given by:

$$P_{electric} = P_{meccanic}\eta_{overall}$$

Assumptions: Series Hybrid Powertrain

In the configuration, there is a series connection between the diesel generator, the battery pack, the motor/generator, and the transmission, in which the generator powers the battery during acceleration, and the electric motor/generator charges the battery in deceleration.

So the efficiency of this power train can be:

- In electrical mode, the $\eta_{overall} = \eta_{overall-electric}$;
- 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:

$$\eta_{overall} = \eta_{overall-electric}\eta_{diesel-generator}$$

```
efficiency_diesel_generator = 0.65;
efficiency_hybrid_series_electric_charging =
    efficiency_pure_electric_charging;
efficiency_hybrid_series_discharging =
    efficiency_pure_electric_discharging*efficiency_diesel_generator;
```

Assumptions: Parallel Hybrid Powertrain

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

- The series between the engine and the transmission;
- 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 velocities up to 20 km/h, the powertrain functions in pure electric mode, for velocities greater than 40 km/h it works on pure combustion engine, and for velocities in between 20 and 40 km/h it demands half the power from the batteries and half from combustion. For breaking it is assumed that regenerative breaking always works.

With this, the efficiencies considered are:

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

```
efficiency_hybrid_parallel_electric_charging =
    efficiency_pure_electric_charging;
efficiency_hybrid_parallel_electric_discharging =
    efficiency_pure_electric_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;

$$F_T = f_m m a + F_{drag} + F_{friction}$$

Being:

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

$$F_{friction} = C_{rr} m g$$

$f_m \rightarrow$ 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 $f_m = 1.05$, $\rho = 1.225 \text{ kg/m}^3$, $v_w = 25 \text{ km/h}$ 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
    end
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 plotted 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
```

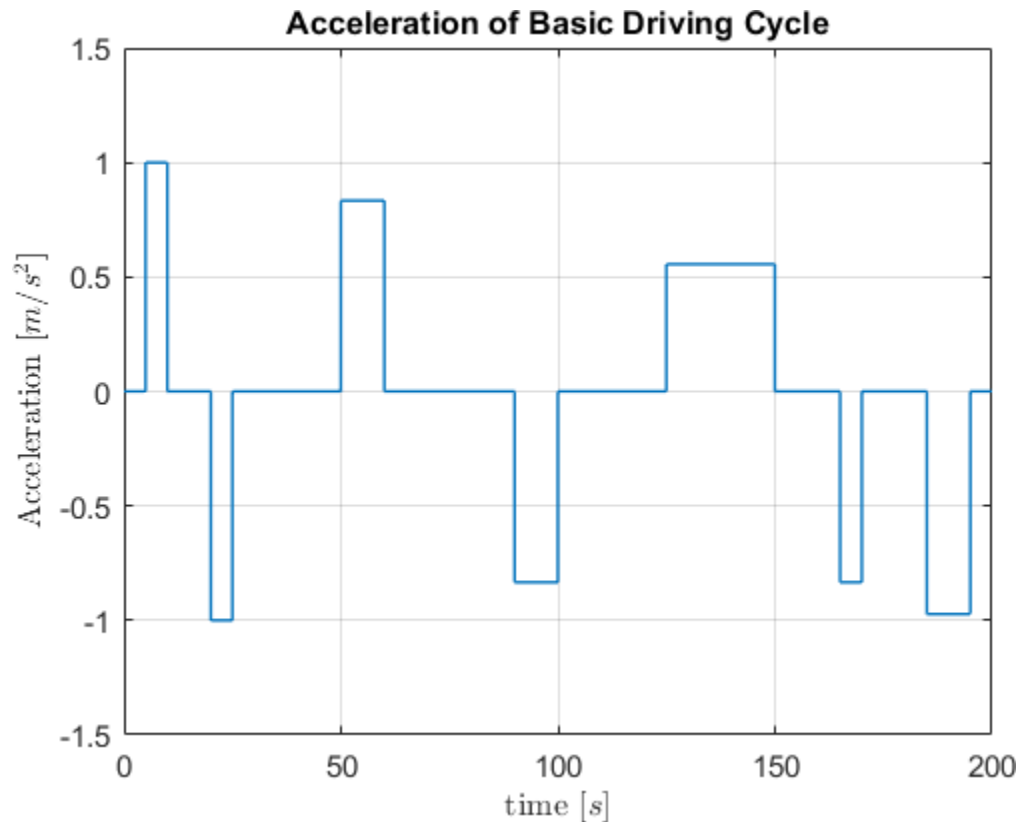
Power Consumption: Basic Driving Cycle

Given the theoretical and functional approach taken above, the power consumption can be computed.

First the acceleration vector is necessary in order to compute 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;
```

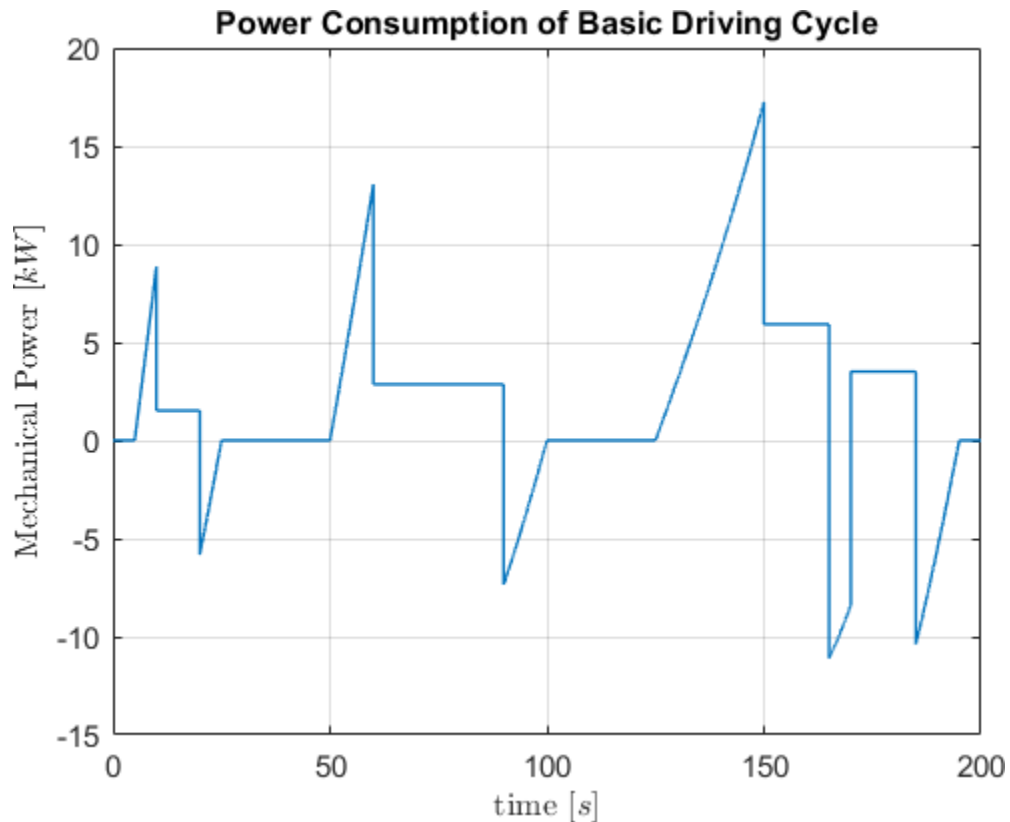



The mechanical power involved is computed by:

