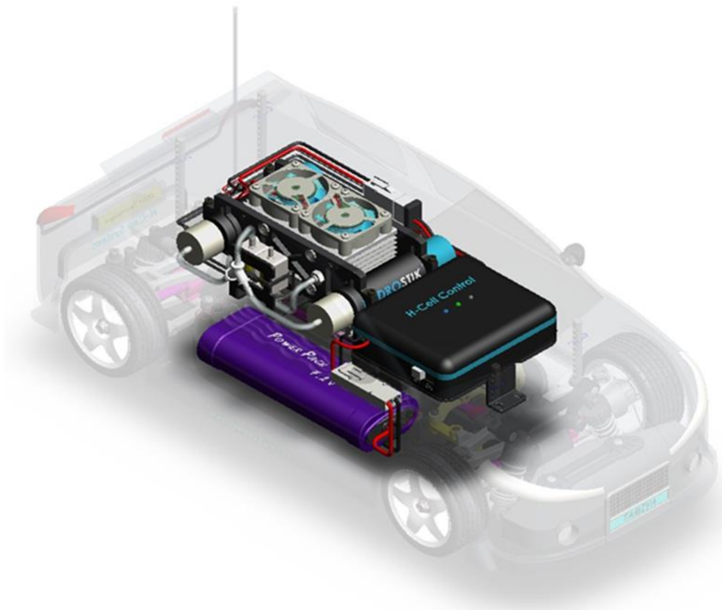
4 – System adaptability

Can the H-Cell system, under maximum load, replace the car's batteries and still provide the same performance levels?



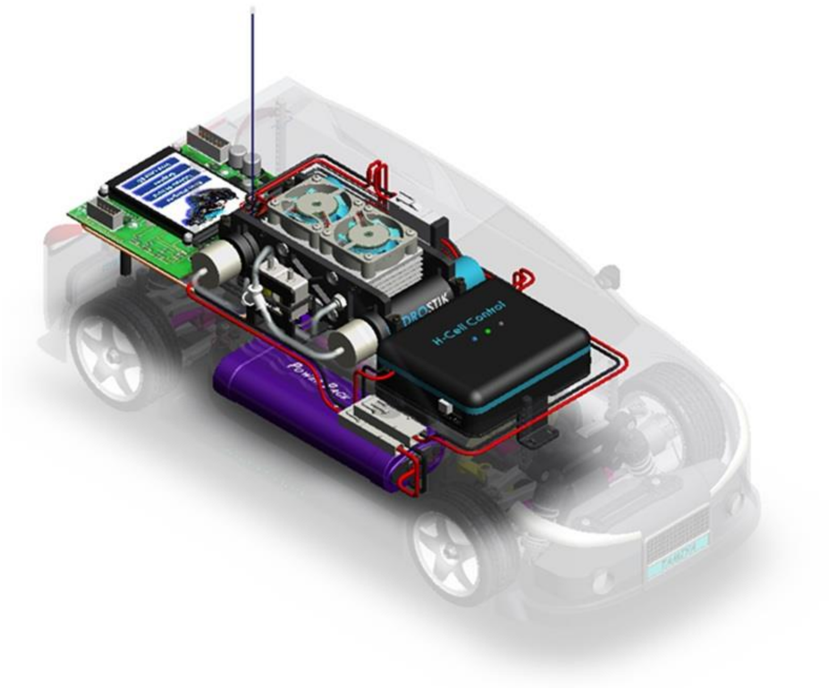
4 – System adaptability

Can the H-Cell system, under maximum load, replace the car's batteries and still provide the same performance levels?

**4.1
Providing power**

Full study

Time required: **1h**



Necessary equipment and resources:

Horizon Equipment:

- **FCAT H-Cell car**

Objectives:

In this activity, we will run simulations and conduct tests of various situations on a car fitted with the H-Cell system, in order to determine the car's ability to cope with a range of work requirements in terms of speed and energy consumption. In other words, we will determine whether the available power gives us full driving capabilities.

Excerpt of technical documents and the scope of work

Vehicle's features taken into account for the calculations:

Masses:

Of the basic model without battery: 1500 g
Of the H-Cell system: 730 g

Tires:

Resistance to rolling: δ = 0.2 mm

Bodywork

Cx = 0.35
Sp = 0.02 m²

Internal losses:

Overall efficiency (engine + transmission) 0.5

Required speed performance

Top speed:

24 km/h min on flat ground
15 km/h min on 15-degree slope

Acceleration:

Acceleration time from 0 to Vmax on flat ground: 5s max

4.1.1

Time required: 10 min

0:00

Here we consider the car moving at top speed (24 km/h) on flat ground.

Question:

Open the "Puissances absorbées.xls" file to display the various forms of power that the engine must generate to overcome the various forms of resistance encountered in our setting.

Absorbed Power

Data to enter

M	2.2	Kg
G	9.81	m/s^2
Vmax	6.66	m/s
Overall efficiency	0.5	
Declivity of slope to climb	15	degrees
Resistance to rolling	0.002	m
Wheel radius	0.028	m
Air density	1.293	Kg/m^3
Sp	0.02	m^2
Cx	0.35	
Required acceleration duration	4	s

Indicate the calculated power in the following table, and mark the results that do not involve any power with an x.

	Resistance to rolling tires/track to overcome	Wind resistance to overcome	Slope to climb (15 degrees)	Time for the acceleration from 0 to Vmax to achieve
Power the engine must provide (W)	20.53	2.67	x	x
Total power the engine must provide: 23.2 W				

4.1.2

Time required: 10 min

0:10

Here we consider the car moving at top speed of 20 km/h (5.55 m/s) on a 15-degree slope.

