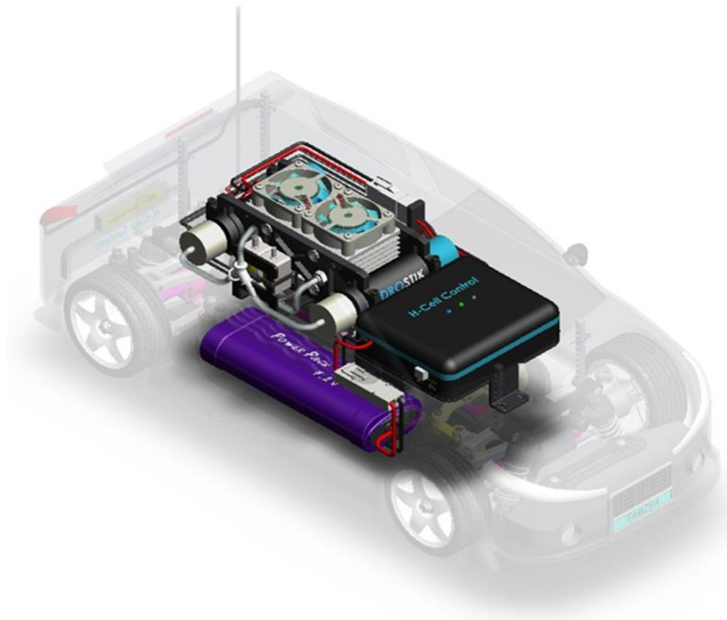
3 - Energy Needs

How much energy is required to move the car?



3 - Energy Needs

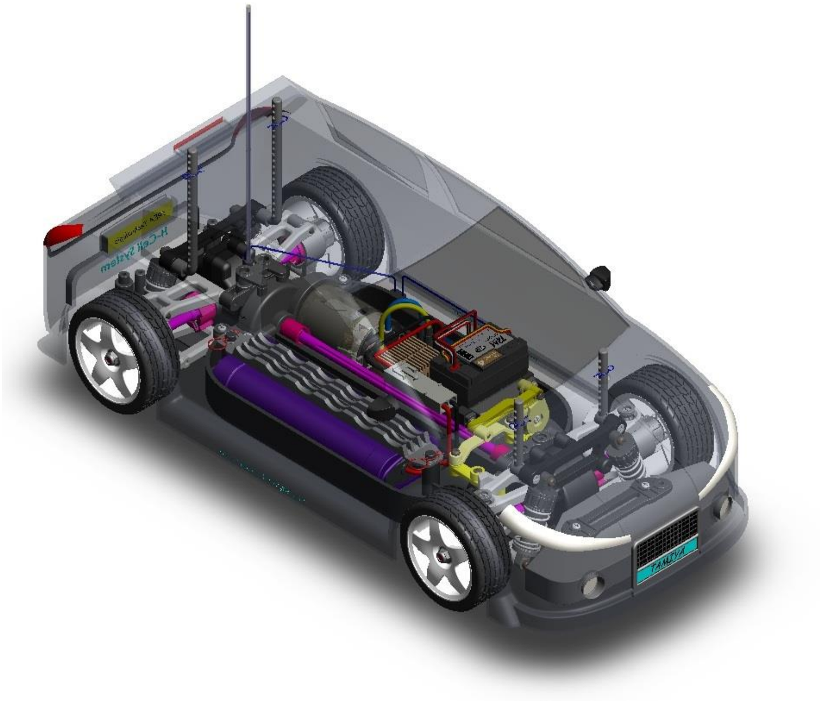
How much energy is required to move the car?

3.1
Using models to describe the car's motion

Full study

Time required:

1h (+ 1h of additional study)



Objectives:

In this activity, we will analyze various models that can be used in our future simulations to analyse the expected behavior of the car in propulsion mode when having to deal with different types of resistance to movement.

Using a model to describe reality…

Reality is messy. There are thousands of things that affect any process you might want to try and describe using a simple model. Therefore, the only way to effectively create a model of a real-life situation is to include certain assumptions (the system is closed, ignore wind resistance, etc.) into your model. However, we must always be aware of the assumptions contained in our model and factor them in when we compare our model to actual experimental data.

When we try to create a model of our car running and the forces that act upon it, we will also be making certain assumptions. This means our model will be imperfect, but it will still be able to accurately describe the running of the car.

In this activity, the following will be examined:

- the forces that resist the car's motion
- the forces exerted on the propulsion system, from the drive wheels to the engine
- the power and energy required for the car to move
- the details of the functioning of the propulsion engine and of equivalent inertias are examined by software simulations or experiments (in an additional activity)

We could analyze many different aspects of the car’s performance, but we don’t want to understand every detail. We’re more interested in getting a broad view of how the car operates. We will therefore limit ourselves to calculation models that seem best suited to this type of analysis.

In subsequent activities, we'll be able to use simulation tools, defined in spreadsheets or software, in which a part of the models developed in this section will be used.

3.1.1

Time required: 15 min

0:15

Let's start by analysing the behavior of the car at constant speed
(see Appendix on page 12)

Question:

Explain briefly, using text and drawings, what creates various types of resistance that stops the car's motion from maintaining a constant speed

Climbing a slope	
Wind resistance	
Resistance to the tires rolling on the track	

3.1.2

Time required: 15 min

0:15

Since the previously-mentioned resistance types can be theoretically calculated, we will carry out some simple preliminary estimations to become familiar with the main quantities associated with this type of modelling (see Appendix on page 12)

Question:

Complete the following tables that correspond to various forms of resistance at constant speed, using the formulas contained in the spread sheet.

Slope to climb					
Angle of the of the slope (degrees)	**Mass "m" of the car (kg)**	**Propulsion force (N)**	**Required speed (m/s)**	**Required power (W)**	**Energy required for 3600 seconds of running (J)**
15	**1.5**		**6**		

Wind resistance						
ρ (kg/m^3)	**Sp (m^2)**	**τx**	**Required speed (m/s)**	**Propulsion force (N)**	**Required power (W)**	**Energy required for 3600 seconds of running (J)**
1.293	**0.02**	**0.35**	**6**			

Resistance to wheels (rolling of the tires on the track)						
P (N)	**R(m)**	**δ (m)**	**Propulsion force (N)**	**Required speed (m/s)**	**Required power (W)**	**Energy required for 3600 seconds of running (J)**
15	**0.0325**	**0.002**		**6**		

3.1.3

Time required: 10 min

0:30

Let's now examine the analysis of behavior during acceleration…

Question:

Explain briefly what other phenomena come into play, in addition to constant speed resistance, when one wants to increase the speed of the vehicle (the "acceleration" phase).

(Think of what happens if you want to push your car forward or when you start pedalling on a bicycle)

3.1.4

Time required: 10 min

0: 40

See Appendix on page 12

Question:

Complete the following table that corresponds to resistance to movement created by inertia during acceleration. In this case, we will assume that the car starts from a stationary position. The minimum time it takes to go from 0 to Vmax reflects the performance we are determining.

Only inertia associated with the acceleration of the moving mass of the vehicle is considered here.

Inertia of the vehicle's translatory mass during acceleration					
Mass "m" of the car (kg)	**Final required speed (m/s)**	**Time of the acceleration from 0 to required Vmax**	**Average propulsion force (N)**	**Average power required (W)**	**Required energy for the duration of the acceleration (J)**
1.5	**6**	**4**			

3.1.5

Time required: 10 min

0:50

Other types of resistance must also be considered when assessing the energy consumed by the car, such as the internal resistances of the car.

When we have assessed the amount of power or energy required for the propulsion of the car, we have to return to the source, i.e. to the power supply of the engine, taking into account all the phenomena that can cause energy losses. However, a detailed theoretical analysis is particularly complex. This is why it's preferable to use a more general modelling method by examining the motor's efficiency. General efficiency is easy to understand and express. For example, in a system with 70% efficiency, we have 100% - 70%, so 30% of energy has been lost.

Question:

Complete the following tables, taking into account the total efficiency of the internal propulsion system (engine + transmission), based on the estimate.

Internal resistances of the car					
Efficiency of the transmission	Efficiency of the engine	Efficiency of transmission and engine	Useful power, to move the car (W)	Power absorbed (consumed) by the engine (W)	Energy consumed for 3600 seconds of running (J)
0.8 (80 %)	0.6 (60%)		6.5		

Additional study modules

(Time required: 1h)

3.1.6

Time required: 15 min

0:15

To study the behavior of an engine (direct current) it is usually necessary to know, for a given operating mode, the transmitted engine torque values, the consumed current, and the revolution speed of the rotor (see Appendix on page 14).

Question:

Considering a given force required for the car to move at a constant speed, determine the angular velocity values of the engine, the engine torque and the amount of current used.

Power absorbed by the engine (W)	Power supply voltage of the engine (V)	Current used by the engine (A)
16	7.2	

Force "T" resisting propulsion (N)	Radius "r" of the driving wheels (m)m:	Resistant torque "τ_{wheel}" transfered to the driving wheels (N•m)	Ratio "R" of transmission	Efficiency "η" of transmission	Resisting torque "τ_{engine}" transferred to the drive shaft (N•m)
4	32.5×10^{-3}		8.34	0.8	

3.1.7

Time required: 5 min

0:05

Question:

Consider the example about the engine given in the appendix on page 15

Determine the value of N engine for τ engine = 20 N•m

N engine (rev/min) =

3.1.8

Time required: 20 min

0:20

In order to simplify the analysis or the laboratory test of the behavior of the car as it accelerates, the real model can be replaced with a simpler model, in the form of a flywheel. We will then use the term equivalent inertia (see Appendix on page 13).

Question:

Only the inertia associated with the total moving mass of the car is considered in this approach. In this case, complete the following tables to better understand the link between these various possibilities of modelling the inertia phenomenon.

m (kg)	Radius "r" of the driving wheels (m)	Moment "I equ" of equivalent energy, taken on the axle of the driving wheels ($kg•m^2$)
1.5	32.5×10^{-3}	

m (kg)	Radius "r" of the driving wheels (m)	Ratio of "R" transmission	Moment "J equ " of equivalent inertia, taken on the drive shaft ($kg•m^2$)
1.5	32.5×10^{-3}	8.34	

To stay closer to reality, the inertia of rotating parts within the car, such as the wheels, the gears, etc. should also be taken into account, although their impact is a lot less important than the total moving mass.

If I is the moment of inertia in $kg•m^2$ of a rotating part taken into consideration in our calculation, and R is the transmission ratio between that element and the drive shaft, the equivalent inertia moment is "$Im = I / R^2$" and will have to be added to the value of "Im" calculated above.

3.1.9

Time required: 20 min

0:20

A detailed analysis of the behavior of the car as it accelerates relies heavily on the behavior of the accelerating rotor of the drive shaft, according to the resistance torque "τ" that is applied to it. (See the Appendix). As long as the engine torque "τm" is greater than "τr", the car will accelerate. However, in a direct current engine, "τm" diminishes during the acceleration, so when "τm" reaches the value of "τr" there is equilibrium of torques, and the speed will become constant. As the engine starts, the "τm" torque is at its maximum (equal to "τd"). At that moment, acceleration will be at its maximum and the faster the rotor turns, the more the acceleration will decrease as the car starts moving.

This complex behavior can nevertheless be theoretically analysed with a mathematical model, resting on the resolution of differential equations, as is shown in the Appendix.

Question:

Considering the values given below, use the acceleration behavior law of the drive shaft (provided in the Appendix), to define the theory governing the evolution of speed of the car through time.

Example of engine characteristics (Mabuchi RS-540RH-7520 model, page 15):

τd = 0.196 N•m **ω_o = 2430 rad/s**

Resisting torque applied to the drive shaft (provoked by resistance to motion):

τr = 0.020 N•m

Equivalent moment of inertia, taken on the drive shaft:

$I = 227 \cdot 10^{-7}$ kg•m²

Use a calculator or a spread sheet to visualise the curve that represents this function, and reproduce its general aspect in the box below.

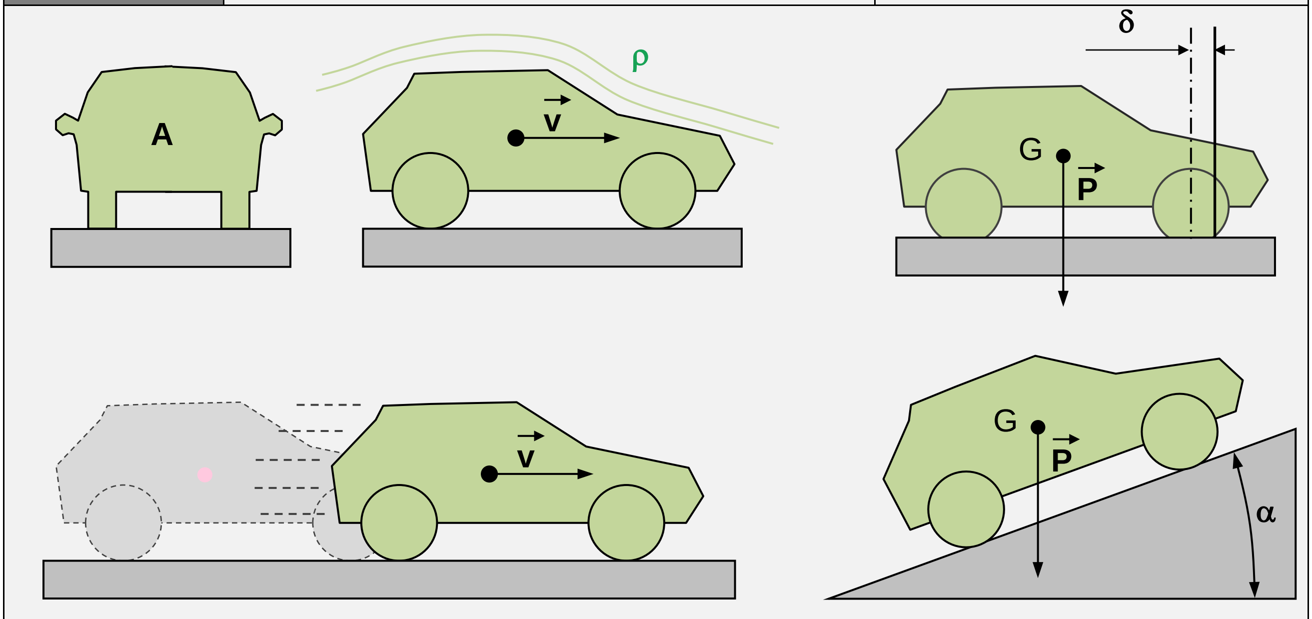
ω (t)	
General relationship	

Appendix

Calculation of the force* resisting the car's propulsion and its effect on the power to supply and the part of energy that has to be stored onboard