```

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 braking, this power is used by the regenerative braking (if in operation).

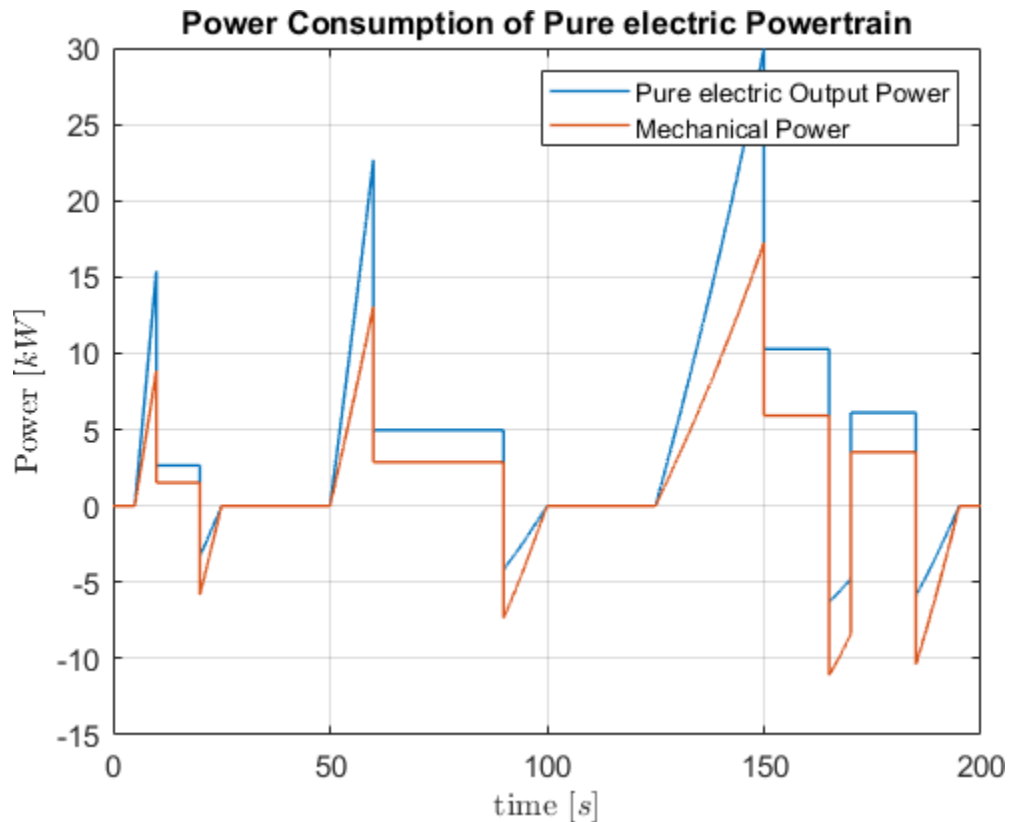
Power Consumption: Pure electric in Basic Driving Cycle

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

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

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

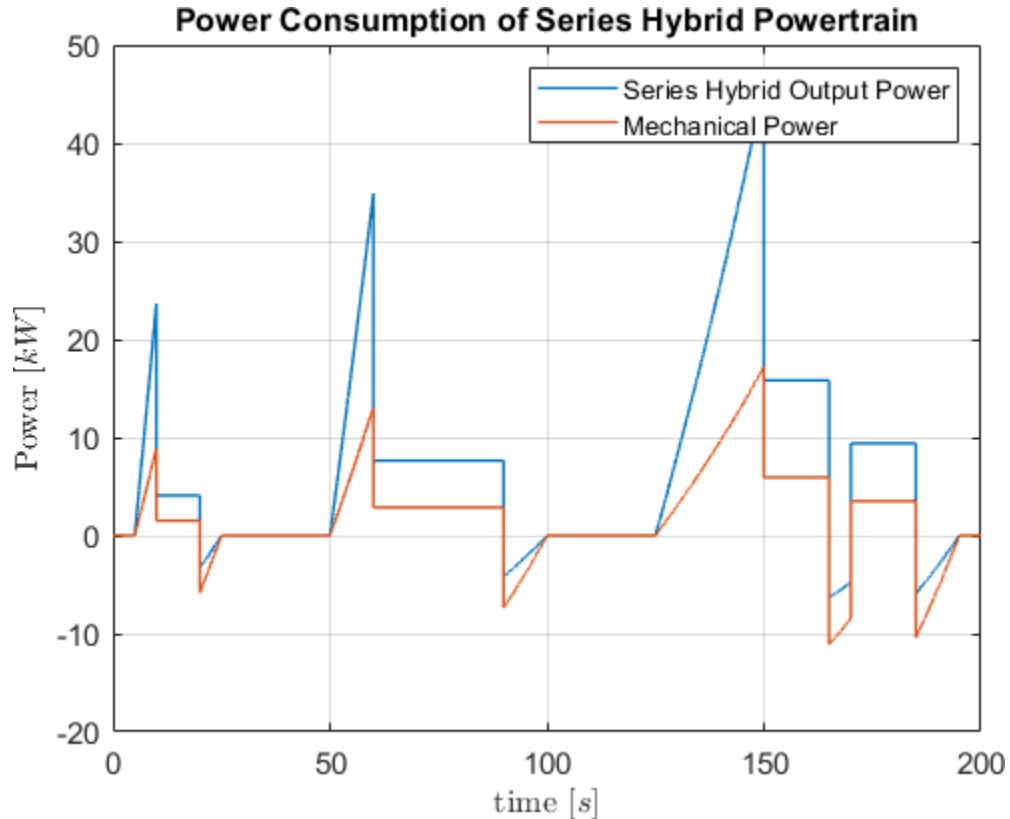
```
pure_electric_power_basic_cycle = zeros(1,
    length(mechanical_power_basic_cycle));
pure_electric_power_basic_cycle =
    AuxPowerCalculator(mechanical_power_basic_cycle, basic_velocity,
    pure_electric_power_basic_cycle, efficiency_pure_electric_charging,
    efficiency_pure_electric_discharging,
    efficiency_pure_electric_discharging);
AuxShowPowerResults(basic_time, pure_electric_power_basic_cycle,
    mechanical_power_basic_cycle, 'Pure electric');
```