Question:

Open the "Puissances absorbées.xls" file to display the various forms of power that the engine must generate to overcome the various forms of resistance encountered in our setting.

Absorbed Power

Data to enter

M	2.2	Kg
G	9.81	m/s^2
Vmax	5.55	m/s
Overall efficiency	0.5	
Declivity of slope to climb	15	degrees
Resistance to rolling	0.002	m
Wheel radius	0.028	m
Air density	1.293	Kg/m^3
Sp	0.02	m^2
Cx	0.35	
Required acceleration duration	4	s

Indicate in the following table the calculated power, and mark the results that do not involve any power with an x.

	Resistance to rolling tires/track to overcome	Wind resistance to overcome	Slope to climb (15 degrees)	Time for the acceleration from 0 to Vmax to achieve
Power the engine must provide (W)	17.11	1.55	62	x
Total power the engine must provide: 80.66 W				

4.1.3

Time required: 10 min

0:20

The balance of changes at a constant speed on flat ground or on a slope
The fuel cell alone can provide 10 Volts under 3 Amps

Question:

Calculate the value of the corresponding power.
What conclusion can you draw regarding the top speed on flat ground or on a 15-degree slope? (explain your reasoning clearly, using schematics and graphs if necessary)

P_{cell} = 3 * 10 = 30 W
Conclusion: This power may be suitable for traveling 24 km/h on level ground, but not in the case of accelerating to 20 km/h on a slope of 15 degrees.

4.1.4

Time required: 10 min

0:30

We will now consider the vehicle as it accelerates from 0 to Vmax on flat ground. First we simply want to establish an order of magnitude for the power required in various situations (without achieving high accuracy) and for this first study we will consider acceleration on flat ground:

- A "Vmax" top speed reached at the end of the acceleration phase: 24 km/h
- The required acceleration time: 4 s

Important: the engine's actual efficiency is very poor during the initial phase as it needs a lot of current, especially at the moment is starts moving, and it's therefore difficult to establish an accurate theoretical approach to this problem. We will consider here an average overall efficiency value of 0.1 for the engine start simulation.

Question:

In a spreadsheet, use the "Puissances absorbées.xls" file to display the various forms of power that the engine must produce to meet the various forms of resistance encountered in our setting.

What conclusions can you draw in this instance regarding the power provided by the fuel cell alone?

Indicate in the following table the calculated powers, and mark the results that do not involve any power with a cross.

	To achieve an acceleration time from 0 to Vmax of 4s
Average power generated by the engine (W)	121
Conclusion: The power generated by the fuel cell is insufficient in this case.	

4.2.5

Time required: 20 min

0:40

Additional analysis of track measurements

Question:

Use the result of various test measurements* performed on the track for the TAMIYA TT-01 car loaded with 2200 g and fitted with track tires.

What conclusions can you draw regarding the relevance of previous theoretical estimates?

*defined in the following table

	V max (km/h)	Average P (W)
Test 1: **Acceleration from stationary start**		
Test 2: **Top speed (flat ground)**		
Test 3: **Top speed (15-degree ramp)**		
Conclusion:		

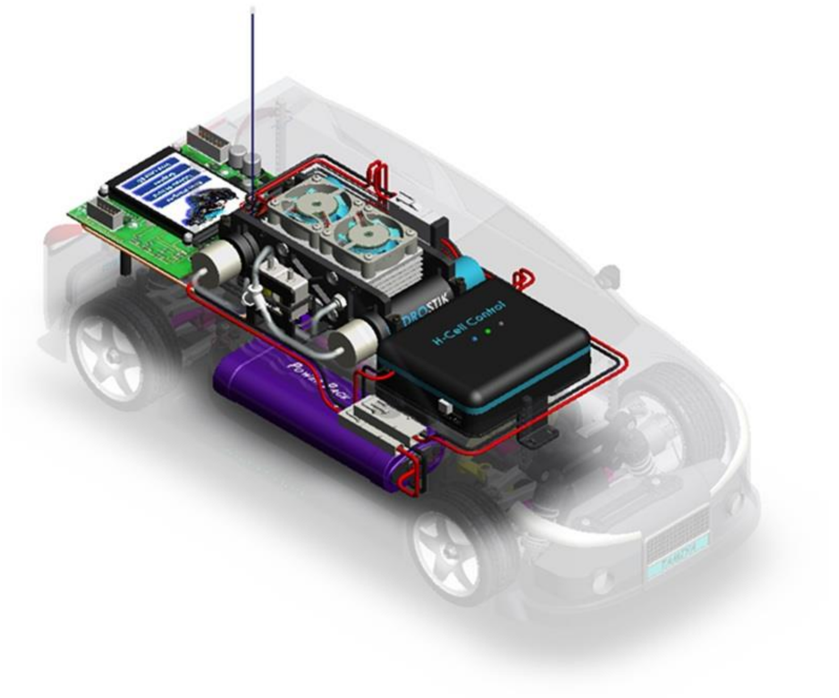
4 – System adaptability

Can the H-Cell system, under maximum load, replace the car's batteries and still provide the same performance levels?

4.2
H-Cell power

Full study

Time required: **1h**



Necessary equipment and resources:

Horizon Equipment:

- **FCAT H-Cell car**

Objectives:

In this activity, we will conduct preliminary simulations and real experiments in various situations on a car fitted with the H-Cell system in order to determine the car's capacity to meet operation requirements such as minutes of functioning at top speed or number of possible starts from 0 to Vmax. In other words, we will determine whether a satisfactory amount of power is stored on board the vehicle in the battery and Hydrostik cartridges.