(*this force corresponds to the effort that a horse pulling the car would have to provide)

	Calculation parameters	Propulsion effort (Newton)
Slope to climb	• Angle of the slope "α" in degrees • Weight "P" of the car in Newtons	$F = P \cdot \sin(\alpha)$
Aerodynamic resistance	• Air density "ρ": 1.293 kg/m^3 • Projected area "A" in m² • Drag coefficient "Cx" • Speed "v" of the car in m/s	$F = 0.5 \cdot \rho \cdot A \cdot Cx \cdot v^2$
Resistance to rolling	• Resistance to rolling "δ" in meters • Radius "r" of the wheel in meters • Weight "P" of the car in Newton	$F = P \cdot \delta / r$
Inertia in acceleration	• Time "t" of the acceleration in seconds • Final speed "v" of the car in m/s • Mass "m" of the car in kg	$F_{average} = m \cdot v / t$ taking only into account the inertia of the car's moving mass



Corresponding power (W): $P = F \cdot v$ or $P_{average}{}^{*} = F_{average} \cdot v / 2$

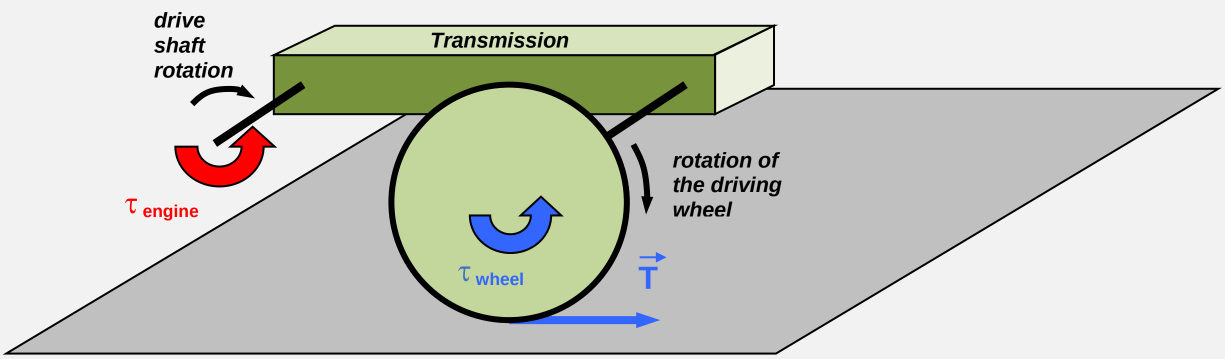
**while accelerating*

Energy required to move for a given amount of time:

$E = P \cdot t$ or $E = P_{average} \cdot t$ with **t : required time in seconds**

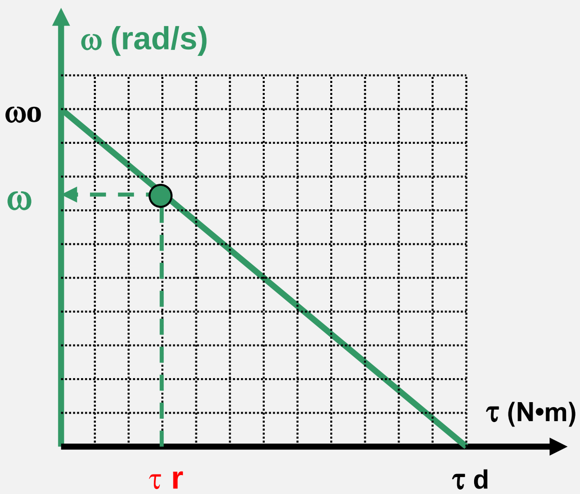
For additional studies

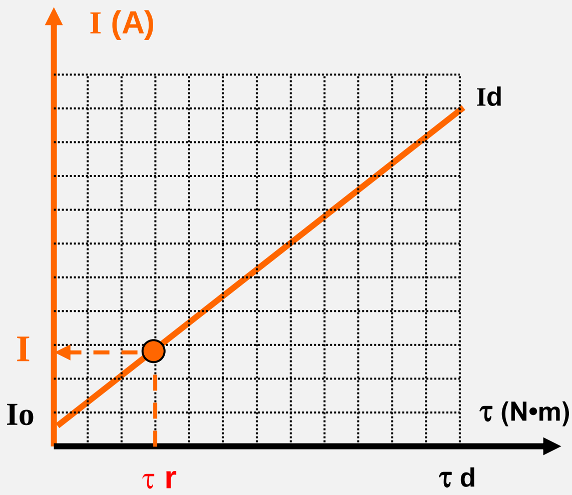
Relationship between the force resisting propulsion and resisting torques applied to the driving wheels or the drive shaft		
Resisting force applied to the driving wheels	T = F* * Defined in the previous table	• F : force required for propulsion (N) • T : resisting force applied by the ground to the driving wheels (N) • r: driving wheel radius (m) • τ wheel: resisting torque applied to the driving wheels (N•m) • τ engine: Resisting torque applied to the drive shaft (N•m) • R: transmission ratio "$\omega_{engine} / \omega_{wheel}$" • η : transmission efficiency (< 1)
Resisting torque applied to the driving wheels	$\tau_{wheel} = T \cdot r$	
Resisting torque applied to the drive shaft	$\tau_{engine} = \tau_{wheel} / (R \cdot \rho)$	

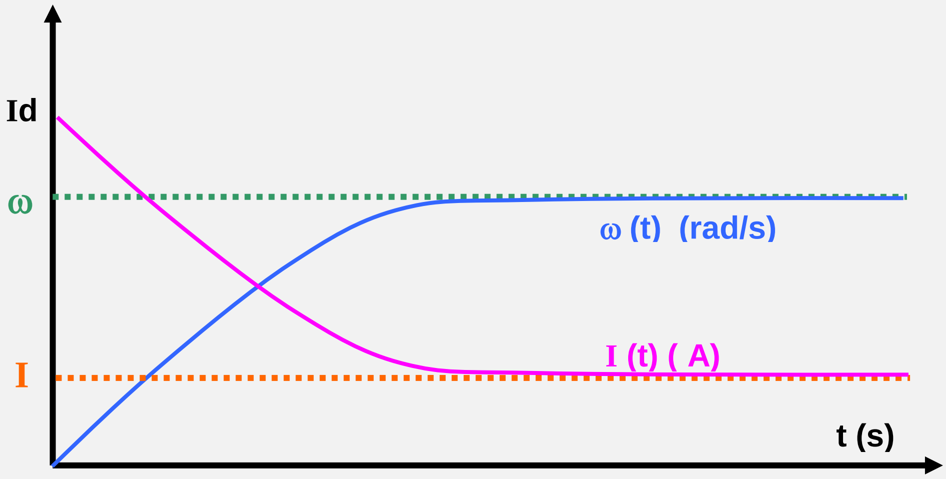


Concepts of equivalent inertias			
	Kinetic energy of the considered object	Moment of equivalent inertia, taken on the drive shaft	Parameters
Translatory object	$\frac{1}{2}$ m•v²	$I_{equ} = m \cdot r^2 / R^2$	• I_{equ}: equivalent moment of inertia in kg•m² • m: mass of the object in kg • r: wheel radius in metres • R: gear ratio between the wheel and the drive shaft • I: moment of inertia of the rotating object
Rotating object	$\frac{1}{2}$ I•ω²	$I_{equ} = I / R^2$	

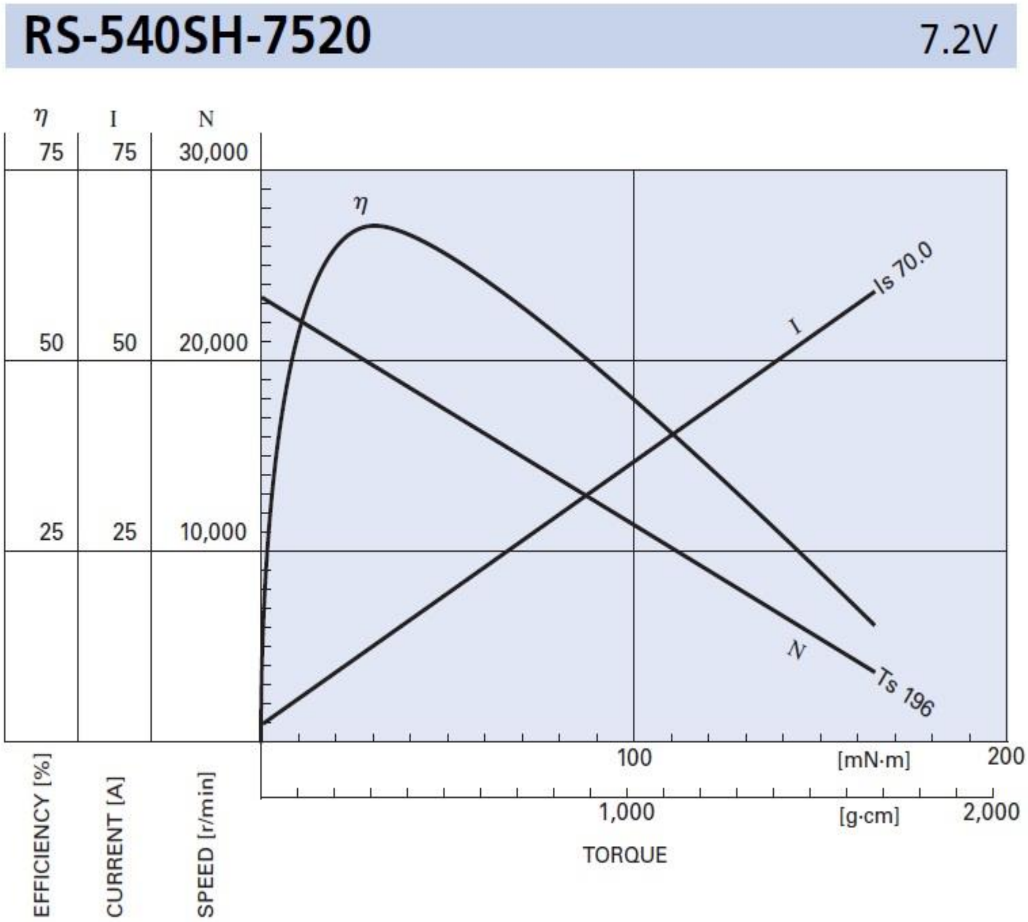
Details of the behavior of an engine with direct current		
	Characteristic equations	**"a" and "b" constants**
Angular velocity In terms of resisting torque	$\omega = a \cdot \tau + b$	• $a = -(\omega_o / \tau d)$ • $b = \omega_o$
Current consumed according to resisting torque	$I = a \cdot \tau + b$	• $a = (Id - I_o) / \tau d$ • $b = I_o$
Angular speed according to time (during acceleration)	$\omega(t) = a \cdot (1 - \exp^{(-b \cdot t)})$	• $a = \omega_o \cdot (1 - \tau r / \tau d)$ • $b = \tau d / (I_{equ} \cdot \omega_o)$
Current consumed according to angular speed	$I = a \cdot \omega + b$	• $a = -((Id - I_o) / \omega_o)$ • $b = Id$







Example of characteristic curves for a Mabuchi direct current engine



3 – Simulation tools

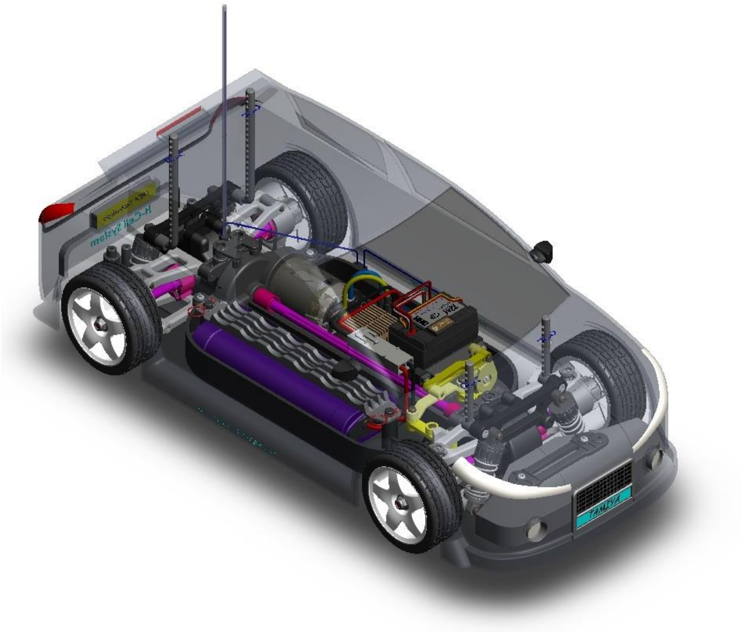
How much energy is required to move the car?

3.2 Simulating the car's motion

Full study

Time Required:

2h +1h additional study



Necessary equipment and resources:

Horizon Equipment

- **Basic H-Cell car**

Other equipment:

- **Multimeter**

Software:

- **"Matlab" software**

Objectives:

How can we model the vehicle using a virtual vehicle that is as close to the real model as possible?

We are going to use simulation software to identify the theoretical impact of certain forms of resistance to movement of the car on its acceleration and top speed performances in terms of speed and consumption.

Theoretical performance at constant speed or during acceleration

Calculating resistance to motion:

Without any resistance to motion, we could drive the vehicle without any power. Of course, this can't happen in reality. During propulsion, the car is faced with numerous forms of resistance to its motion. It is possible to quantify these theoretically, using the laws of physics and the formulas governing motion.

The behavior of an electric motor when faced with different types of resistance:

It is important to know the behavior of the engine when faced with the various types of resistance to motion it encounters. It will allow us to calculate certain theoretical limits that the car can reach, such as its top speed or its maximum acceleration. Additionally, it will tell us about the theoretical performance in terms of energy consumption, which for the purpose of this activity is very useful.

Theoretical analysis methods:

To conduct this analysis, it's possible to use certain hypotheses to calculate formulas that we can use in a programmable calculator or spreadsheet in order to work faster and to obtain graphs that allow us to see certain changes, such as the power of the engine at different speeds.

However, this work takes a long time to implement, and makes the task too difficult, especially for a beginner who wants to know the general ideas, various possible changes of the system, and their theoretical impact on performance. In this case, we can use computer simulation tools that are more or less advanced.

These tools will teach us, in practice, about the various impacts of specific choices (transmission ratio, diameter of the driving wheels, aerodynamic profile of the body, etc.) on the car's speed and energy consumption.