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

Power Consumption: Series Hybrid in Basic Driving Cycle

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



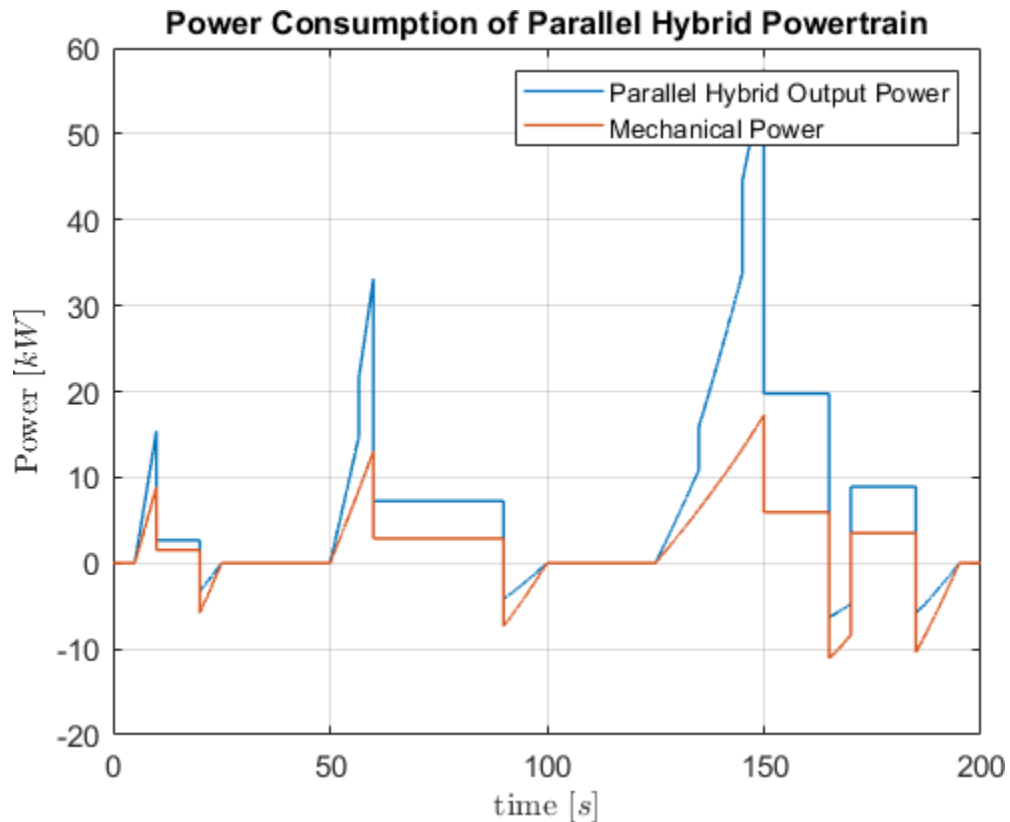
As expected, the power consumption of the series hybrid powertrain is greater than that of the pure electric powertrain measured earlier.

Power Consumption: Parallel Hybrid in Basic Driving Cycle

This power train will behave in the following manner:

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

```
parallel_hybrid_electric_power_basic_cycle = zeros(1,
    length(basic_acceleration));
parallel_hybrid_electric_power_basic_cycle =
    AuxPowerCalculator(mechanical_power_basic_cycle,
        basic_velocity, parallel_hybrid_electric_power_basic_cycle,
        efficiency_hybrid_parallel_electric_charging,
        efficiency_hybrid_parallel_electric_discharging,
        efficiency_hybrid_parallel_combustion_discharging);
AuxShowPowerResults(basic_time,
    parallel_hybrid_electric_power_basic_cycle,
    mechanical_power_basic_cycle, 'Parallel Hybrid');
```