Excerpt from technical documents on the specifications of the system

Vehicle's features taken into account for the calculations:

Masses:

Of the basic model without battery: 1500 g
Of the H-Cell system: 700 g

Tires:

Resistance to rolling: δ = 2 mm

Bodywork:

Cx = 0.35
Sp = 0.02 m^2

Internal losses:

Overall efficiency (engine + transmission):

0.5 at top speed
0.1 during startup (average value, approximative)

4.2.1

Time required: 10 min

0:05

Here we consider the car moving at top speed (24 km/h) on flat ground.

Question:

In a spreadsheet, use the "Energies consommées.xls" file to see the various forms of energy that the engine uses to overcome the various forms of resistance encountered in our setting.

Absorbed Power

Data to enter ↓

m	2.2	Kg
g	9.81	m/s^2
Vmax	6.66	m/s
Overall efficiency	0.5	
Declivity of slope to climb	0	degrees
Resistance to rolling	0.002	m
Wheel radius	0.0325	m
Air density	1.293	Kg/m^3
Sp	0.02	m^2
Cx	0.035	
Required autonomy at Vmax	3600	s
Required number of starts	0	

Indicate the corresponding energy values in the following table, and mark the results that do not involve any energy with a "0".

Required autonomy at top speed: 1 hour, or 3600 seconds				
	Resistance to rolling tires/track to overcome	**Wind resistance to overcome**	**Slope to climb (0 degrees)**	**Inertia to overcome for acceleration**
Energy used by the engine (J)	63,686	9625	0	0
Total energy used by the engine: 16,966 Joules				

4.2.2

Time required: 10 min

0:15

Here we consider the car moving at top speed of 20 km/h (5.55 m/s) on a 15-degree slope.

Question:

In a spreadsheet, use the "Eneregies consommées.xls" file to see the various forms of energy that the engine uses to overcome the various forms of resistance encountered in our setting.

Absorbed Power

Data to enter

m	2.2	Kg
g	9.81	m/s^2
Vmax	6.66	m/s
Overall efficiency	0.5	
Declivity of slope to climb	0	degrees
Resistance to rolling	0.002	m
Wheel radius	0.0325	m
Air density	1.293	Kg/m^3
Sp	0.02	m^2
Cx	0.035	
Required autonomy at Vmax	3600	s
Required number of starts	0	

Indicate the corresponding energy values in the following table, and mark the results that do not involve any energy with a cross.

Required autonomy at top speed: 30 minutes, or 1800 seconds				
	Resistance to rolling tires/track to overcome	**Wind resistance to overcome**	**Slope to climb (15 degrees)**	**Inertia to overcome for acceleration**
Energy used by the engine (J)	26 ,535	2785	111,604	0
Total energy used by the engine: 140,924 Joules				

4.2.3

Time required: 5 min 0:25

The balance of energy changes at constant speed on flat ground or on a slope

Question:

The energy that the H-cell system can provide alone, with two fully-charged Hydrostik cartridges, is of 100 000 joules.

What conclusion can you draw regarding the required running time on flat ground or on a 15-degree slope?

The energy that the H-Cell system alone can provide is sufficient to meet our needs on level ground, but not on a 15-degree slope.

4.2.4

Time required: 10 min 0:30

We will now consider the vehicle as it accelerates from 0 to Vmax on flat ground.

For now, we simply want to establish an order of magnitude for the power required in various situations (without high accuracy) so at first we will consider acceleration on flat ground:

- A "Vmax" top speed reached at the end of the acceleration phase: 24 km/h (6,66 m/s)

Important: the engine's actual efficiency is very poor during the starting phase as it needs a lot of current, especially at the moment is starts moving, and it's therefore difficult to establish an accurate theoretical approach to this problem. We will consider here an average overall efficiency value of 0.1 for the engine-start simulation.

Question:

With a spreadsheet, use the "Energies consommées.xls" file to indicate in the following table the energy value necessary to perform 50 accelerations.

What can be said, purely theoretically, about this quantity of energy?

Required running: 50 accelerations 0 to V max	
Energy used by the engine (J) for an average overall efficiency of 0.1	**24,395**

4.2.5

Time required: 20 min

0:40

Additional analysis of track measurements

Question:

Use the result of various test measurements* performed on the track for the FCAT car with a 2200g load and fitted with track tires.

What conclusions can you draw regarding the relevance of previous theoretical estimates?

*defined in the following table

	V max (km/h)	Average Power (W)	Test duration (s)	Expended energy (J) (to be calculated)
Test 1: **Acceleration from stationary start**				
Test 2: **Top speed/flat ground**				
Test 3: **Top speed/15-degree ramp**				

Conclusion:

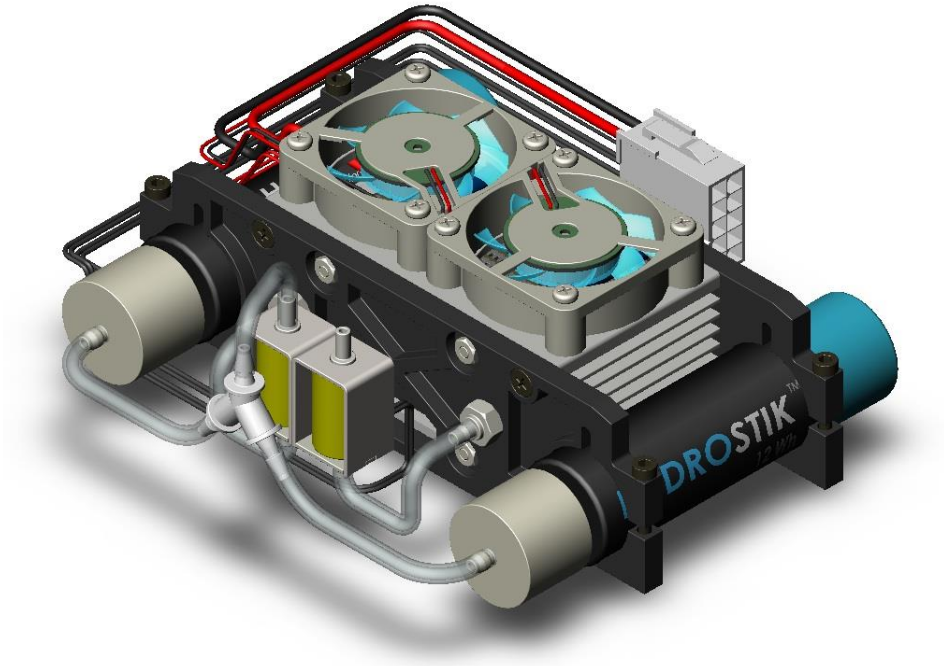
4 – System adaptability

Can the H-Cell system, under maximum load, replace the car's batteries and still provide the same performance levels?

4.3 Influence of the arrangement of the components of the fuel cell

Full study

Time required: **1h**



Necessary equipment and resources:

Horizon Equipment:

- **H-Cell system**

Objectives:

In this activity, we use the spreadsheet detailing the simulation results for the car at top speed or during its acceleration phase to determine the ideal conditions for the fuel cell to provide power to the car's propulsion system, and to check whether these conditions remain within the tolerances imposed by the energy requirements.

Power, voltage, and current consumed

Without resistance to motion, the power the engine has to exert would be zero, but according to the magnitude of resistance, this value will only increase. How does this affect the supply of voltage and the current consumed?

The voltage "V" (Volts) depends solely on the technology of the power supply, in this case a battery or a fuel cell. Therefore, its value doesn't vary according to the amount of resistance.

The intensity "I" (Amps) of the current consumed, however, depends on the resistance load applied to the drive shaft. Without resistance, the intensity would be zero (which is impossible as there are always areas that are subject to resistance phenomena, even inside the engine). At the moment the engine starts, or if the drive shaft is blocked, the value of this intensity is at its maximum.

It should be noted here that the product of "V" and "I" gives us the value of the power "P" (Watts) exerted by the engine. This means that based on the power and supply voltage values, it is easy to determine the current consumed.

$$I = P / V$$

- **<u>at constant speed:</u>**

  Power the engine has to exert to overcome resistance to motion:

  $P = F \cdot v / \eta$,

  therefore

  $I = (F \cdot v / \eta) / V$

- **<u>during acceleration:</u>**

  Average power the engine has to exert to overcome resistance to motion:

  $P_{average} = F_{average} \cdot v_{average} / \eta$,

  therefore

  $I = (_{average} \cdot v_{average} / \eta) / V$

- **F (Newton): resistance force (see documents…)**
- **v (m/s): speed of the vehicle**
- **η: overall efficiency (engine + transmission)**

4.3.1

Time required: 05 min

0:10

Engine supply voltage

First let's examine the manufacturer's data on the direct current engine used for the car's propulsion (maker's document: Mabuchi RS-540SH-7520 engine), as well as the features of the battery that provides the power supply.

Questions:

A – Under what maximum voltage can the engine run?

B – What would happen generally if the voltage were insufficient?

V engine = 7.2 V
Power would be lost, as well as speed and torque

4.3.2

Time required: 10 min

0:20

Voltage that the fuel cell can supply

Questions:

Having examined the data provided on pages 6 and 7, answer the following questions:

A - What is the maximum width "w" available to us based on the specifications of the fuel cell?

B - What cell width is needed to provide at least 7.2 V? How many elements does it correspond to?

C - Conclusion

A - w max = 70 mm
B - w required = (7.2 / 0.7)*3 = 30.85 mm **Number of elements: 10 (p = 30 mm) or 11 (p = 33 mm)**
C - Conclusion: **30.85 mm <70, the battery can therefore provide 7.2V maximum**

4.3.3

Time required: 15 min

0:30

Current consumed by the engine

Questions:

A - In a spreadsheet (S3-Puissances absorbées.xls) note the motion resistance force values and corresponding power (average values in case of acceleration) for the specific case of operating modes mentioned in the following table to fill in. Calculate the corresponding intensity and consumed current values.
(reminder: P = I•V)

Absorbed Power

Data to enter

m	**2.2**	Kg
g	**9.81**	m/s^2
Vmax	**6.66**	m/s
Global efficiency	**0.5**	
Declivity of slope to climb	**15**	degrees
Resistance to rolling	**0.002**	m
Wheel radius	**0.028**	m
Air density	**1.293**	Kg/m^3
Sp	**0.02**	m^2
Cx	**0.35**	
Required number of starts	**4**	s

(mass of the vehicle with H-Cell system, without accumulator)

B – In general, what would happen if the cell or the batteries failed to provide this value?

	at constant speed equal to 24 km/h (6.66 m/s)		**at engine start, from 0 to 24 km/h in 4 s**
	Flat ground	**15-degree slope**	**Flat ground**
P_{abs} (W)	**21.15**	**88.12**	**$P_{abs\ average}$ = 21.96**
I (A)	**21.15 / 7.2 = 2.93 A**	**88.12 / 7.2 = 12.2 A**	**$I_{average}$ = 21.96 / 7.2 = 3.05 A**

Power would be lost, as would speed and torque.

4.3.4

Time required: 05 min

0:45

Current consumed by the engine upon starting

Questions:

A - In the documents provided by the manufacturers (Mabuchi RS-540SH-7520 engine) find the value of the current the engine consumes upon starting, which is described as "Id" (Stall current).

B - What would happen generally if the cell or the batteries failed to provide this value?

