Optimization of the mass for a low-power electric vehicle and consumption estimator (e-bike, e-velomobile and e-car)

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Abstract: The design and optimization of the motor vehicle is a multidisciplinary problem that must consider the average speed, average elevation, resistive power, vehicle mass, luggage mass, motor mass, aerodynamics, performance, mechanical constraints, etc.

The search to minimize cost and maximize autonomy adds to the difficulties of making technology choices. In recent years, the e-bike and e-motorcycle are marketed but what is optimal based on the weight of the battery and motor? What is the potential average speed without using the electric motor? What are the performances (consumption and acceleration) of a vehicle based on the added mass? What will be the autonomy of an e-bike based on its mass?

To answer these questions, the actual performance of an e-bike and a fully faired e-velomobile along with the optimization coefficients will be presented. This e-velomobile provides a range of about 200 km at an average speed of 50 km/h for a mass of 50kg including the electric motor and a fairing that also provides protection against inclement weather. This e-velomobile is a single-passenger vehicle for someone up to 100kg plus 30 kg of luggage. Electric power consumption is only €1 per 2000 km and the charging time is one hour on a standard outlet. On a long route, average speed depends on the average grade of the road. Therefore, a consumption estimator can be used to determine the average speeds the vehicle can achieve without the risk of running the batteries empty. The electric bike is an excellent educational tool because all students can use it without any safety issues. When pedaling, the student can identify with the motor drive and understand the meaning of torque, speed and power.

Keywords – Mass optimization, Eco Marathon Challenge, Motor power, Lithium battery, Project-based teaching, Energy management, e-bike, e-velomobile, electric car, Consumption estimator, Autonomy

1 INTRODUCTION

Low energy consumption electric vehicles are becoming active participants in our daily commutes. These types of electric vehicles have emerged in the Eco-marathon challenges [12, 13] and meet the demand of minimizing CO_2 emissions as well as the future energy transition [2, 3].

Rickshaws, velotaxis and cargo tricycles are fully faired new vehicles with masses of 50 to 150kg for average speeds of 45 km/h. This mass and speed require some power. But a difficult compromise must be found between the mass, volume, power, autonomy, battery technology and price.

This article will present:

- The resistive power and energy consumption for a route based on a vehicle's average speed and drag coefficient,
- The energy consumption based on vehicle mass.
- The selection of motor characteristics and battery based on the mass, autonomy, speed, etc.,
- A consumption estimator based on a trajectory and an average speed, mass and grade,
- A comparison of different electric vehicles (consumption, price, ergonomics, etc.),
- The driving stability of vehicles based on the mass and center of gravity
- The choice of brakes based on the vehicle mass.

The conclusion will present how to optimize building a low consumption vehicle and its role in the educational system.

2 VEHICLE CHARACTERIZATION

Determining the resistive power of a vehicle can be used to compare the energy consumption of various types of vehicles and to make choices [1, 2, 3, 4, 5] between types of tires, vehicle aerodynamics, design, etc.

Indeed, the resistive force depends on many criteria (tires, road surface condition, surface air penetration, Cx drag coefficient (air fluid dynamics). The resistance forces of a vehicle can be broken down by the following equation:

$$F_{Resistance}(N) = F_{Rolling} + F_{Slope} + F_{Air} \quad (1)$$

$F_{Rolling}$ [1, 11] is considered a constant, especially for tires whose equation is:

$$F_{Rolling} = M(kg).g.C_r \qquad (2)$$

With Cr rolling-resistance tires and M vehicle mass, g is the gravitational constant (9.8 m/s^2). The Cr coefficient will depend on the tire's width, type of rubber, design, inflation and the road surface condition, etc.

In general, tire tread is getting increasingly wide and therefore the tire consumes more. The aerodynamic force corresponding to the following equation (3) with "Sur" surface air penetration, where ρ is the mass density of the air and S is the speed:

$$F_{Air}(N) = k_{Air} \cdot [S(m/s) + S_{wind}]^2$$
$$= \frac{1}{2} \cdot \rho \cdot Sur \cdot Cx \cdot [S(m/s) + S_{wind}]^2$$

The resistive force of the road grade corresponds to the following equation:

$$F_{slope}(N) = M(kg) \cdot g \cdot slope(\%)/100 \qquad (4)$$

At steady state speed, resistive power corresponds to following equations (5):

$$P_{resistive}(W) = F_{resistive} \cdot S(m/s) = k_{Air} \cdot S^3 + (k_{rolling} + k_{slope}) \cdot S(m/s)$$

To model the resistive power of a vehicle, it is easier to use the speed in km/h with two coefficients:

$$P_{resistive}(W) = k_{Aero} \cdot Sp^3 + (k_{rol} + k_{slope}) \cdot Sp(km/h) \qquad (6)$$

The relationship between the power and speed coefficients in km / h are as follows:

$k_{Rolling}$ (N) = k_{rol} (W/km/h).3.6
k_{Air} ($N/(m/s)^3$) = k_{Aero} ($W(/km/h)^3$).3.6^3

From the figure below, we can see that the aerodynamic coefficient only starts to be dominant from 30 km/h, prior to that the rolling resistance is decisive.