To develop models that remain close to reality, we have to quantify a certain number of measurements of the real model and integrate these into the virtual model.

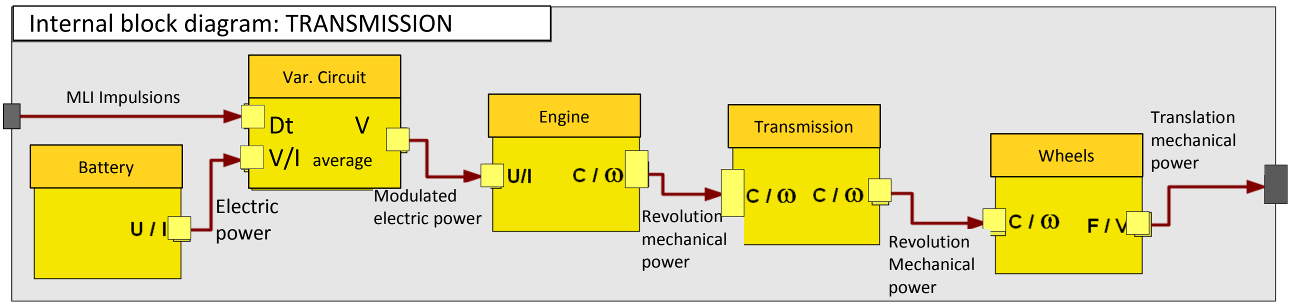
This is the purpose of this activity.

3.2.1

Time Required: 5 min

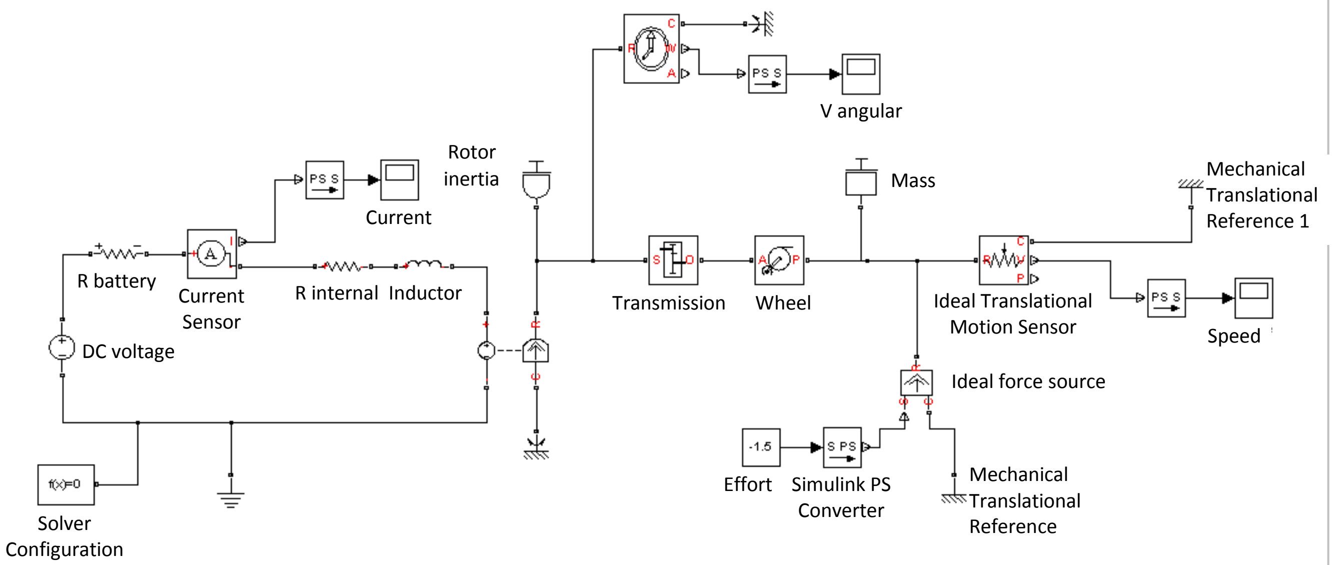
0:05

Observe the flow of energy in the car on the following SYSML diagram:



The chain includes the battery that powers the vehicle, the controller that modulates the energy sent to the engine, the engine, the transmission and the wheels.

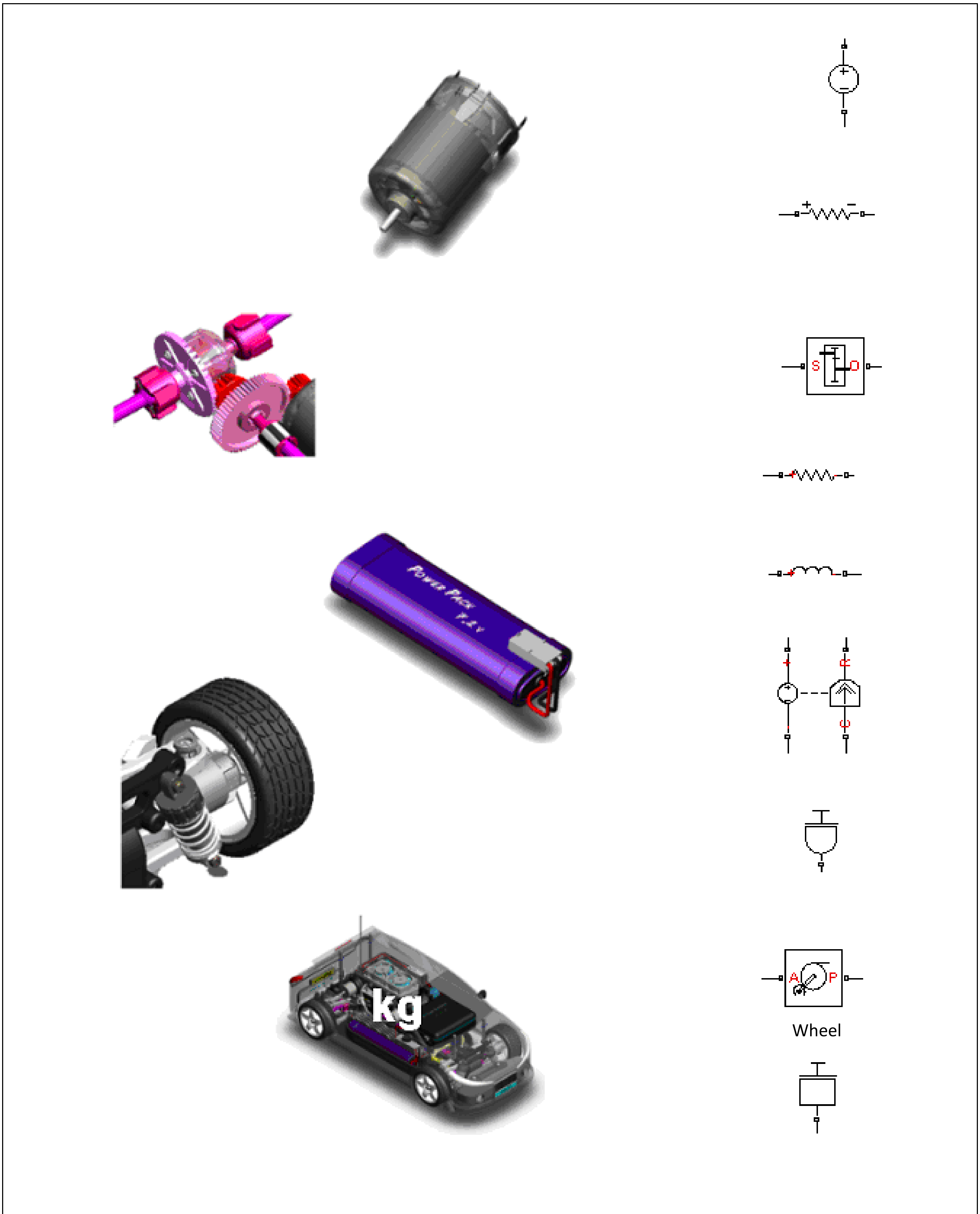
We will encounter all these elements in the theoretical model.



To continue this section, you have to open the FCAT_30.mo file in Matlab software

Question:

On the following page, match the various parts of the vehicle with the theoretical model (some elements include several parts)


S
O
kg
A
P
Wheel

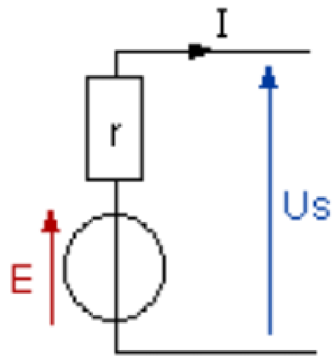
3.2.2

Time Required: 5 min

0:10

Modelling the battery

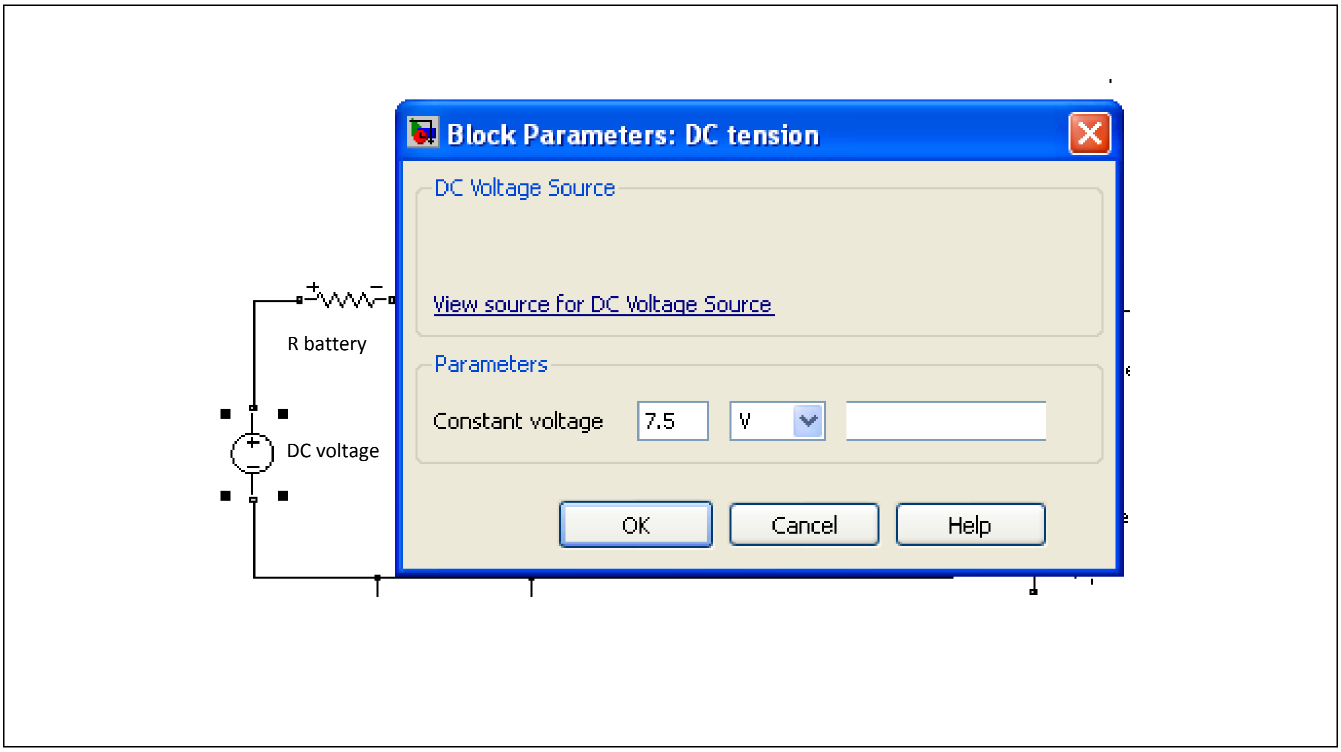
Like any generator, a battery can be modelled as a producer of voltage with an internal resistance, as shown in the following diagram.



E: voltage of the generator (V)
r: internal resistance (Ω)
I: current in the battery (A)

Question:

Measure the voltage on a charged battery and complete the command circuit model of the generator using that voltage.



3.2.3

Time Required: 10 min

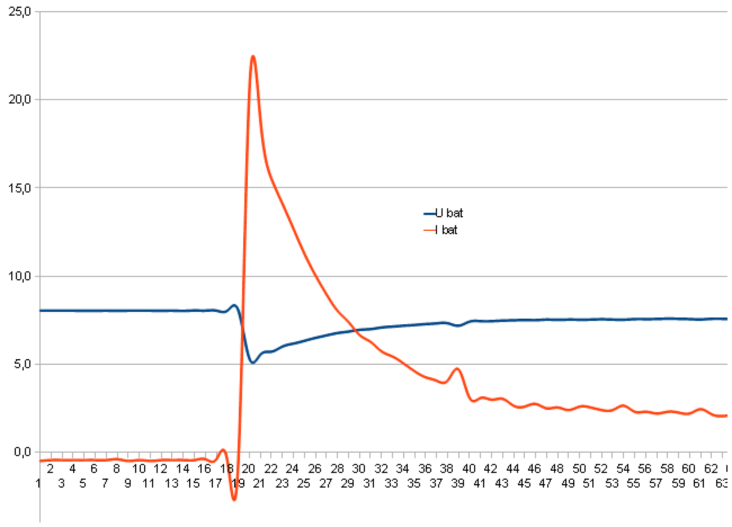
0:15

Internal resistance of the battery

The internal resistance of the battery brings the voltage down when the current increases (V=IR).

The graph below shows the current and voltage of the battery as the car is in motion, note the maximum current and the corresponding fall in voltage.

The no-load voltage is 8v in this case.

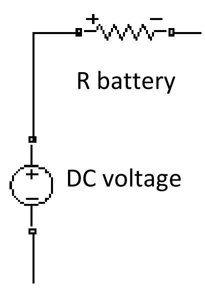


Instructions:

A - Using the diagram of the battery and the measurements below, calculate its internal resistance.

B - Enter the resistance value of the battery in Matlab.

C - Check that the battery is now correctly modelled using the following method:



3.2.4

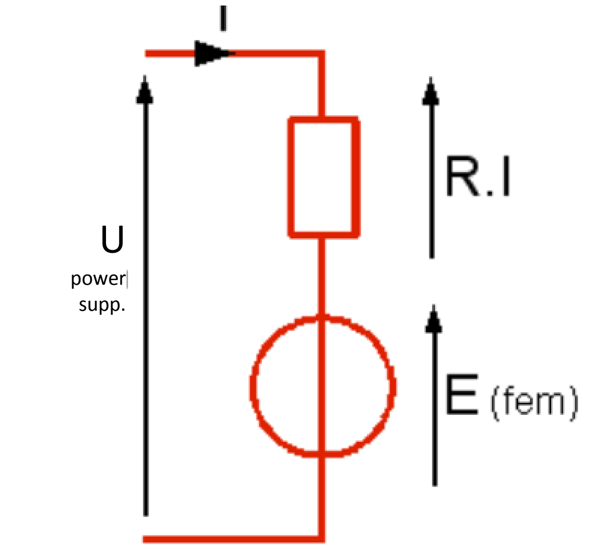
Time Required: 15 min

0:25

Modelling the engine

We can electrically model an engine as a generator, an internal resistance and an inductance. In many cases, the inductance can be ignored as it is equal to 0.