Id = 70 A

Power would be lost, as in speed and torque. In other words, the car would be less energetic at the start time.

4.3.5

Time required: 10 min

0:50

Current that the fuel cell can supply

Questions:

A - What max area (w x l) does the element have according to the specifications?

B - What max intensity would it correspond to, considering that it is proportional to the area?

C - Draw a qualitative conclusion about the theoretical performance of the car, if the engine were only powered in energy by the fuel cell.

A - **S max = 70 * 20 = 1400 mm²**

B- **I max = 3 * 1400 / (64 * 20) = 3.28 A**

Conclusion:

This current is not sufficient under the following conditions:

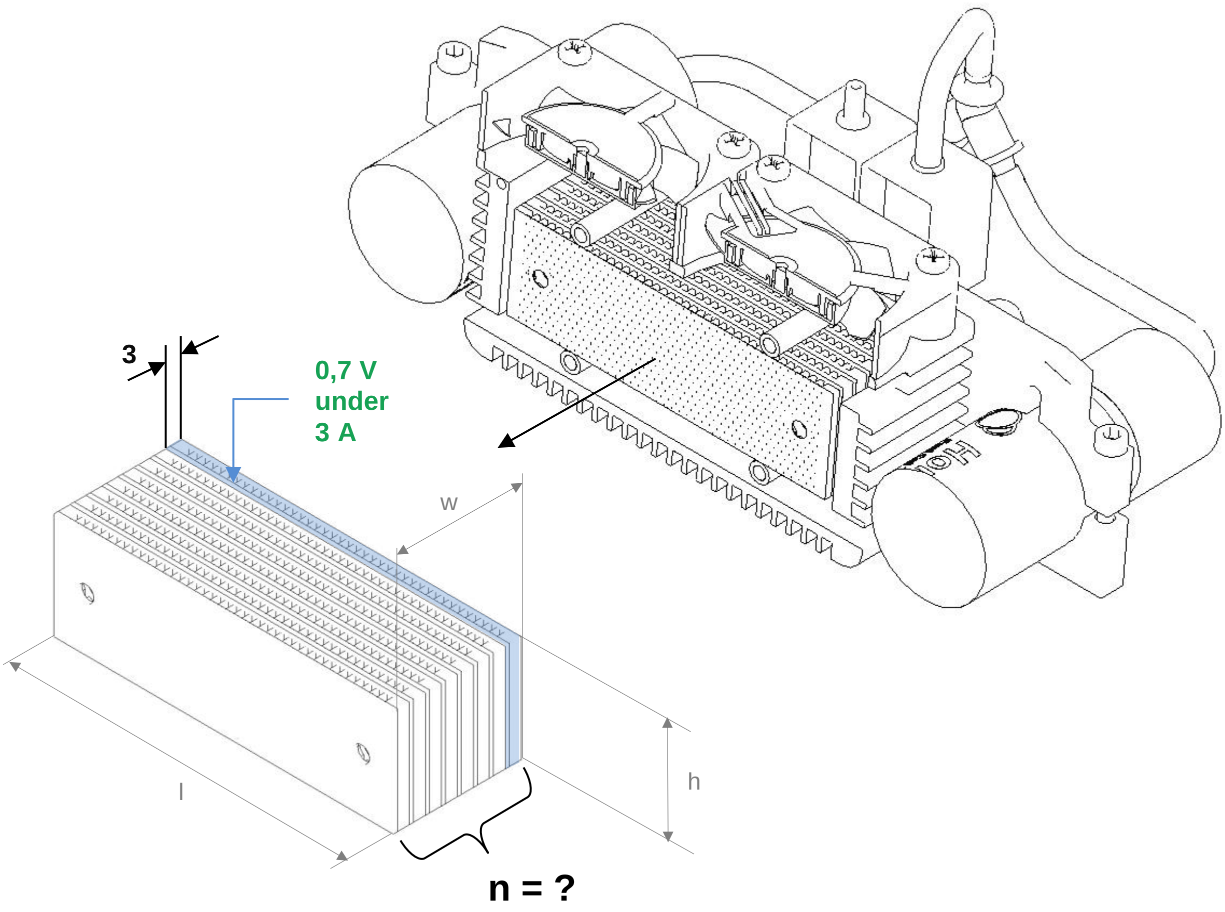
On a slope at 15 degrees accelerating to 24 km / h

At start time

Features of a fuel cell element:

The fuel cell is a stack of "n" elements that are defined by the required overall voltage.

Each element can provide, according to the specifications given by the manufacturer for a size of 64 x 20 x 3 mm » (l x w x h), a voltage of 0.7 V under 3 A.