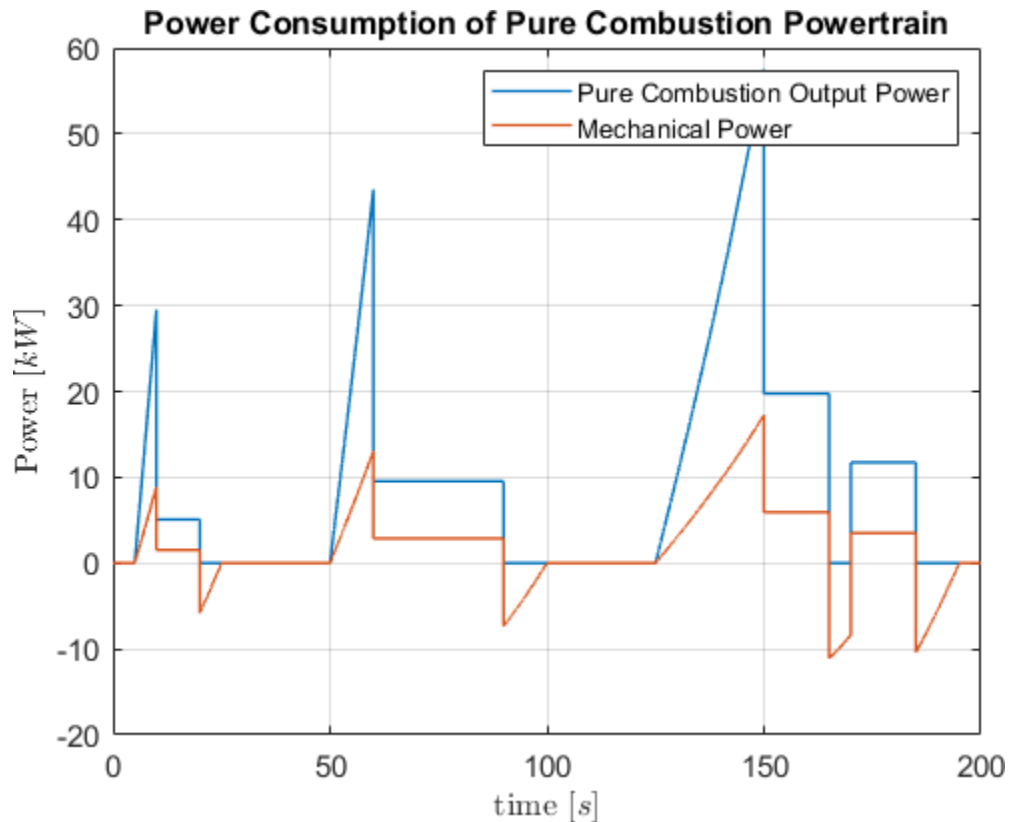


As expected, for velocities under 20 km/h, the parallel powertrain has the same consumption as the pure electric powertrain, however, when the velocity reaches 20 km/h the performance decreases due to the combustion engine, and it decreases even more when the car reaches the velocities of 40 km/h.

Power Consumption: Pure Combustion in Basic Driving Cycle

The power combustion power will have always 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.