We then add an FEM electrical-mechanical conversion object to the model:



The model's equations are:

V = E+I•R
E = k•w
τ = k•I

V: supply voltage (V)
E: Fem voltage
Electromotive force in V
R: internal resistance (Ω)
I: current in the engine (A)
w: angular velocity (rad/s)
τ: torque (Nm)

Internal resistance of the engine:

The internal resistance of the engine is the resistance of the copper wires of the coil. It is difficult to measure it with an ohmmeter since the value is small and the collector hampers the measurement. It is best to apply a low voltage to the engine with the axle blocked and to measure the current that passes through it. This measurement is hard to conduct on the car.

If you have an isolated engine, you can carry out the measurement, but if not, you may use these values.

Instructions:

A - Measurements give us a current of 5.2A for a voltage of 1V.
Deduce the value of the coil's resistance, and enter the value into the model.

B - Enter the resistance value of the engine inMatlab.

Note concerning the coil's inductance.

We can measure inductance with a measurement of the time constant of the RL circuit, but it is a difficult measurement that will contribute nothing to the model, so we will ignore inductance.

3.2.5

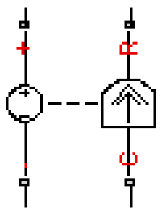
Time Required: 15 min

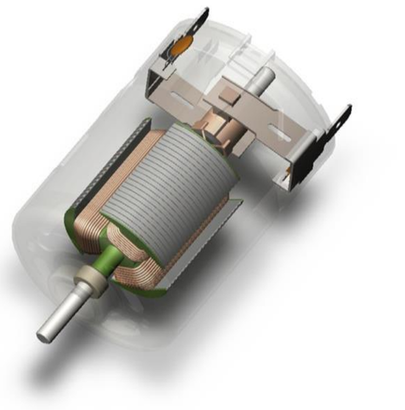
0:40

FEM machine

This component of the software library enables us to convert current to torque and voltage to angular velocity.
It is characterised by the coefficient k of the engine's equations.

$E = k \cdot \omega$
$\tau = k \cdot I$





Measuring torque is tricky, so we will measure speed in order to determine the value of the coefficient.

Instructions:

If you have an isolated engine, you can power it and measure the supply voltage V,
the current I and the speed N.

If you don't have an engine, you may use these measurements.
In our case, the engine is supplied with 3V and runs at 6460 rev/mn with a current of 1.5A

A - In this case, determine the value of f.e.m. "E" (V = E+IR)

B - Determine angular velocity "ω" in radians/second

C - Calculate the coefficient k = E / ω

A – f.e.m. "E"	
B - angular velocity "ω"	
C - coefficient k = E / ω	

3.2.6

Time Required: 10 min

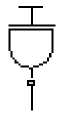
0:55

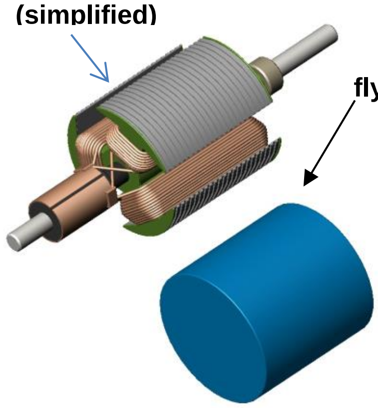
Mechanical inertia of the rotor

The engine's rotor is a mass that rotates at high speed and that represents an inertia that slows down the starting of the car. The moment of inertia is the equivalent for the rotation of the mass and for linear motion.

Modelling the rotor:

M: mass in kg
R: radius in m
J: moment of inertia in Kg.m²





It would be easy to calculate the moment of inertia of the rotor if it were cylindrical and made of solid steel with a density of 7800kg/m^3. The flywheel includes hollow and solid parts, but we can model it as a cylindrical flywheel with the same dimensions but with a lower average density of 3000kg/m^3.

It is difficult to disassemble the rotor to measure its parts, but we can nonetheless measure its dimensions with a volume modeller that gives us a diameter and length of 23 mm each.

With these three values of average density, length and diameter, we can now calculate the moment of inertia:

$$I = 1/2\ m \cdot r^2$$

Questions:

Follow the steps for this calculation, paying attention to units!
Enter this value in the inertia component.

Characteristics of the real rotor and its model	
Volume calculation in m^3	
Mass calculation in kg	
Calculation of the moment of inertia in kg•m²	

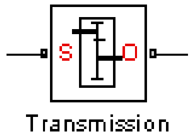
3.2.7

Time Required: 15 min

1:05

Modelling the transmission

Reduction ratio: to achieve a complete model of our vehicle, we have to know the gear ratio between the engine and the wheels. (see appended notes on page 12)

R = Nm / Nr 	

It is the product of two reductions:
The first with the gear and the cogwheel at the engine's output,
The second is at the differentials' gears.

Instructions:

With the instructions provided on page 12, determine the value of the global reduction ratio between the drive shaft and the driving wheels, and enter the value in the model under the "ratio" parameter.

3.2.8

Time Required: 15 min

1:20

Modelling the efficiency of transmission

Mechanical transmission is subject to energy losses, as in any other technical system.
The output power at the wheels is therefore smaller than the power provided by the engine. The difference is dissipated as heat caused by friction of the various mechanisms.

The efficiency is very difficult to measure, and we will estimate it here at 0.6.

Instruction:

Enter the value in the model (it has to feature twice, for each drive direction).

3.2.9

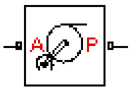
Time Required: 15 min

1:35

Model the transformation of movement between the wheels and the ground.

The wheel on the ground ensures the transformation of the rotation into a linear movement that the vehicle follows. The rotation of the wheel is characterized by an angular velocity in rad/s
The vehicle's translation is characterised by its speed in m/s. We have to determine the ratio between these two parameters: **$k = \omega / V$**

Rad/s m/s



Wheel

As in both cases, the denominator is in seconds, we have to determine the ratio between the wheel's angle of rotation in radian and the distance travelled by the wheel in meters (see page 12).

Instruction:

Complete the model when you have determined the ratio.

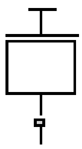
3.2.10

Time Required: 10 min

1:50

Modelling the mass of the vehicle
We still have to enter the mass of the vehicle

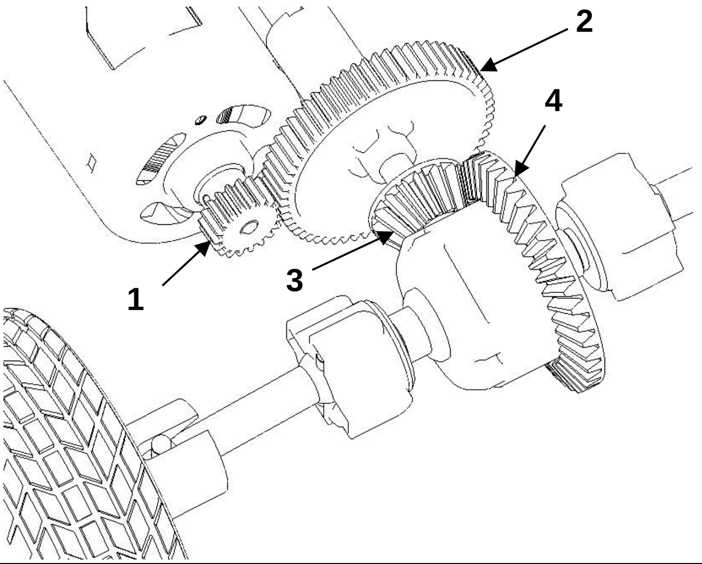
kg

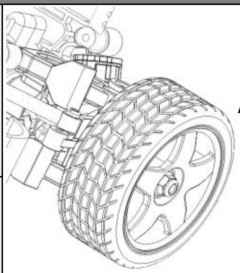
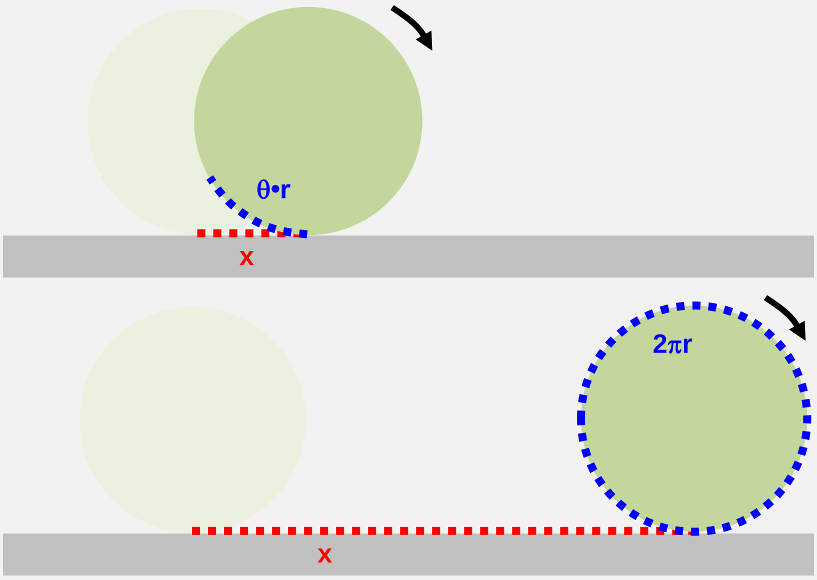


Mass

Instruction:

Weigh the fully-loaded vehicle and enter the value in the model as kg.

<table>
<tr><th colspan="2">Reduction ratio</th></tr>
<tr><td rowspan="3"></td><td>Gear "a":
Z1 = 19 cogs; Z2 = 61 cogs</td></tr>
<tr><td>Gear "b":
Z3 = 15 cogs; Z4 = 39 cogs</td></tr>
<tr><td>Reduction ratios:
$r_a = \omega 2 / \omega 1 = Z1 / Z2$
$r_b = \omega 4 / \omega 3 = Z3 / Z4$
with $\omega 2 = \omega 3$
Global ratio: $r_g = r_a . r_b$</td></tr>
</table>

<table>
<tr><th colspan="3">Relation between the wheel's rotation angle and the distance travelled.</th></tr>
<tr><td>$x = \theta \cdot r$</td><td>x: travelled distance (m)
θ: rotation angle of the wheel (rad)
r: wheel radius (m)</td><td rowspan="2"></td></tr>
<tr><td colspan="2">For a full rotation of the wheel: $\theta = 2.\pi$ rad,
therefore $x = 2\pi r$
(which corresponds to the perimeter of the wheel)</td></tr>
<tr><td colspan="3"></td></tr>
</table>

Additional study modules

(Time Required: 1h)

Comparing the virtual and the real models

We still have to validate our model by comparing it to the real model. To do this, we will conduct a series of measurements on the car using the acquisitions' card and draw the Speed and Supply Current graphs.

You will accelerate at full power until you reach top speed and then you will import your measurements in the spread sheet (see the appended Help section)

You will be able to compare the speeds, the currents and the acceleration times.

3.2.1

Time Required: 20 min

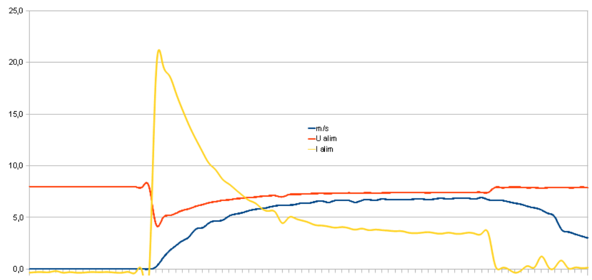
0:00

Measurement on the real vehicle

Question:

Accelerate to full power and record values on the SD card, to draw the required graphs on the spreadsheet (see the Help section on pages 17 and 18).

Required answer model:



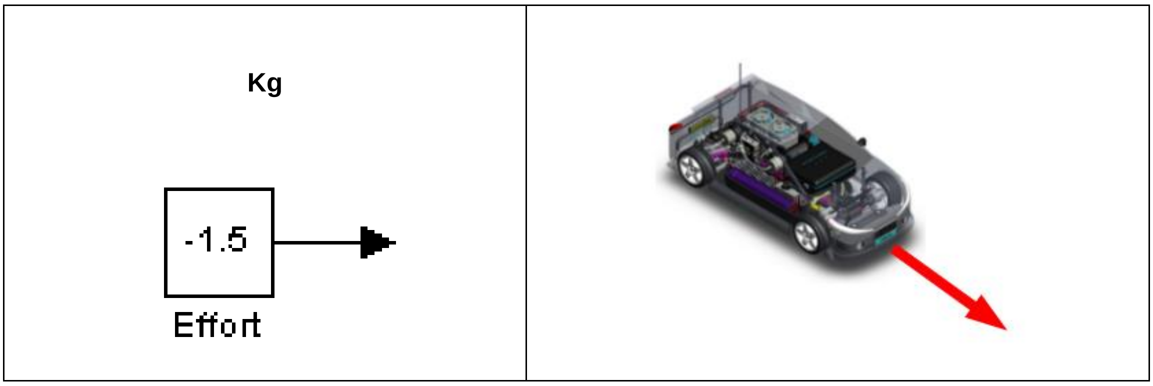
3.2.1

Time Required: 10 min

0:20

Adapting the model

Remember: to stay close to reality, you must estimate the traction force on your vehicle and apply it to the virtual model.



Instructions:

Move your vehicle along the track at constant speed, pulling it with a dynamometer, note the traction force required.