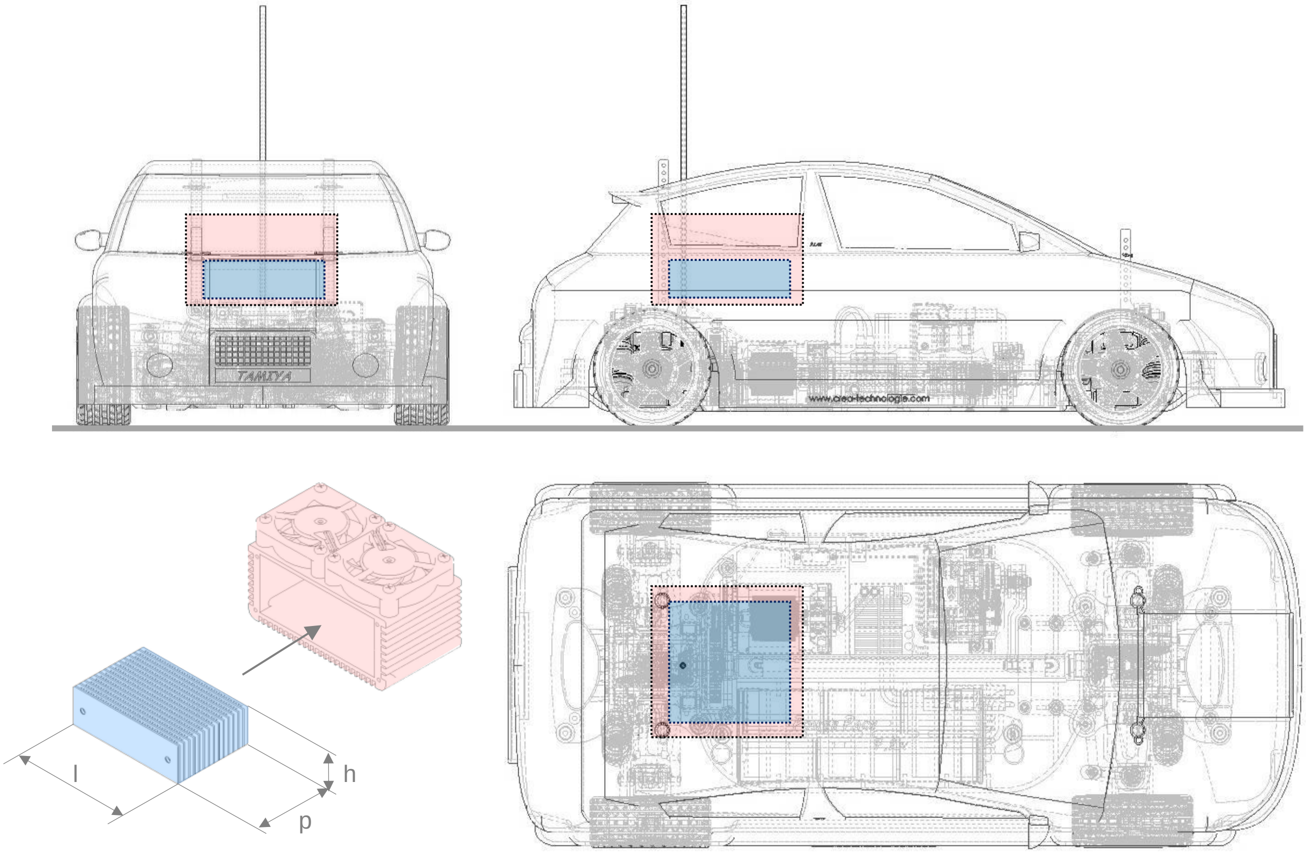


Extracts from specifications:

Size limit of the fuel cell

The size and the arrangement of the fuel cell at the rear of the car must meet the following conditions:

- The size limit of the fuel cell and its housing are represented respectively in blue and pink in the drawing below.
- For the fuel cell: the size must be contained, as a maximum, within the limits imposed by the space available between the bodywork and the chassis, within the size 70 x 20 x 70 (l x w x h) mm.



H-Cell project - Scale: 1 : 4

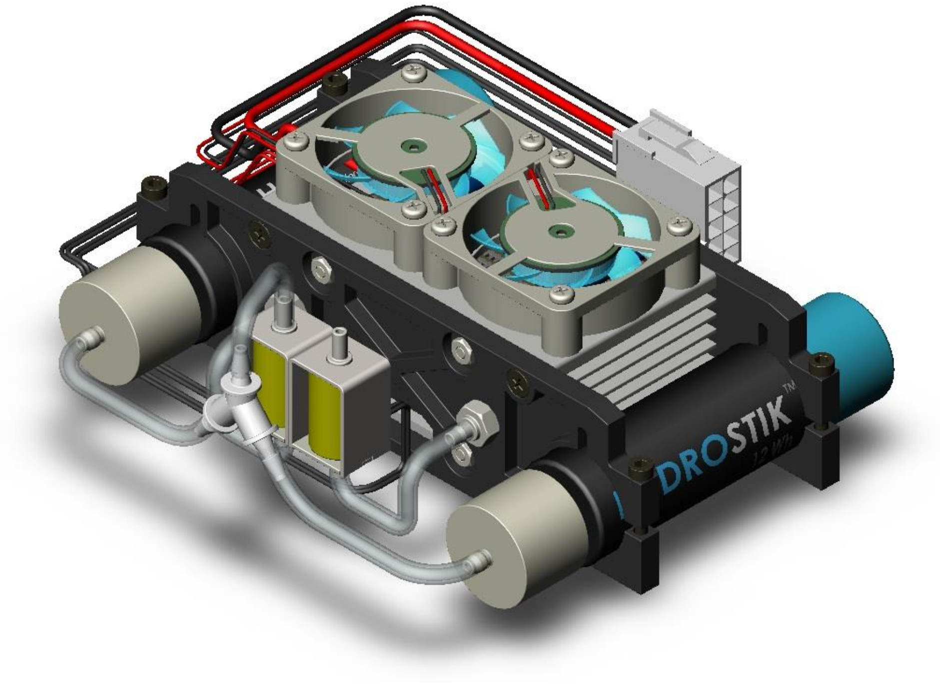
4 – System adaptability

Can the H-Cell system, under maximum load, replace the car's batteries and still provide the same performance levels?

4.4 Effects of the arrangement of the Hydrostiks

Full study

Time required: **1h**



Necessary equipment and resources:

Horizon Equipment:

- **H-Cell system**

Objectives:

In this activity, we use the spreadsheet detailing the simulation results on the car at top speed or during its acceleration phase to determine the number of Hydrostik cartridges that would be sufficient to provide the electric power to the car's propulsion system, ensuring a certain running time, and to check whether it's possible to install such devices in the car, considering the limits of the car's specifications.