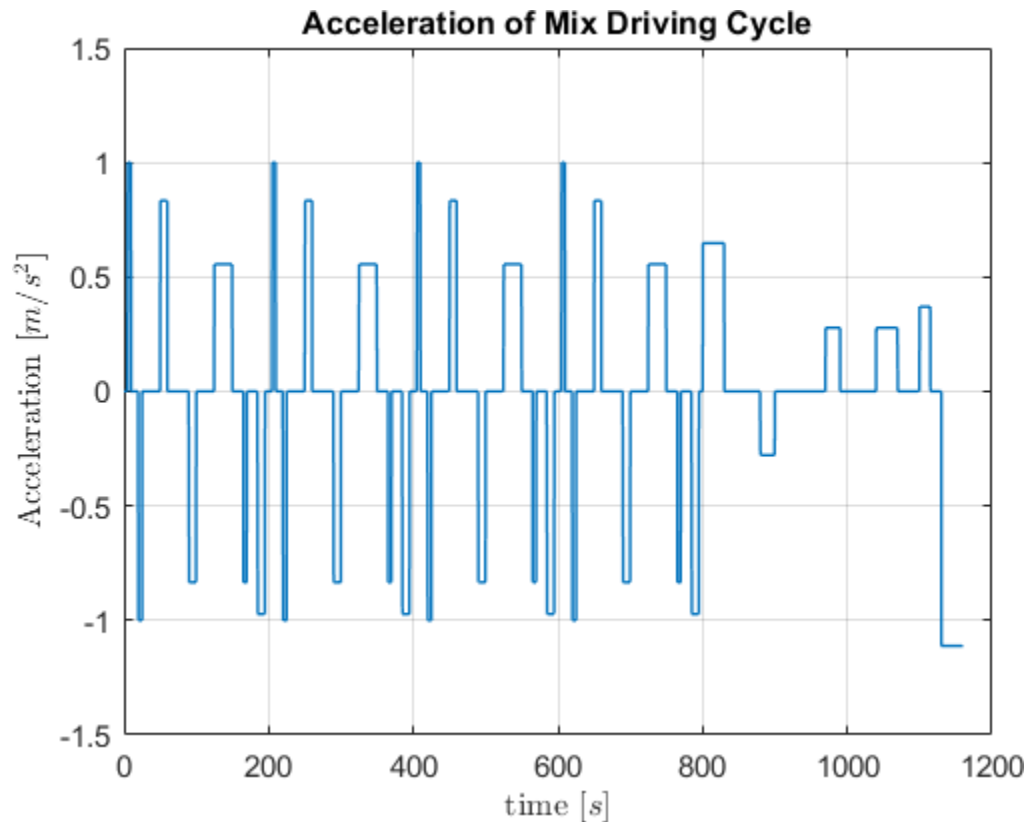
Power consumption: Mixed Driving Cycle

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

```

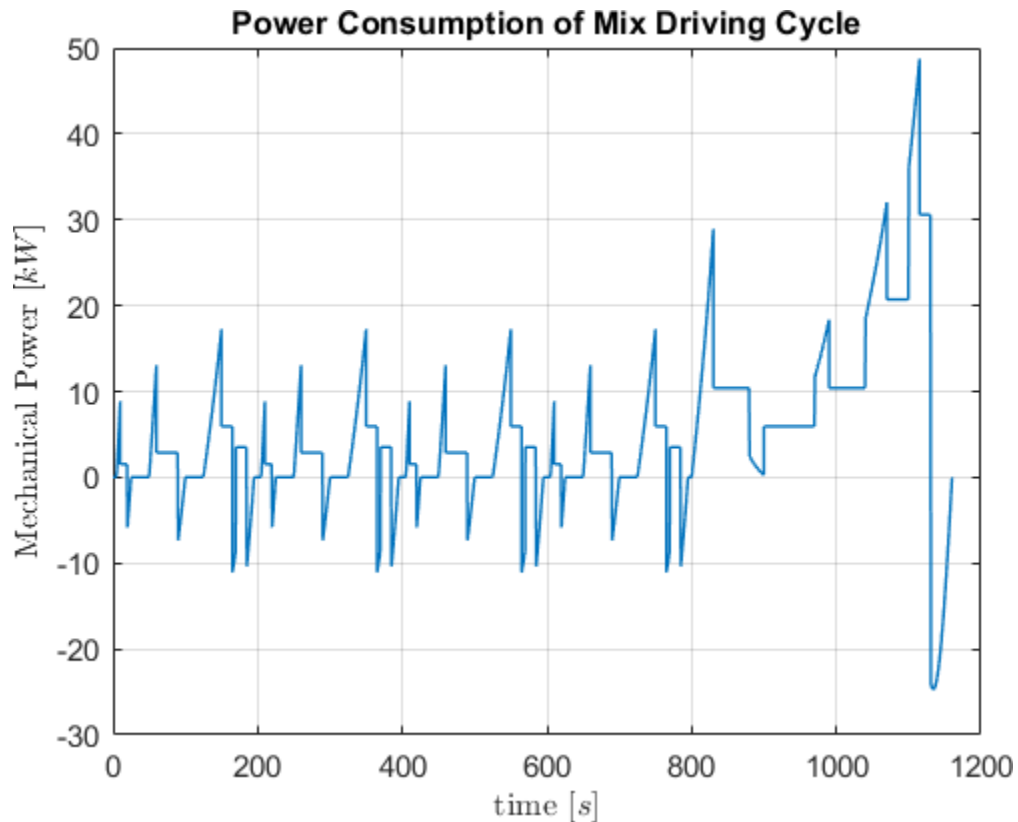
mix_velocity = mix_velocity/3.6;
time_step = mix_time(4) - mix_time(3);
mix_acceleration = diff(mix_velocity)/time_step;
% It is necessary to pop the last value of the time and velocity
% arrays due
% to the previous derivative:
mix_time(end) = [];
mix_velocity(end) = [];
figure();
plot(mix_time, mix_acceleration, '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 computed:

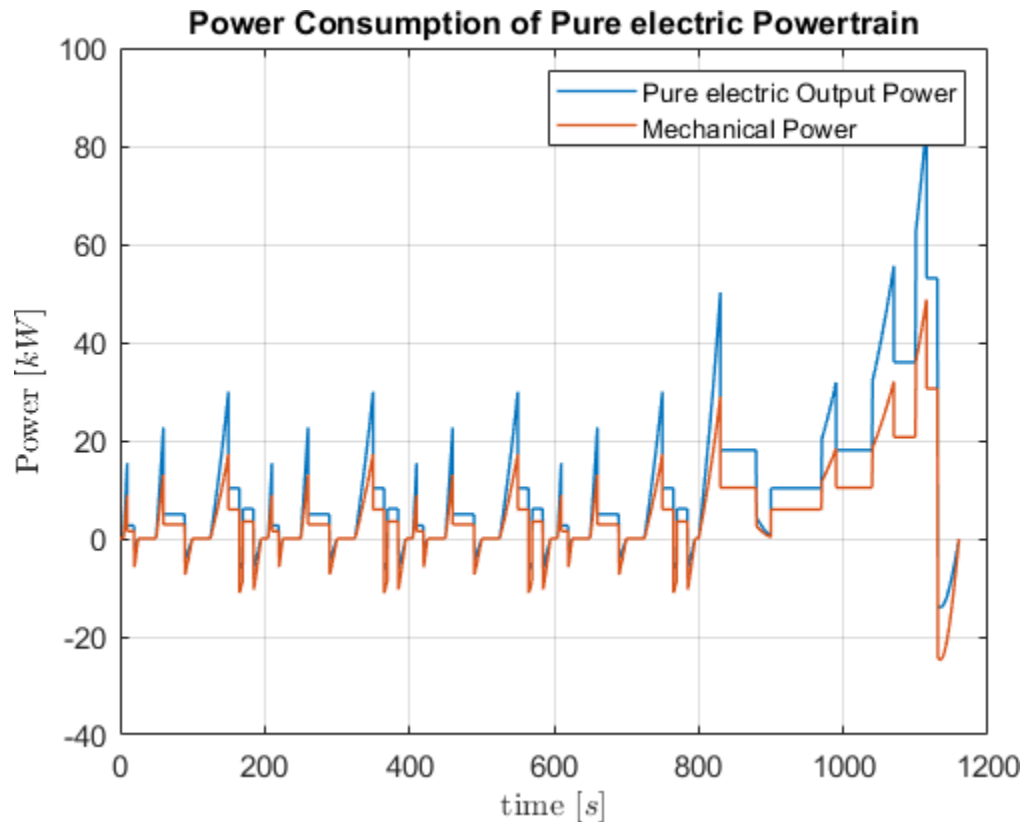
```
force_motor = mass_factor * mass * mix_acceleration;
force_drag = 0.5 * air_density * drag_coefficient * surface_area *
    (mix_velocity + wind_speed).^2;
force_friction = rolling_resistance_coefficient * mass * gravity;
force_traction = force_motor + force_drag + force_friction;
mechanical_power_mix_cycle = 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 maintain 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.

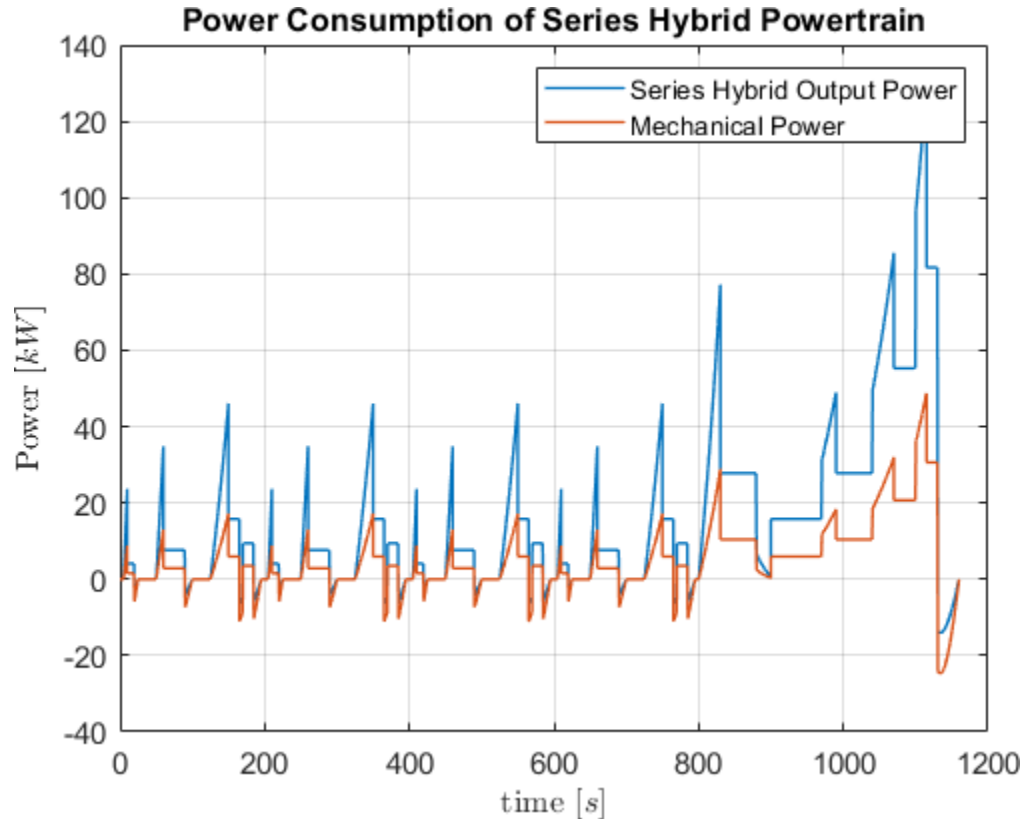
Power Consumption: Pure electric in Mix Driving Cycle

```
pure_electric_power_mix_cycle = zeros(1,
    length(mechanical_power_mix_cycle));
pure_electric_power_mix_cycle =
    AuxPowerCalculator(mechanical_power_mix_cycle, mix_velocity,
        pure_electric_power_mix_cycle, efficiency_pure_electric_charging,
        efficiency_pure_electric_discharging,
        efficiency_pure_electric_discharging);
AuxShowPowerResults(mix_time, pure_electric_power_mix_cycle,
    mechanical_power_mix_cycle, 'Pure electric');
```