Enter the value in the virtual model (constant)

3.2.1

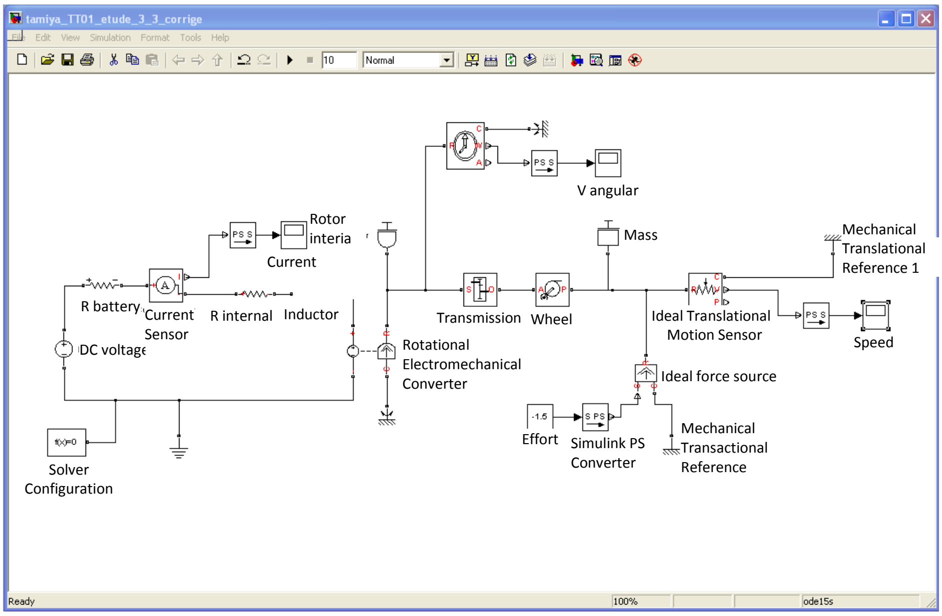
Time Required: 15 min

0:30

Simulation with the virtual model

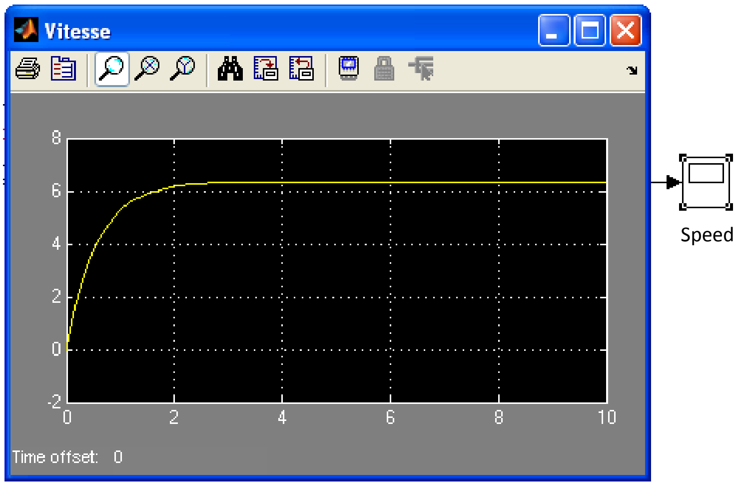
We are now going to ask the simulation software to supply the same speed and current curves as the measured ones, but this time using the virtual model.

Launch the simulation with the black arrow of the tools header, and set the simulation duration at 10s



Click on the oscilloscopes to visualise the current and speed graphs

Click on the binoculars to adjust the graph to the size of the window.



For more info access: www.horizoncurriculum.com

3.2.1

Time Required: 15 min

0:45

Simulation with the virtual model

You can now compare your results and validate or reject your model.

Question:

Note the required values on your measurements and compare both sets of values.
(Acceleration ends when the current and speed are stabilised).

Conclusion

Measurement examples:

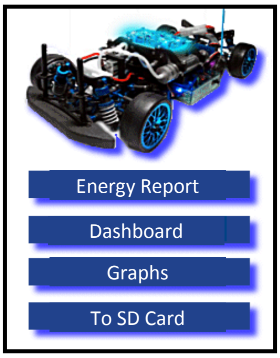
	Max speed (m/s)	Acceleration time (s)	Stall current (Id) (A)	Established current (A)
Real model				
Virtual model				

Conclusion about the validity of the model

Recording measurements on the SD card

Power up the vehicle and the card using the switch.

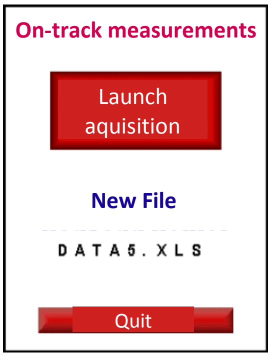
1 - The general menu is then displayed



2 - A first screen prompts you to insert the SD card if it's absent.

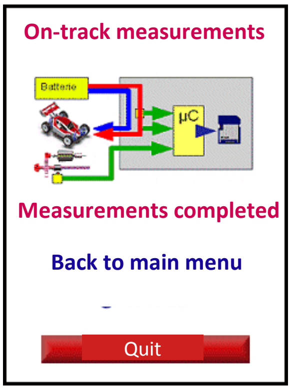
3 - It is then initialized and a new measurement file is created.

4 - You then have to launch the acquisition of measurements.



5 - Data is recorded until you press STOP

6 - The measurements end, and you go back to the menu.



Transferring files and graphs

For this operation, use the tutorial on the CD named "Exploiting measurements".

You must now retrieve the data on the SD card to draw your graphs on the spread sheet. You may use the CD's tutorial to get additional information.

Check the content of the SD card on a computer to see all your measurement files.

Open the first one in the latest creation batch with your usual spread sheet (Excel or OpenOffice) and accept tabulation as separator.

You should see something resembling this.

	A	B	C	D	E	F	G
1	0	951	751	960	514	541	493
2	0	951	751	960	514	541	493
3	0	951	751	960	514	540	492
4	0	951	751	960	514	541	493
5	0	951	751	960	514	540	493
6	0	929	742	941	539	543	538
7	3	845	710	890	646	554	601
8	12	815	692	851	697	560	653
9	26	825	696	851	687	555	660
10	45	795	689	837	711	557	671
11	69	772	678	822	746	562	678
12	98	726	665	784	813	567	745
13	135	722	670	783	837	571	780
14	179	725	667	783	817	568	754
15	228	743	667	793	778	567	719
16	281	749	670	797	767	565	710
17	339	770	677	813	739	563	685
18	399	767	659	808	730	551	697

Open the calculation called calcul-TP-modelisation.xls in another window.
Import your measurement data in the file.

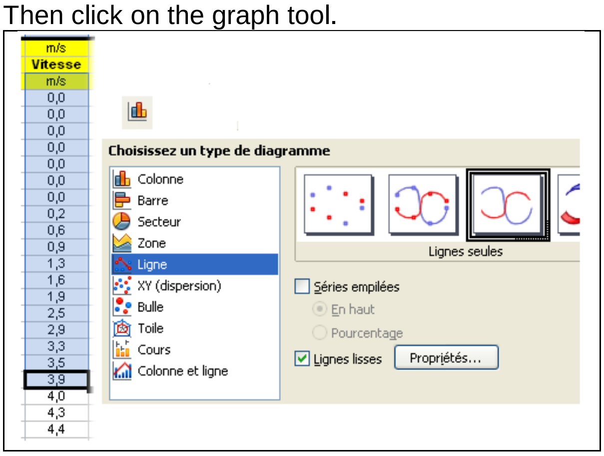
Gross	Gross	Gross	Gross	Gross	Gross	Gross	Seconds	meter	m/s	Km/h	Upower sup.	U cell	U bat	Ipower sup.
Dist	Upower sup.	Ucell	Ubat	Ipower sup.	Icell	Ibat	Time	Distance	Speed	Speed	variator	hydro	battery	variator
									m/s	Km/h	Upower sup.	U cell	U bat	I power sup.
0	952	753	960	514	542	492	0,10	0,0	0,0	0,0	7,9	10,1	8,0	0,1
0	952	753	960	513	541	492	0,20	0,0	0,0	0,0	7,9	10,1	8,0	0,0

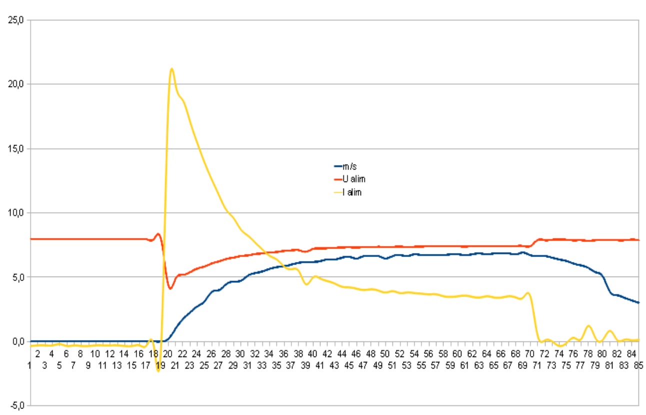
In your measurement file, select all the cells of the measurement table from the top left cell (A1) to the bottom right one in the seventh column. Copy and paste the data in another table under columns ABC.

Tip: open both XLS files and copy the values of the first to paste them in the second (select cell A4 to paste).

Then select the column(s) for which you want to draw the graph(s).

Then click on the graph tool.



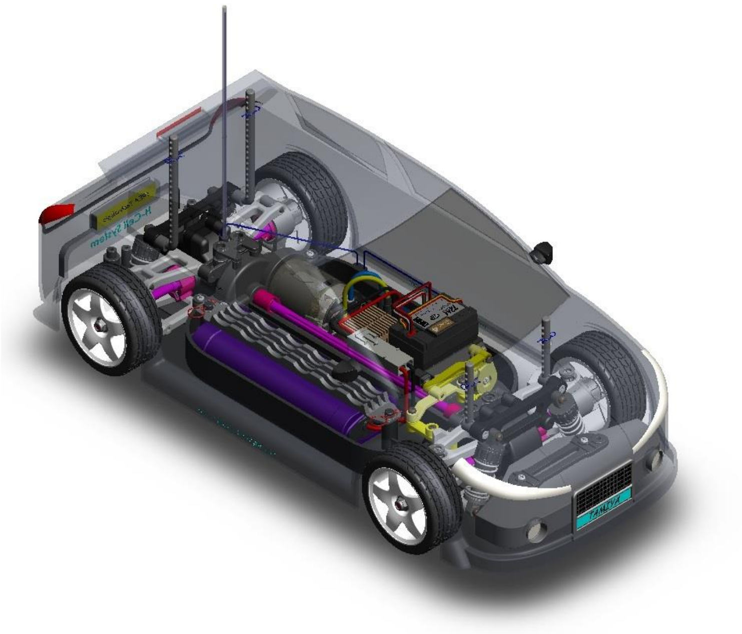


3 – Simulation tools

How much energy is required to move the car?

3.2.1 Simulating the car's motion

Time required: **2h +1h additional study** ***Full study***



Necessary equipment and resources:

Horizon Equipment:

- **Basic H-Cell car**

Other equipment:

- **Multimeter**

Software:

- **"Open Modelica" software (free)**

Objectives:

How can we model the vehicle using a virtual vehicle that is as close to the real model as possible?

We are going to use simulation software to identify the theoretical impact of certain forms of resistance to movement of the car on its acceleration and top speed performances in terms of speed and consumption.

Theoretical performance at constant speed or during acceleration

Calculating resistance to motion:

Without any resistance to motion, we could drive the vehicle without any power. Of course, this can't happen in reality. During propulsion, the car is faced with numerous forms of resistance to its motion. It is possible to quantify these theoretically, using the laws of physics and the formulas governing motion.

The behavior of an electric motor when faced with different types of resistance:

It is important to know the behavior of the engine when faced with the various types of resistance to motion it encounters. It will allow us to calculate certain theoretical limits that the car can reach, such as its top speed or its maximum acceleration. Additionally, it will tell us about the theoretical performance in terms of energy consumption, which for the purpose of this activity is very useful.

Theoretical analysis methods:

To conduct this analysis, it's possible to use certain hypotheses to calculate formulas that we can use in a programmable calculator or spreadsheet in order to work faster and to obtain graphs that allow us to see certain changes, such as the power of the engine at different speeds.

However, this work takes a long time to implement, and makes the task too difficult, especially for a beginner who wants to know the general ideas, various possible changes of the system, and their theoretical impact on performance. In this case, we can use computer simulation tools that are more or less advanced.

These tools will teach us, in practice, about the various impacts of specific choices (transmission ratio, diameter of the driving wheels, aerodynamic profile of the body, etc.) on the car's speed and energy consumption.

To develop models that remain close to reality, we have to quantify a certain number of measurements of the real model and integrate these into the virtual model.

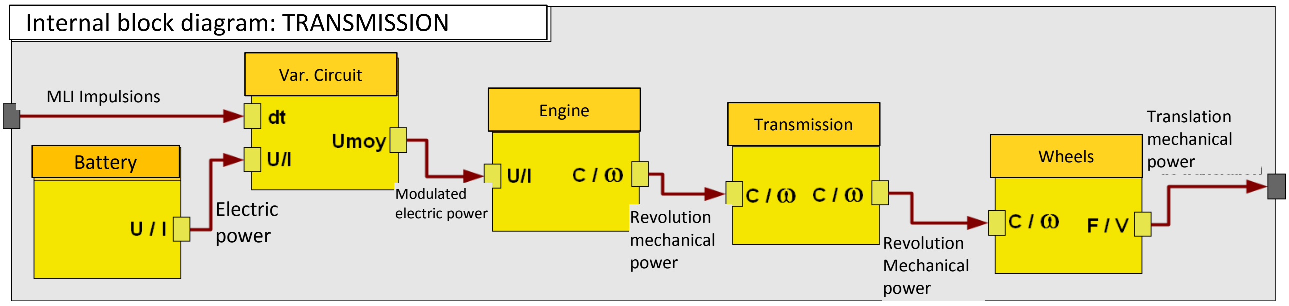
This is the purpose of this activity.