Energy to consume, quantity of hydrogen to store

The quantity of hydrogen to store on board the vehicle can be described as the amount of energy that can be expended.

For each cartridge, the quantity of stored energy is expressed as Watt-hour (Wh). The calculation of the corresponding energy relies on the conversion of hours into seconds:

1 W • 1hr = 1 W • 3600 s, i.e. 3600 Joules

It's worth noting here that the bigger the amount of energy stored on board, the greater the vehicle's range (expressed as maximum travelling time or maximum distance).

The energy consumed by the vehicle while driving can be expressed according to the power expended by the engine and the time required for the distance:

$$E = P_{abs} \cdot t$$

- **At constant speed:**

  Power the engine has to expend to overcome resistance to motion:

  $$P_{abs} = F \cdot v / \eta,$$

  therefore

  $$E = F \cdot v \cdot t / \eta \quad \text{or} \quad E = F \cdot d / \eta$$

- **During acceleration:**

  Average power the engine has to absorb to overcome resistance to motion:

  $$P_{abs\ average} = F_{average} \cdot v_{average} / \eta,$$

  therefore

  $$E = F_{average} \cdot v_{average} \cdot t / \eta \quad \text{or} \quad E = F_{average} \cdot d / \eta$$

  - F (Newton): force of resistance to motion (see documents…)
  - v (m/s): speed of the vehicle
  - d (m) distance travelled
  - η: overall efficiency (engine + transmission)

- **Concerning the complexity of engine efficiency:**

  The optimal engine efficiency here is around 70% for a given rotational speed. Except for the starting phase, this efficiency is not constant and varies between 0% and reaches a very low average value, which is difficult to calculate. Therefore, for the purpose of this analysis, only a simulation of running at top speed will be calculated, to maintain the simplicity of the theoretical approach.

4.4.1

Time required: 05 min

0:10

Energy stored in a cartridge

A Hydrostik cartridge contains 12 Wh, which represents the amount of energy the H-Cell system that would derive from it.

Question:

What quantity of energy, expressed in Joules, corresponds to the value?

12 * 3600 = 43,200 J

4.4.2

Time required: 10 min

0:15

Energy required to move the vehicle

Questions:

In a spreadsheet (S1-Effort-propulsion.xls) note the value of the force of resistance to motion (average value in case of acceleration), for the specific operating cases mentioned in the table below, to fill in, by calculating the corresponding required energy value.

Required effort for propulsion

Data to enter

mass of the car "m"	1.98	Kg
Gravitational constant "g"	9.81	m/s^2
Maximum speed considered for calculations "Vmax"	6.66	m/s
Declivity of slope to climb	15	degrees
Resistance to rolling	0.002	m
Wheel radius	0.028	m
Air density	1.293	Kg/m^3
Sp	0.02	m^2
Cx	0.35	
Required acceleration duration	4	s

(mass of the vehicle with H-Cell system, without accumulator)

	at constant speed		upon starting from 0 to Vmax in 4s,
	Flat ground at 24 km/h	15-degree slope at 24 km/h	Flat ground Vmax = 24 km/h
F (N)	1.59 N	6.62 N	$F_{average}$ = 3.3 N
E (J)	For 10 km travelled: 15,900 J	For 10 km travelled: 66,200 J	For one start 33 J

4.4.3

Time required: 10 min

0:25

Number of cartridges to carry to reach a given range at constant speed.

The range we would like to have:

> 10 km at a constant speed of 24 km/h on flat ground, which represents approximately 16,000 Joules of energy provided to the vehicle.

For storage purposes, we consider the following efficiencies for the propulsion system:

- Transmission: 80 %
- Mabuchi RS-540 engine: supposed operation at maximum efficiency, taken from the manufacturer's document on page 6

Questions:

A – Calculate the value of the overall efficiency: "engine" + "Transmission"

B - How much energy must one store for the overall efficiency, considering that the energy needed for the vehicle to cover 10 km is 16,000 J?

C - What would then be the ideal number of Hydrostick cartridges to carry to satisfy this range requirement alone?

A : Overall efficiency = 0.8 * 0.68 = 0.544
B : E = 16,000 / 0.544 = 29,411 J
C : Nb =29,411 / 43,200 = 0.68 or 1 cartridge

4.4.4

Time required: 25 min

0:35

Arrangement of Hydrostik cartridges

Let's consider an endurance race with no resupplying stations, which the car has to travel at constant speed or with accelerations on flat or sloped ground. We have calculated the stored amount of energy for this case: 160,000 J