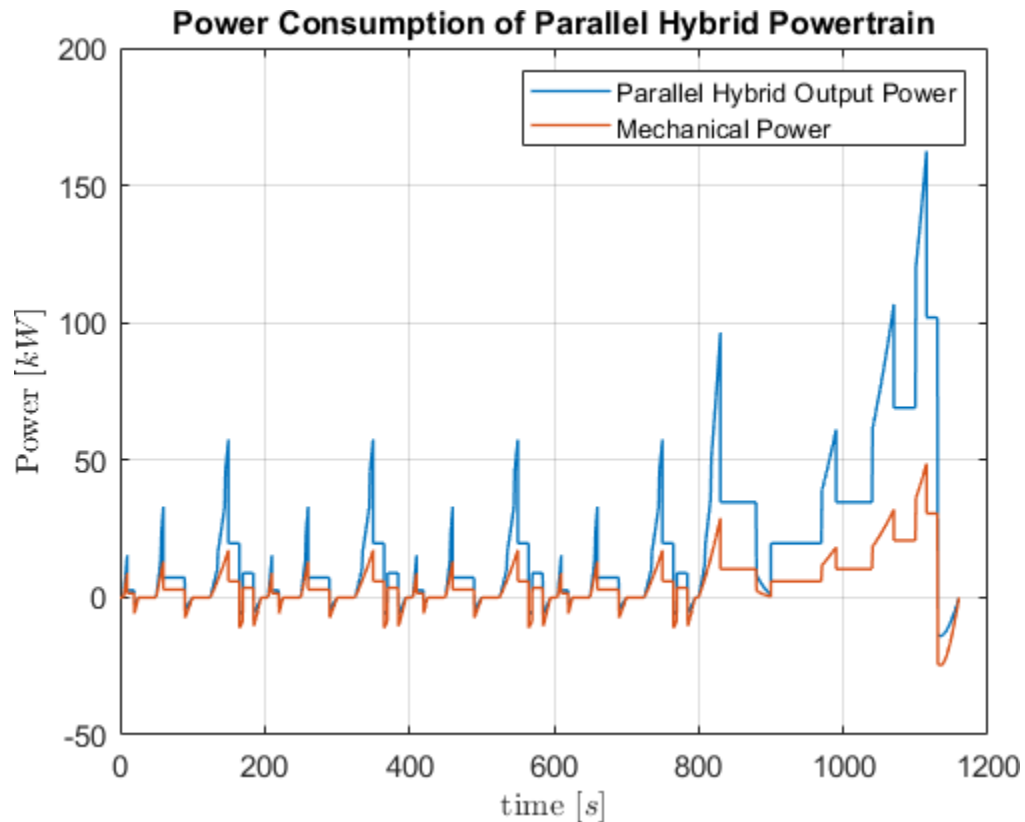
Power Consumption: Series Hybrid in Mix Driving Cycle