3.2.1

Time Required: 5 min

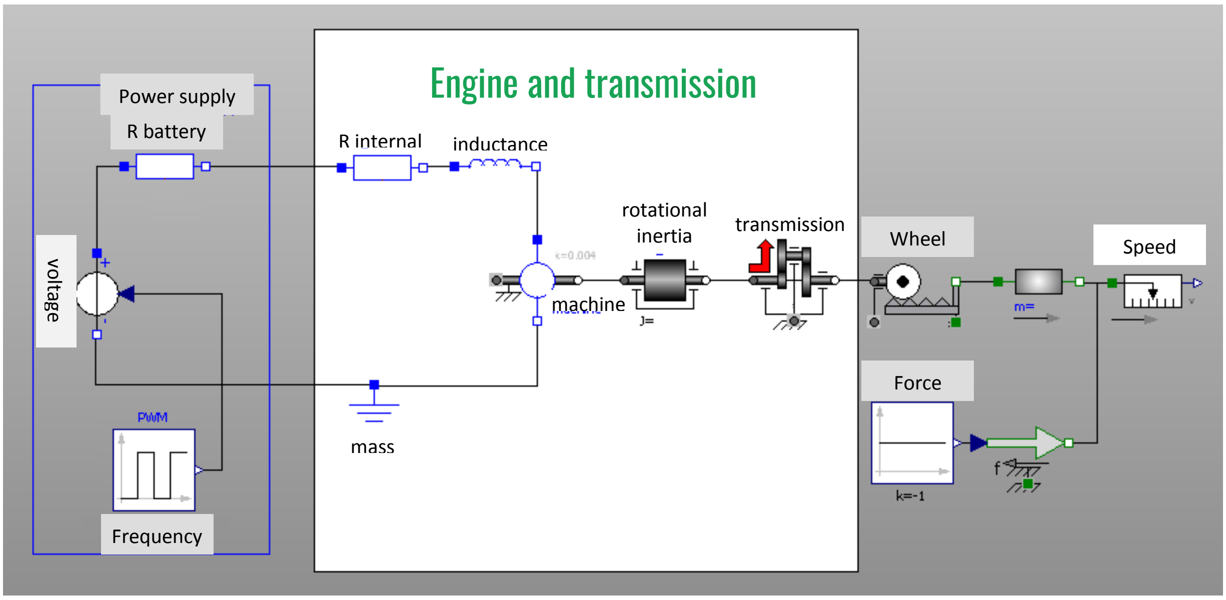
0:05

Observe the flow of energy in the car on the following SYSML diagram:



The chain includes the battery that powers the vehicle, the controller that modulates the energy sent to the engine, the engine, the transmission and the wheels.

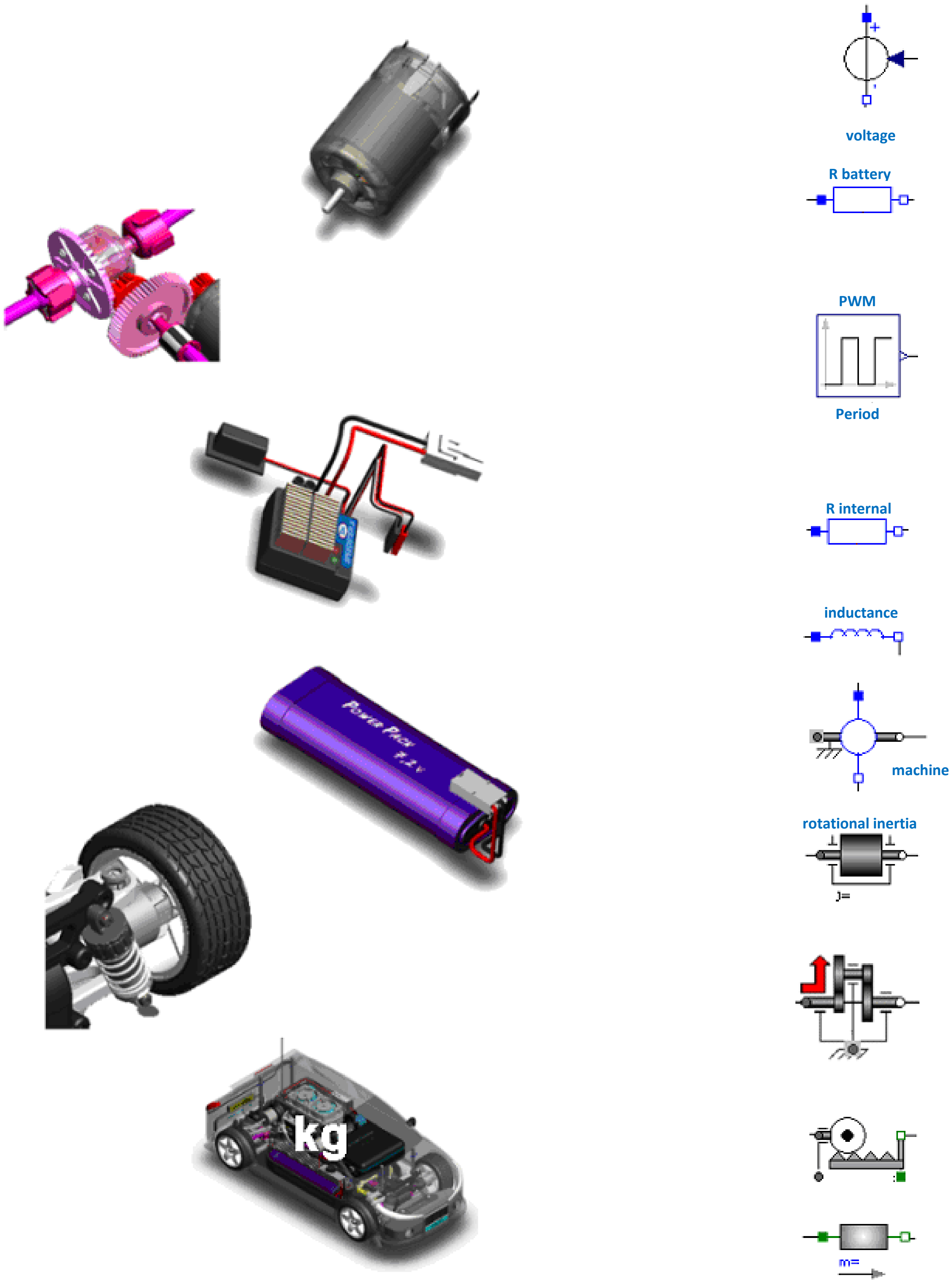
We will encounter all these elements in the theoretical model.



To continue this section, you have to open the FCAT_30.mo file in Matlab software

Question:

On the following page, match the various parts of the vehicle with the theoretical model (some elements include several parts)


voltage
R battery
PWM
Period
R internal
inductance
machine
rotational inertia
J=
kg
m=

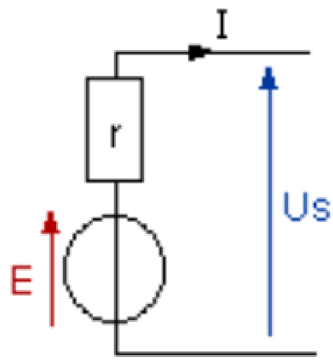
3.2.2

Time required: 5 min

0:10

Modelling the battery

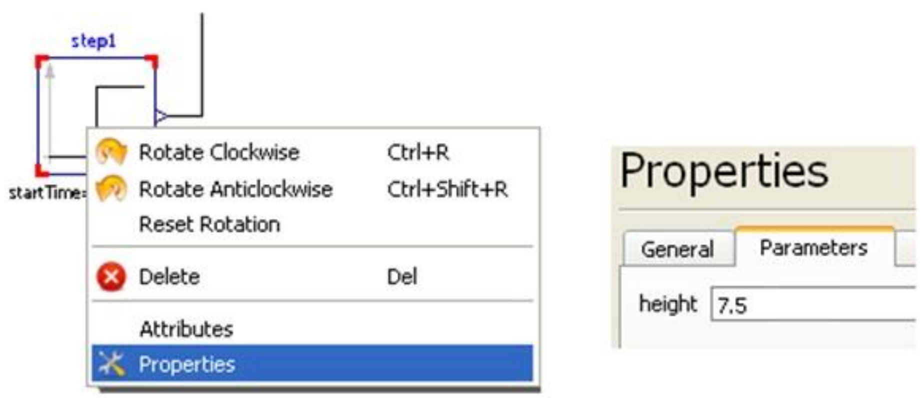
Like any generator, a battery can be modelled as a producer of voltage with an internal resistance, as shown in the following diagram.



E: voltage of the generator (V)
r: internal resistance (Ω)
I: current in the battery (A)

Question:

Measure the voltage on a charged battery and complete the command circuit model of the generator using that voltage.



3.2.3

Time required: 10 min

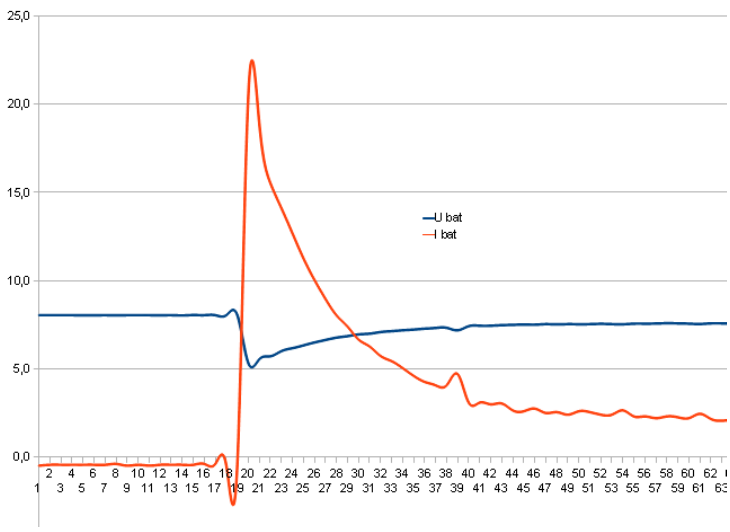
0:10

Internal resistance of the battery

The internal resistance of the battery brings the voltage down when the current increases (V=IR).

The graph below shows the current and voltage of the battery as the car is in motion, note the maximum current and the corresponding fall in voltage.

The no-load voltage is 8v in this case.

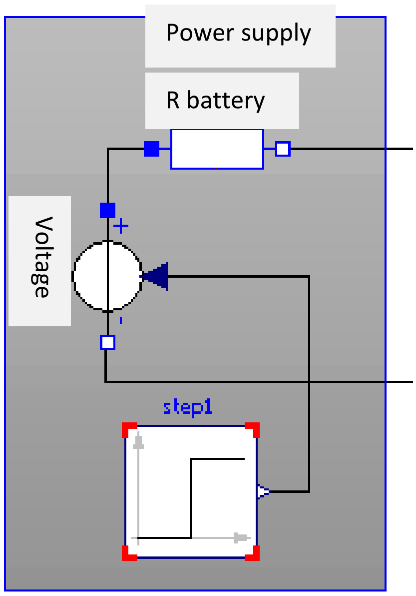


Instructions:

A - Using the diagram of the battery and the measurements below, calculate its internal resistance.

B - Enter the resistance value of the battery in OpenModelica.

C - Check that the battery is now correctly modelled using the following method:



3.2.4

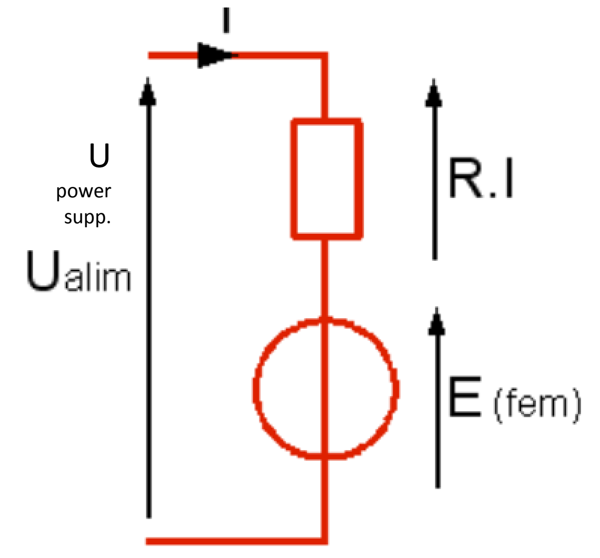
Time required: 15 min

0:25

Modelling the engine

We can electrically model an engine as a generator, an internal resistance and an inductance. In many cases, the inductance can be ignored as it is equal to 0.

We then add an FEM electrical-mechanical conversion object to the model:



The model's equations are:

V = E+I•R
E = k•w
τ = k•I

V: supply voltage (V)
E: Fem voltage
Electromotive force in V
R: internal resistance (Ω)
I: current in the engine (A)
w: angular velocity (rad/s)
τ: torque (Nm)

Internal resistance of the engine:

The internal resistance of the engine is the resistance of the copper wires of the coil. It is difficult to measure it with an ohmmeter since the value is small and the collector hampers the measurement. It is best to apply a low voltage to the engine with the axle blocked and to measure the current that passes through it. This measurement is hard to conduct on the car.

If you have an isolated engine, you can carry out the measurement, but if not, you may use these values.

Instructions:

A - Measurements give us a current of 5.2A for a voltage of 1V.
Deduce the value of the coil's resistance, and enter the value into the model.

B - Enter the resistance value of the engine in OpenModelica**.**

Note concerning the coil's inductance.

We can measure inductance with a measurement of the time constant of the RL circuit, but it is a difficult measurement that will contribute nothing to the model, so we will ignore inductance.

3.2.5

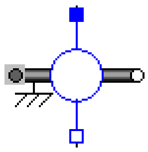
Time required: 15 min

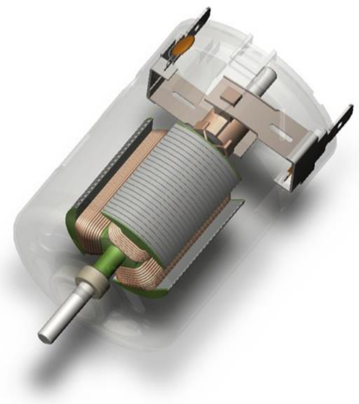
0:40

FEM machine

This component of the software library enables us to convert current to torque and voltage to angular velocity. It is characterised by the coefficient k of the engine's equations.

$$E = k \cdot \omega$$
$$\tau = k \cdot I$$





Measuring torque is tricky, so we will measure speed in order to determine the value of the coefficient.

Instructions:

If you have an isolated engine, you can power it and measure the supply voltage V, the current I and the speed N.

If you don't have an engine, you may use these measurements.
In our case, the engine is supplied with 3V and runs at 6460 rev/mn with a current of 1.5A

A - In this case, determine the value of f.e.m. "E" ($V = E+IR$)

B - Determine angular velocity "ω" in radians/second

C - Calculate the coefficient $k = E / \omega$

D - Enter this value in the electro-mechanic converter.