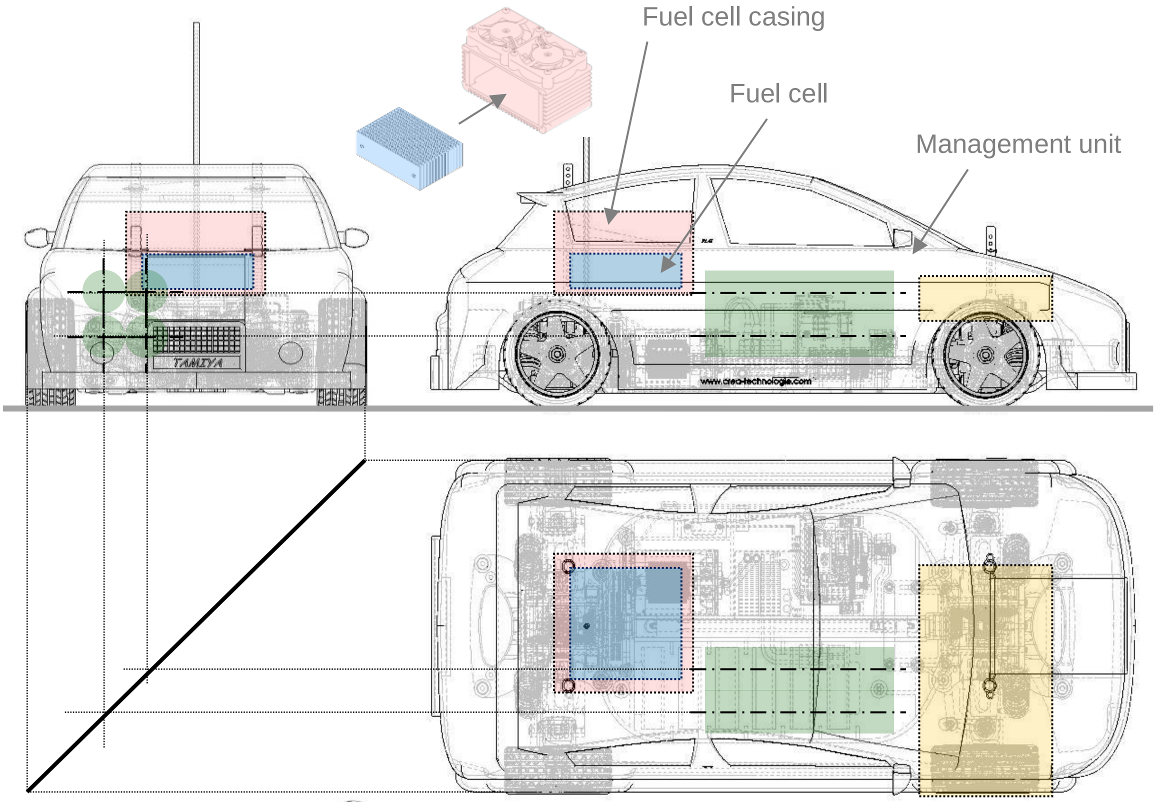
Questions:

A - In this case, calculate the required number of Hydrostik cartridges.

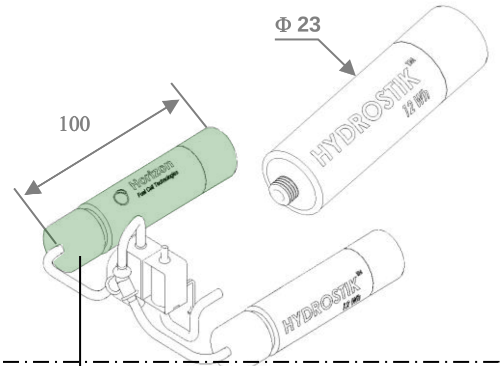
B - On the following page, in the form of a 1:4 scale drawing, suggest a general arrangement idea for the cartridges keeping in mind the maximum size specification imposed by the specifications (coloured surface cannot be used).

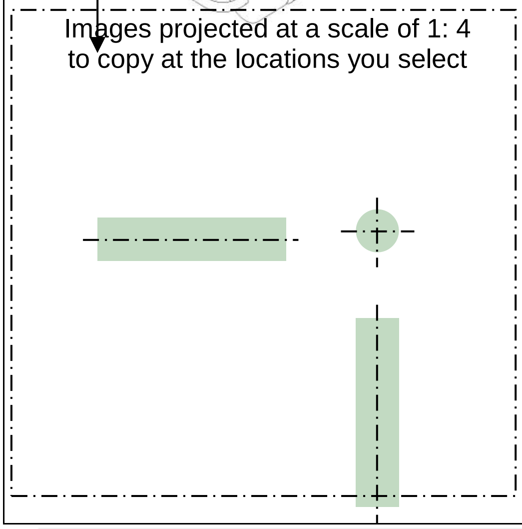
A : N = 160,000 / 43,200 = 3.7, or 4 cartridges

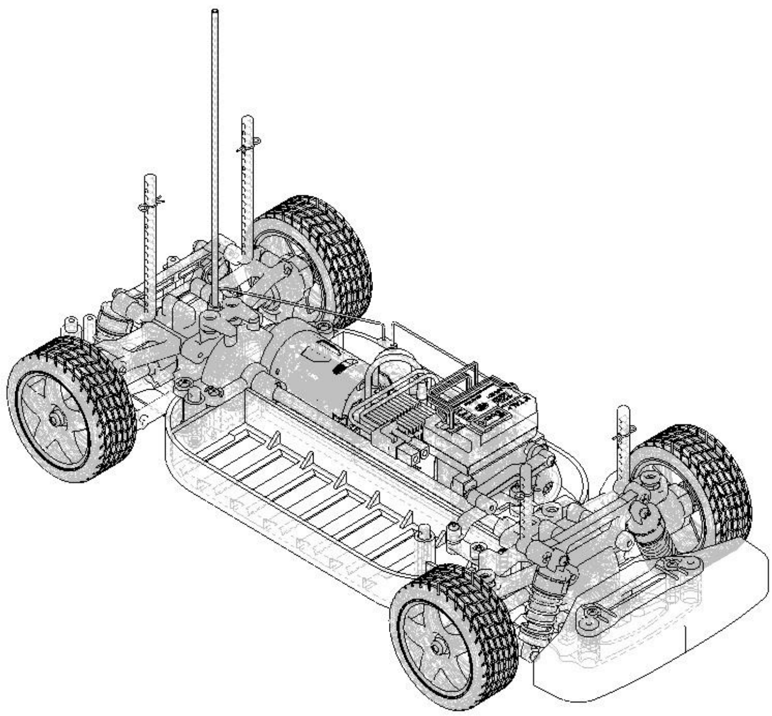
Installation of Hydrostick cartridges



H-Cell project - Scale: 1 : 4







Excerpt from the Mabuchi-Motor document