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



Power Consumption: Parallel Hybrid in Mix Driving Cycle

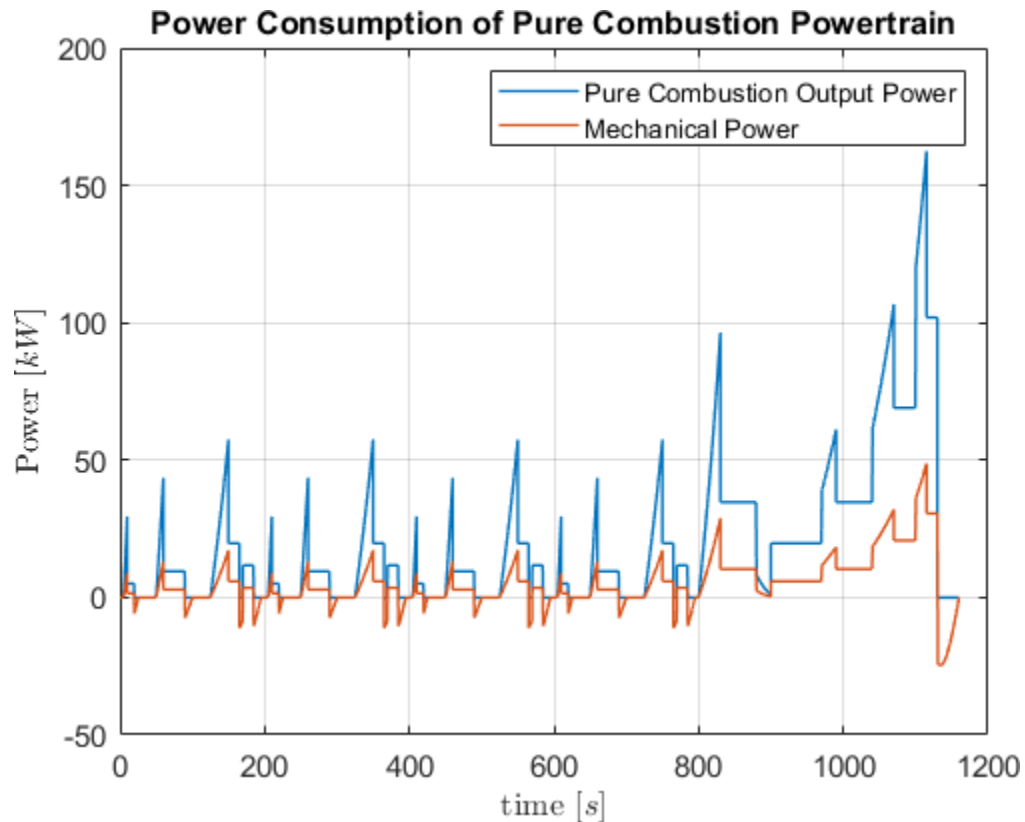
```
parallel_hybrid_electric_power_mix_cycle = zeros(1,
    length(mix_acceleration));
parallel_hybrid_electric_power_mix_cycle =
    AuxPowerCalculator(mechanical_power_mix_cycle,
        mix_velocity, parallel_hybrid_electric_power_mix_cycle,
        efficiency_hybrid_parallel_electric_charging,
        efficiency_hybrid_parallel_electric_discharging ,
        efficiency_hybrid_parallel_combustion_discharging);
AuxShowPowerResults(mix_time,
    parallel_hybrid_electric_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);

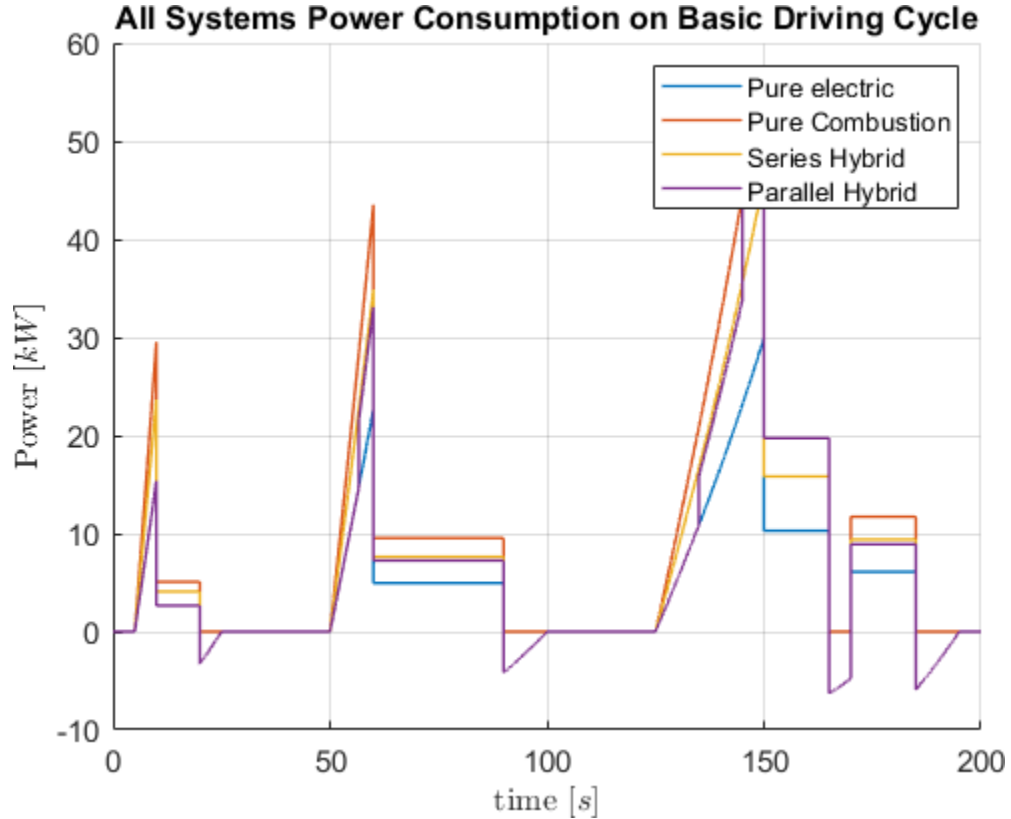
AuxShowPowerResults(mix_time, pure_combustion_power_mix_cycle,
    mechanical_power_mix_cycle, 'Pure Combustion');
```