A – f.e.m. "E"	
B - angular velocity "ω"	
C - coefficient $k = E / \omega$	

3.2.6

Time required: 10 min

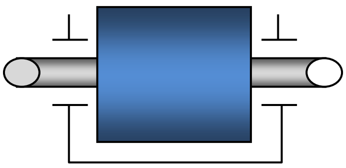
0:55

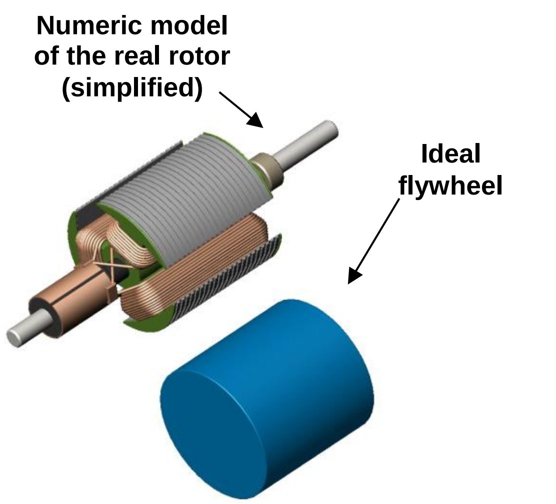
Mechanical inertia of the rotor

The engine's rotor is a mass that rotates at high speed and that has an inertia that slows down the starting of the car. The moment of inertia is the equivalent for the rotation of the mass and for linear motion.

Modelling the rotor:

M: mass in kg
R: radius in m
J: moment of inertia in Kg.m²





It would be easy to calculate the moment of inertia of the rotor if it were cylindrical and made of solid steel with a density of 7800kg/m^3. The flywheel includes hollow and solid parts, but we can model it as a cylindrical flywheel with the same dimensions but with a lower average density of 3000kg/m^3.

It is difficult to disassemble the rotor to measure its parts, but we can nonetheless measure its dimensions with a volume modeller that gives us a diameter and length of 23 mm each.

With these three values of average density, length and diameter, we can now calculate the moment of inertia:

$$I = 1/2\ m \cdot r^2$$

Questions:

Follow the steps for this calculation, paying attention to units!
Enter this value in the inertia component.

Characteristics of the real rotor and its model	
Volume calculation in m^3	
Mass calculation in kg	
Calculation of the moment of inertia in kg•m²	

3.2.7

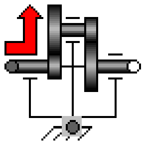
Time required: 15 min

1:05

Modelling the transmission

Reduction ratio: to achieve a complete model of our vehicle, we have to know the gear ratio between the engine and the wheels. (see appended notes on page 12)

R = Nm / Nr



It is the product of two reductions:
The first with the gear and the cogwheel at the engine's output,
The second is at the differentials' gears.

Instructions:

With the instructions provided on page 12, determine the value of the global reduction ratio between the drive shaft and the driving wheels, and enter the value in the model under the "ratio" parameter.

3.2.8

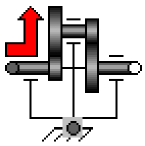
Time required: 15 min

1: 20

Modelling the efficiency of transmission

Mechanical transmission is subject to energy losses, as in any other technical system.
The output power at the wheels is therefore smaller than the power provided by the engine. The difference is dissipated as heat caused by friction of the various mechanisms.

[0,0.6,0.6,0,0]



The efficiency is very difficult to measure, and we will estimate it here at 0.6.

Instruction:

Enter the value in the model (it has to feature twice, for each drive direction).

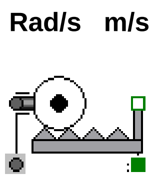
3.2.9

Time required: 15 min

1: 35

Model the transformation of movement between the wheels and the ground.

The wheel on the ground ensures the transformation of the rotation into a linear movement that the vehicle follows. The rotation of the wheel is characterized by an angular velocity in rad/s
The vehicle's translation is characterised by its speed in m/s. We have to determine the ratio between these two parameters: **k = ω / V**



As in both cases, the denominator is in seconds, we have to determine the ratio between the wheel's angle of rotation in radian and the distance travelled by the wheel in meters (see page 12).

Instruction:

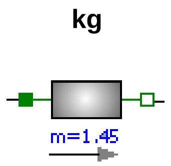
Complete the model when you have determined the ratio.

3.2.10

Time required: 10 min

1:50

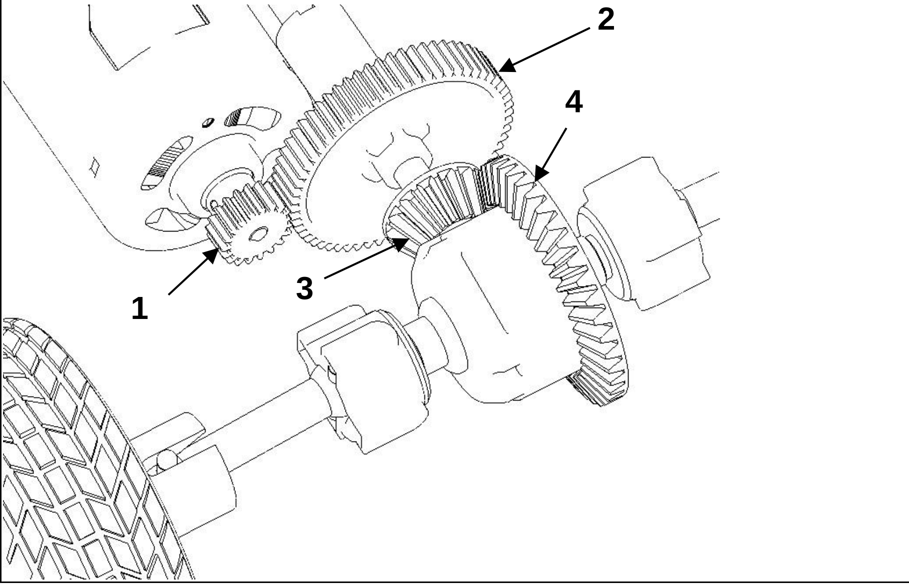
Modelling the mass of the vehicle
We still have to enter the mass of the vehicle



Instruction:

Weigh the fully-loaded vehicle and enter the value in the model as kg.

Reduction ratio



Gear "a":

Z1 = 19 cogs; Z2 = 61 cogs

Gear "b":

Z3 = 15 cogs; Z4 = 39 cogs

Reduction ratios:

$r_a = \omega 2 / \omega 1 = Z1 / Z2$

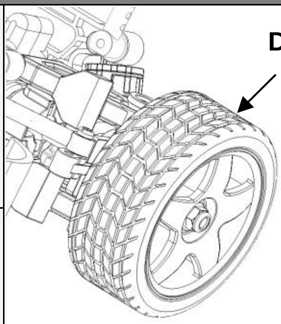
$r_b = \omega 4 / \omega 3 = Z3 / Z4$

with $\omega 2 = \omega 3$

Global ratio: $r_g = r_a . r_b$

Relation between the wheel's rotation angle and the distance travelled.

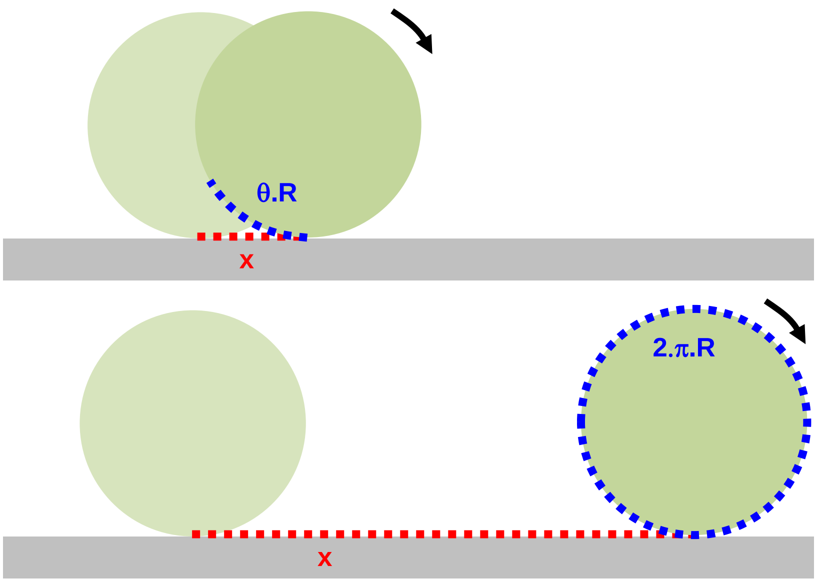
$x = \theta \bullet r$	• x: travelled distance (m) • θ: rotation angle of the wheel (rad) • r: wheel radius (m)



For a full rotation of the wheel: $\theta = 2\pi$ rad,

therefore $x = 2\pi r$

(which corresponds to the perimeter of the wheel)



Additional study modules
(Time required: 1h)

Comparing the virtual and the real models

We still have to validate our model by comparing it to the real model. To do this, we will conduct a series of measurements on the car using the acquisitions' card and draw the Speed and Supply Current graphs.

You will accelerate at full power until you reach top speed and then you will import your measurements in the spread sheet (see the appended Help section)

You will be able to compare the speeds, the currents and the acceleration times.

3.2.11

Time required: 20 min

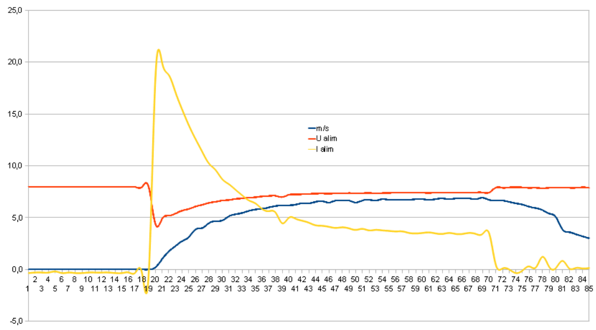
0:00

Measurement on the real vehicle

Question:

Accelerate to full power and record values on the SD card, to draw the required graphs on the spreadsheet (see the Help section on pages 17 and 18).

Required answer model:



3.2.12

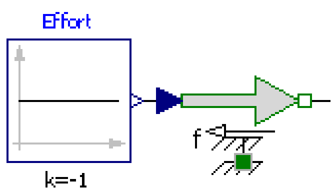
Time required: 10 min

0:20

Adapting the model

Remember: to stay close to reality, you must estimate the traction forc on your vehicle and apply it to the virtual model.

kg



Instructions:

Move your vehicle along the track at constant speed, pulling it with a dynamometer, note the traction force required.
Enter the value in the virtual model (constant)

3.2.13

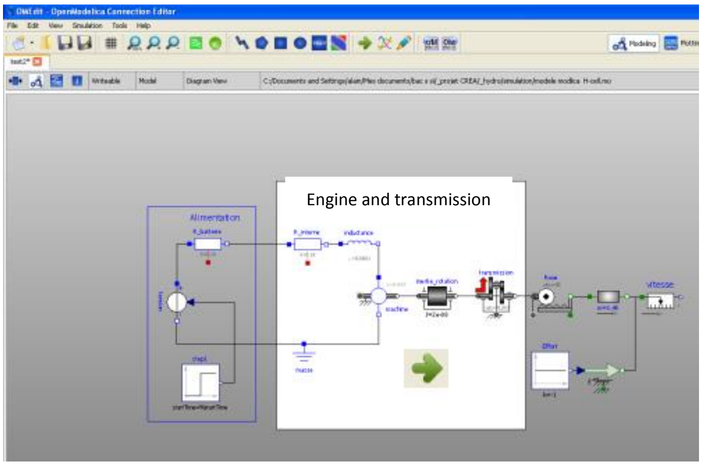
Time required: 15 min

0:30

Simulation with the virtual model

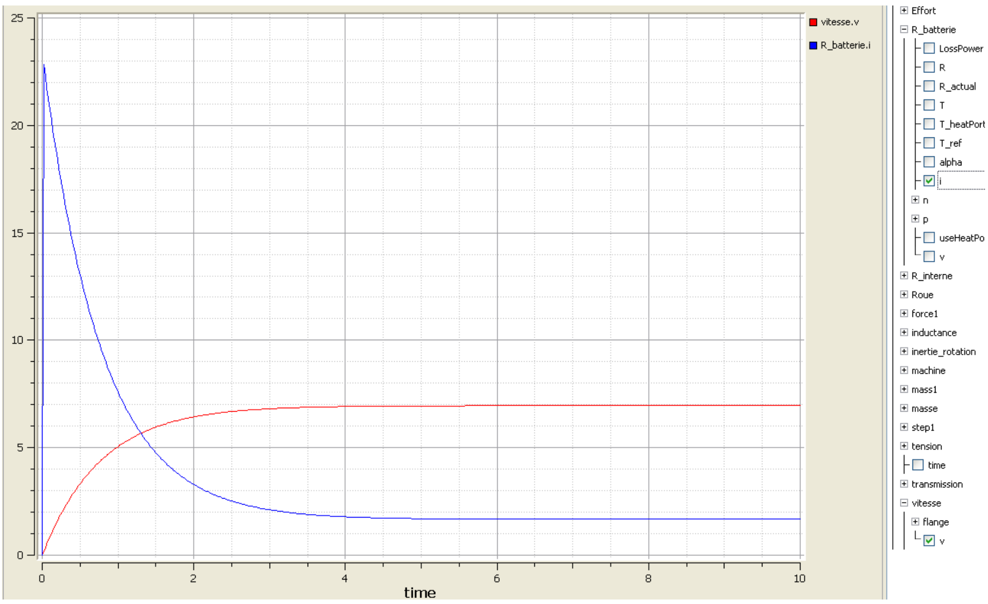
We are now going to ask the simulation software to supply the same speed and current curves as the measured ones, but this time using the virtual model.

Launch the simulation with the green arrow of the tools header, and set the simulation duration at 10s (stop time)



Open the graphs display with the Plotting button: 

Check speed and current to display the graphs



3.2.14

Time required: 15 min

0:45

Simulation with the virtual model

You can now compare your results and validate or reject your model.

Question:

Note the required values on your measurements and compare both sets of values.
(Acceleration ends when the current and speed are stabilised).

Conclusion

Measurement examples:

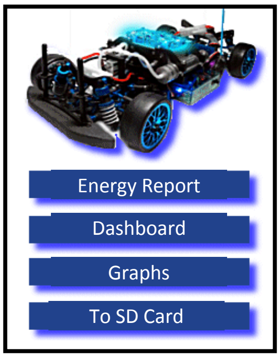
	Max speed (m/s)	Acceleration time (s)	Stall current (Id) (A)	Established current (A)
Real model				
Virtual model				

Conclusion about the validity of the model

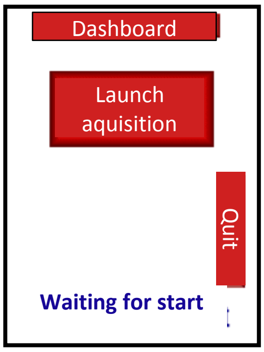
Recording measurements on the SD card

Power up the vehicle and the card using the switch.

1 - The general menu is then displayed



2 - A first screen prompts you to insert the SD card if it's absent.