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_electric_power_basic_cycle/1000, 'LineWidth',
1);
plot( basic_time, pure_combustion_power_basic_cycle/1000, 'LineWidth',
1);
plot( basic_time,
series_hybrid_electric_power_basic_cycle/1000, 'LineWidth', 1);
plot( basic_time,
parallel_hybrid_electric_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 electric', 'Pure Combustion', 'Series Hybrid', 'Parallel
Hybrid');
grid on;
```

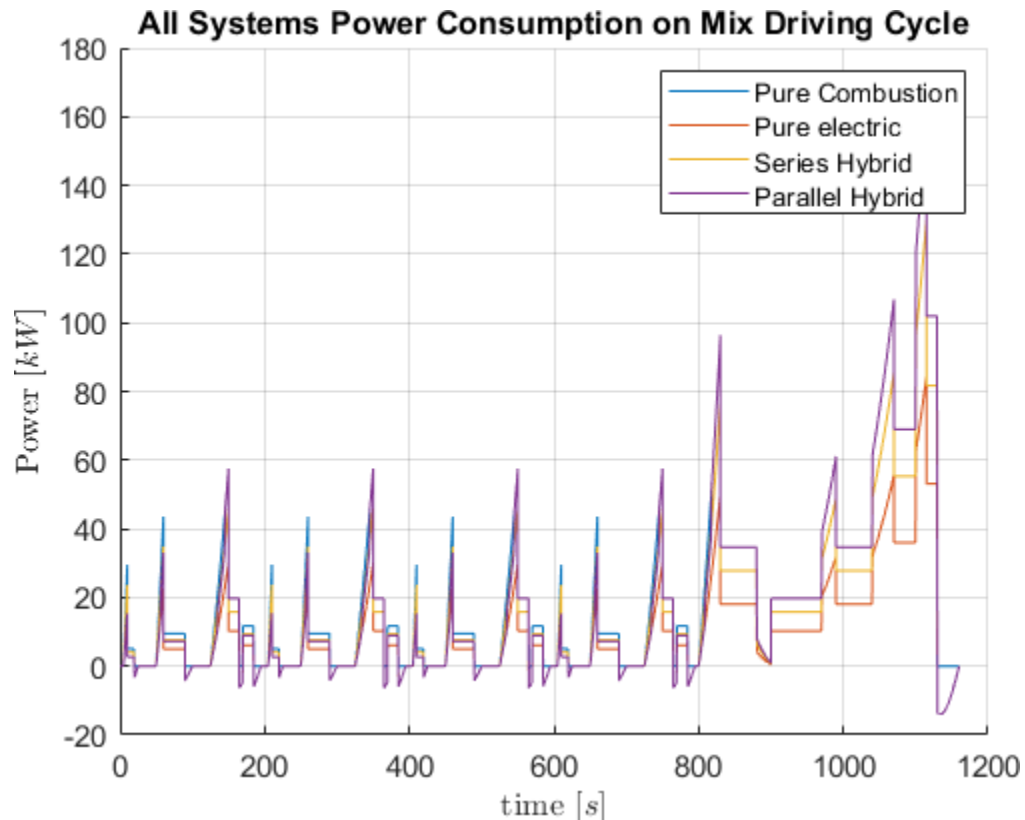


One can see that, for the basic driving cycle, the combustion powertrain performs worse when compared to the electric and hybrid powertrains, due to the intrinsic low efficiency of the diesel motor.

For speed under 20 km/h, the electric and the parallel hybrid perform the same way, given that in the speed range from 0 to 20 km/h they all function with a pure electric powertrain. However, once the velocity reaches the 20 km/h mark, the combustion engine starts providing half the energy, therefore increasing the power consumption. Then, when the speed reaches 40 km/h the parallel hybrid work on pure combustion engine, presenting the same power consumption as a pure combustion car.

Finally, the series hybrid powertrain performs allways in between the pure electric 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 electric being more active with the increasing velocity.

```
figure()
hold all
plot(mix_time, pure_combustion_power_mix_cycle/1000);
plot(mix_time, pure_electric_power_mix_cycle/1000);
plot(mix_time, series_hybrid_electric_power_mix_cycle/1000);
plot(mix_time, parallel_hybrid_electric_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 electric', 'Series Hybrid', 'Parallel Hybrid');
grid on;
```



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

- As always, the pure electric car has the best performance of all the power trains;
- Next comes the series hybrid, that has its efficiency diminished due to the presence of the diesel generator, that for these speeds powers the battery;
- Finally, the parallel hybrid and the pure combustion powertrains perform the worst, due to the low efficiency of the diesel motor;

Energy Recovery

The powertrains that have an electric motor/generator, can harness the power of the braking to restore the energy in the velocities. In this section, the quantity of this saved energy will be studied for each powertrain in each driving cycle.

Energy Recovery: Theoretical 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, between other factors 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 needs only to 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 electric Powertrain Basic Driving Cycle

```
[energy_recovered_basic_cycle, energy_spent_basic_cycle] =  
    AuxEnergyCalculator(basic_time, pure_electric_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_electric_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_electric_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 Cycle

For this driving cycle, pure electric powertrain performed 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 last the pure combustion which can't recover any energy.

Even though the hybrids and the electric recover energy the same way, the reason that they show a different value in the percentage of energy recovered is because they spend different amounts.

Energy Recovery: Pure electric Powertrain Mix Driving Cycle

```
[energy_recovered_mix_cycle, energy_spent_mix_cycle] =  
AuxEnergyCalculator(mix_time, pure_electric_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_electric_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_electric_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 Cycle

As expected, the powertrains that spend less energy have a greater percentage of the energy recovered. The pure electric vehicle recovers ~5.4%, followed by the series hybrid which recovers ~3.5%, followed by the parallel hybrid that recovers ~3.0% of the energy.

Thus, it is noticeable that for the extra-urban cycle, the energy recovery does not have such great results as the urban cycle.

It is also to notice that in a real life scenario, not all breakings correspond to a regenerative break, because if it is needed to 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 covered 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 electric powertrain is given by:

```
total_cost_electric = AuxFuelCalculator(mix_time, mix_velocity,  
    pure_electric_power_mix_cycle, number_of_mix_cycles_per_year, 'Pure  
    Electric');  
display(total_cost_electric);
```

total_cost_electric =

627.6865

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

```
total_cost_series_hybrid = AuxFuelCalculator(mix_time,  
    mix_velocity, series_hybrid_electric_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_electric_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 pure combustion powertrain spending approximately twice as much as the pure electric, and the parallel hybrid spending 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 it to be worth it. However, if the costumer has the majority of his driving time in a urban area (a Uber driver for instants), it will spend less money due to the better performance 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 practiced, the extra money would be paid off quicker;
- Finally, the pure electric 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;

Discussing Solutions

Verifying the assumptions made, the pure electric powertrain is the most efficient out of the 4 overall. And in last place comes the combustion one with the lowest efficiency, which creates some doubts on it's powerful position in the vehicle industry, with a smashing presence around the world.

Looking at the economic conclusions taken, the reason why combustion motor cars are prevalent on the market is basically the overall price, with the other 3 options coming a bit behind moneywise. It would be interesting to maybe consider the Series/Parallel approach which has some good efficiency results but we didn't get to study.

Although the combustion powertrain is the cheapest one we should consider certain important aspects about the newer electric solution.

The most prominent problem with electric cars is the buying price, with the battery price continuing to be really high and, in some cases, needing to be replaced after an accident. But this issue may change soon, with the development of electric cars technology as well as the virtuous cycle of ever-lower prices that leads to increasing demand and therefore the economies of scale manufacturers need to produce ever-cheaper batteries and cars.

Second important aspect is climate friendly aspect which the combustion car lacks. This being an serious care for most countries around the world it is understandable the government efforts to help grow this market, which once again helps buying power of customers in an initial phase. In the middle we got the series and parallel powertrains that have lower gas emissions than the combustion but still are a problem for the environment.

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