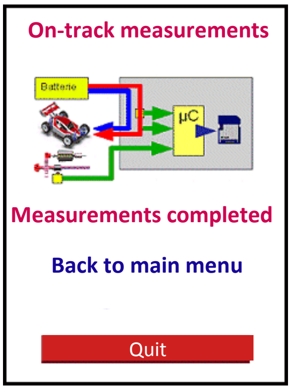


3 - It is then initialized and a new measurement file is created.

4 - You then have to launch the acquisition of measurements.

5 - Data is recorded until you press STOP

6 - The measurements end, and you go back to the menu.



Transferring **files and graphs**

For this operation, use the tutorial on the CD named "Exploiting measurements".

You must now retrieve the data on the SD card to draw your graphs on the spread sheet. You may use the CD's tutorial to get additional information.

Check the content of the SD card on a computer to see all your measurement files.

Open the first one in the latest creation batch with your usual spread sheet (Excel or OpenOffice) and accept tabulation as separator.

You should see something resembling this.

	A	B	C	D	E	F	G
1	0	951	751	960	514	541	493
2	0	951	751	960	514	541	493
3	0	951	751	960	514	540	492
4	0	951	751	960	514	541	493
5	0	951	751	960	514	540	493
6	0	929	742	941	539	543	538
7	3	845	710	890	646	554	601
8	12	815	692	851	697	560	653
9	26	825	696	851	687	555	660
10	45	795	689	837	711	557	671
11	69	772	678	822	746	562	678
12	98	726	665	784	813	567	745
13	135	722	670	783	837	571	780
14	179	725	667	783	817	568	754
15	228	743	667	793	778	567	719
16	281	749	670	797	767	565	710
17	339	770	677	813	739	563	685
18	399	767	659	808	730	551	697

Open the calculation called calcul-TP-modelisation.xls in another window.
Import your measurement data in the file.

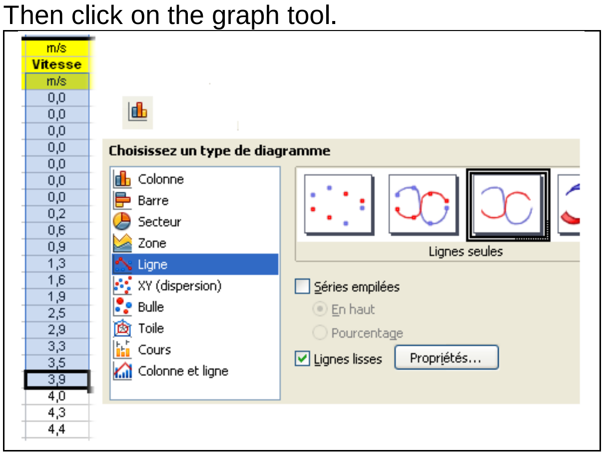
Gross	Gross	Gross	Gross	Gross	Gross	Gross	Seconds	meter	m/s	Km/h	Upower sup.	U cell	U bat	Ipower sup.
Dist	Upower sup.	Ucell	Ubat	Ipower sup.	Icell	Ibat	Time	Distance	Speed	Speed	variator	hydro	battery	variator
									m/s	Km/h	Upower sup.	U cell	U bat	Ipower sup.
0	952	753	960	514	542	492	0,10	0,0	0,0	0,0	7,9	10,1	8,0	0,1
0	952	753	960	513	541	492	0,20	0,0	0,0	0,0	7,9	10,1	8,0	0,0

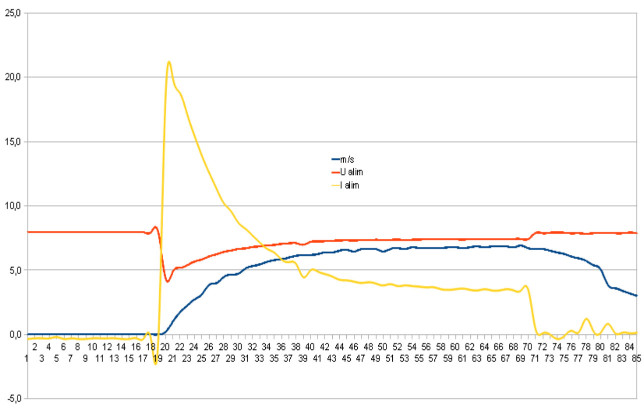
In your measurement file, select all the cells of the measurement table from the top left cell (A1) to the bottom right one in the seventh column. Copy and paste the data in another table under columns ABC.

Tip: open both XLS files and copy the values of the first to paste them in the second (select cell A4 to paste).

Then select the column(s) for which you want to draw the graph(s).

Then click on the graph tool.





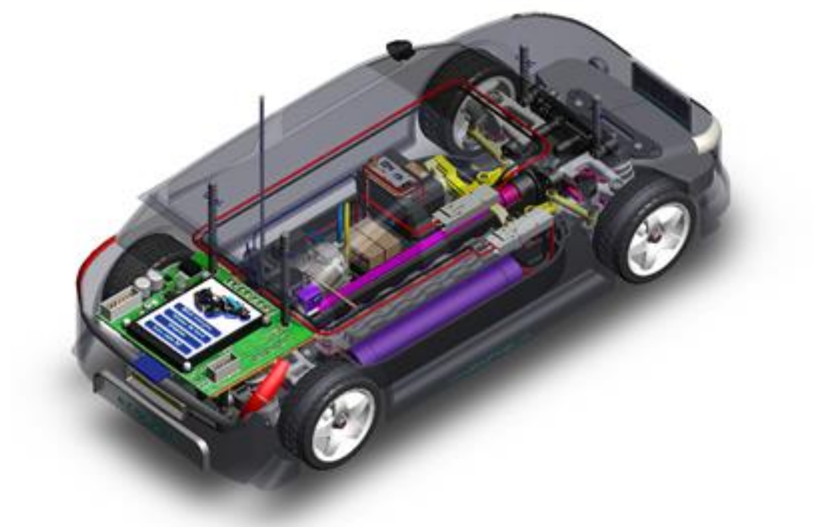
3 - Energy needs

How much energy is required to move the car?

3.3 Making measurements on the track

Full study

Time required: **1h**



Necessary equipment and resources:

Horizon equipment

- **Basic FCAT car with acquisition card**

Objectives:

We will now implement the test in real track conditions, to measure a set of values that we can later use to analyse the car's performance in terms of speed and consumption.

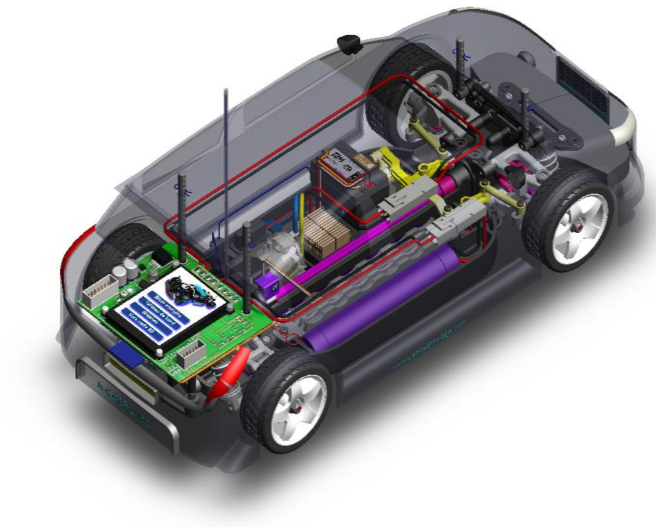
3 - Energy needs

How much energy is required to move the car?

3.4 Making measurements on the charging bench

Full study

Time required: **1h**



Necessary equipment and resources:

Horizon Equipment:

- **Basic FCAT car with acquisition card**
- **Test bench***

Objectives:

In this section we will use the test bench to highlight the exact impact of a certain resistance forms to the car's motion on its performance in terms of speed and consumption

* available as optional equipment

Real testing... on the laboratory track

Is it possible to observe the effects of different forms of resistance on the track?

When conducting measurements in real track conditions, we find ourselves confronted with an analysis problem for interpreting the results: what are the exact impacts of each specific form of resistance on the car's behavior (speed, energy consumption, etc.)? We soon realize that it is impossible to provide an answer to that question. The results give us a view of the total effects, and not of each individual one.

What can we do in laboratory conditions?

A testing bench enables us to measure a specific phenomenon: for instance, in our case study, the effect of inertia on the motion of the car along the track.

By comparing two types of test configurations we can clearly identify, based on our measurements, the exact impact of one particular phenomenon on the car's behavior.

3.4.1

Time required: 5 min

0:05

Exploring the test bench

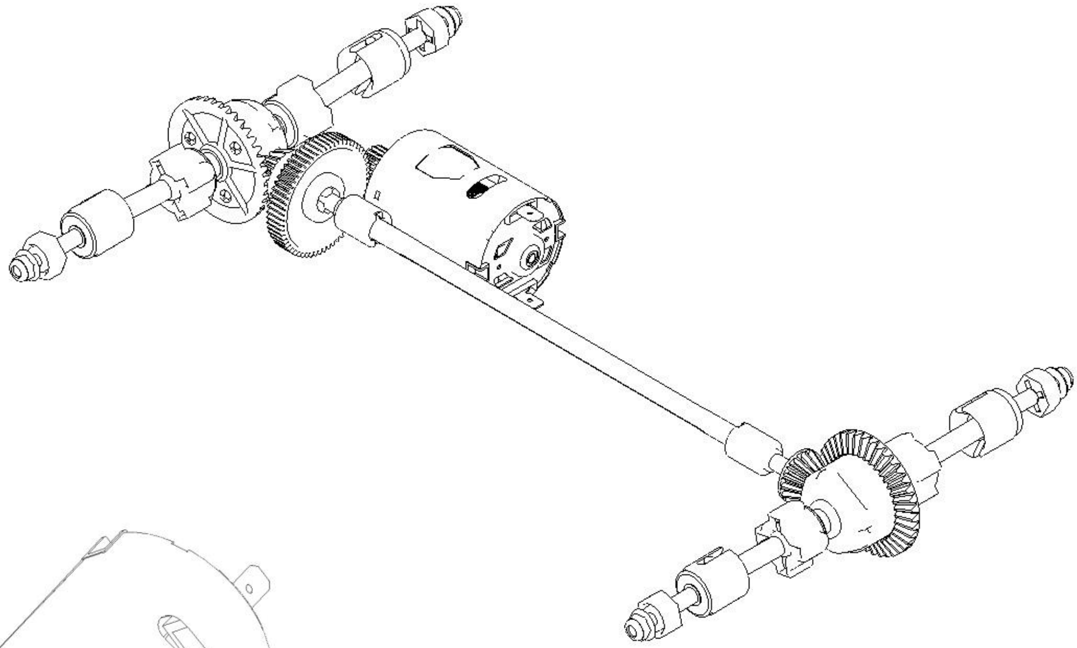
Question:

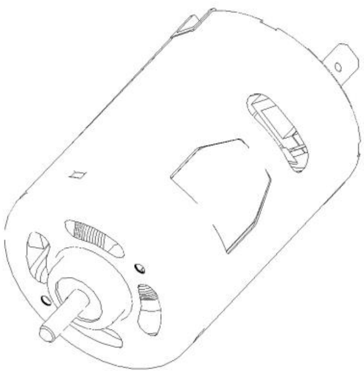
Observe the equipment used to test the car on a laboratory bench, along with its specifications, bearing in mind that controls are only implemented with the acquisition card.

On the drawings below, indicate the areas that have an inertia value equivalent to that of a car moving around a track:

A: applied to the drive shaft (label to copy and paste: A)

B: applied to the driving wheels' axle (label to copy and paste: B)





3.4.2

Time required: 10 min

0:10

Identifying the phenomena that can be studied

Question:

Mark with an x* in the following table the phenomena taken into account for various car testing configurations, in laboratory conditions or on a flat horizontal track. The first two lines have already been completed. (tip: proceed by column)

* or color/shade in the box (format - border and pattern,...)

	Aerodynamic resistance	**Rolling resistance tires/track**	**Friction** *transmission alone*	**Internal losses of the engine**	**Rotation inertia** *transmission alone*	**Rotation inertia** *internal to the engine*	**Translation inertia** *of the car*
A - No-load engine alone							
B - Engine alone with inertia flywheel							
C - Car on bench without load							
D - Car on bench with flywheel							
E - Car on the track							

3.4.3

Time required: 5 min

0:20

Possible comparisons and their interpretations

Question:

Based on your answers from the previous section, explain in which case it is possible to highlight these phenomena, using the comparisons given below.

Comparisons	Highlighted resistance phenomena
Test A / Test B	
Test C / Test D	
Test D / Test E	
Test B / Test D	

Time required: 25 min

3.4.4

0:25

The results of comparative studies

Question:

Indicate below the performance loss values in terms of acceleration time and energy consumptions at top speed and during engine start.

Highlighted resistance	Induced loss of time during acceleration (sec)	Over-consumption induced at top speed (Amps)	Over-consumption induced during engine start (Amps)
Total inertia values: while transmission parts are rotating and during the car's translatory motion			
Friction within transmission alone			
Translatory inertia of the scale model			
External resistance: aerodynamic resistance and friction of tires on track			

3.4.5

Time required: 10 min

0:50

Final result

Question:

Draw your conclusions regarding the priorities to follow in this case, in terms of ways to improve the system and to make it more efficient in terms of speed and consumption

Real behavior at constant speed or during acceleration

Different types of resistance to movement:

Without any resistance to movement, we drive the vehicle without any power. Of course, this doesn't exist in reality. While moving, the car faces a certain amount of resistance to motion, and we will now examine its impact on speed and consumption.

The measurement device used:

The car is fitted with a data acquisition card that measures variables such as the speed, electric current consumed, or the power of the engine.

3.3.1

Time required: 20 min

0:05

Behavior of the car as it accelerates, and then travels at top speed, on a flat horizontal track.

Question:

Acquire general data concerning the behavior of the car during a test on a flat horizontal track, from 0 to Vmax, having maintained the car at top speed over a given distance.

Total travelled distance (m)	
Top speed (km/h)	
Average speed (km/h)	
Max absorbed power (W)	
Acceleration (n x g m/s²)	
Average absorbed power (W)	
Expended energy (J)	

3.3.2

Time required: 15 min

0:25

Data transfer to a computer

Question:

Repeat the test, for the purpose of transferring the data to a computer as a spreadsheet.

To do this, copy the test file from your computer.

Describe below the various parameters that can be used to directly display the changes through time.

3.3.3

Time required: 20 min

0:40

Interpreting the results

Question:

Use the results to display the change of current consumption through time and the power of the the propulsion engine both during the acceleration phase and the top speed phase.

Paste the graphs and add any comments that would help interpret them.