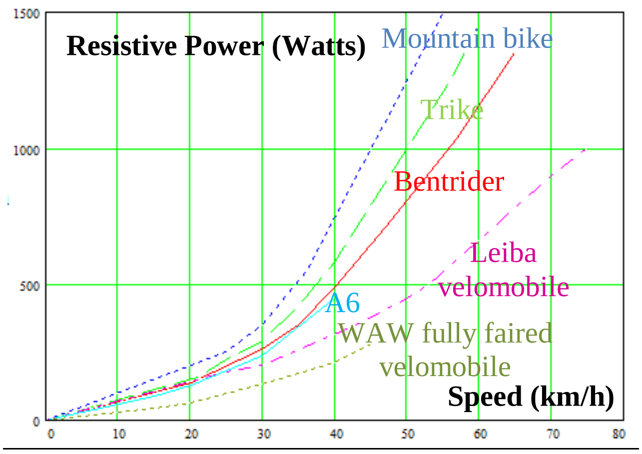


Fig 1: Resistive power vs. the speed on a flat road (without pedaling) different cycle

From the above figure, vehicle performance coefficients are shown in the following table:

Kind of vehicle	k_{aero} $W/(km/h)^3$	k_{rol} W/(km/h)
bike	0.0065	7 to 3
tricycle	0.005	7 to 3
bentrider	0.003 to 0.004	7 to 3
velomobile	0.001 to 0.002	5 to 3
car	0.015	200 to 40

Table 1: vehicle coefficient

The human average power is 100W (normal man) to 300W (good sportsman). The average speed (the algebraic solution of equation 6) cannot be presented here because there is not enough space. On a 100 km route with an average power of 100W and 300W, an average elevation difference of 0.5% and an 80kg cyclist, the average speed values correspond to the following table:

Kind of vehicle	Mass kg	k_{aero} $W/(km/h)^3$	k_{rol} W/(km/h)	Average speed 100W	Average speed 300W
bike	17	0.0065	3.4	**15 km/h**	**29 km/h**
bent rider	17	0.004	3.4	**17 km/h**	**32 km/h**
velomobile	30	0.0015	3.8	**18 km/h**	**39 km/h**

Table 2: speed vs. power, mass (Cr=0.01)

From the above table, we can see that the average speed is limited by the power of the cyclist and the aerodynamic coefficient. If we want to increase the average speed, we have to motorize the cycle.

But how much energy will the cycle's motor consume?

What will happen to the cycle's performance with the added mass of the electric motor and the battery?

For a given route, the energy consumed by a motorized cycle in Wh can be approximated by equation (7):

$$E(W.h) = (P_{resistive}(S_{avg}) - P_{human}) \cdot \frac{(distance - D^{-})}{S_{average}(km/h)} + \frac{M \cdot g \cdot D^{+}}{3,6}$$

With the average speed in km/h, D+ the elevation gain and the distance in km. The motor's resistive power, less efficiency losses, is shown in Figure 1. The negative elevation D- can be neglected on traditional roads.

The elevation gain D+ can be in the form of the equation where energy consumption is proportional to the distance:

$$D^{+} = distance \cdot slope_{average} \qquad (8)$$

From Equation 7 and 8, the energy consumed by the vehicle will be:

$$Ev(W.H) = (M_b + M_v + M_m + M_p) \cdot K_{consu} \cdot distance \qquad (9)$$

With M_v vehicle mass, M_m motor mass, M_p mass of the person and the consumption coefficient (Wh)/(kg.km), we have the following equation (10):

$$k_{conso} = \frac{k_{aero} \cdot S^2_{avg}}{M_T} - \frac{P_{human}}{M_T \cdot S_{avg}} + \frac{g}{3.6} \cdot (C_r + slope_{average})$$

M_T is the total mass of the vehicle. One can see that when the mass of the batteries or the motor increases, the consumption ratio is less dependent on the drag coefficient of the human power.

Therefore, the consumption coefficient depends primarily on the average grade and the tires' C_r. In this case, the energy consumption is almost proportional to the vehicle mass and the distance, the average grade and the tires' C_r.

From the energy consumed (9) and the following Wb battery energy equation with battery energy density of:

$$Eb(W.H) = M_b \cdot Wb \qquad (11)$$

The vehicle autonomy is determined by the following equation (12):

$$Autonomy(km) = \frac{M_b \cdot Wb}{(M_b + M_v + M_m + M_p) \cdot K_{conso}} \cong \frac{M_b \cdot Wb}{(M_v + M_p) \cdot K_{conso}}$$

The following figure shows the autonomy based on the battery mass for the velomobile coefficients shown in Table 2 for a battery life energy density of 133 Wh/g.

In this figure, the autonomy is almost proportional to the added weight of the battery because it is lower than the mass of the rider and the vehicle. The price of the battery is also proportional to the battery mass. P_b is the price per battery power (about 0.3 €/Wh for battery life)

$$Batteryprice(€) = P_b \cdot M_b \cdot Wb \qquad (13)$$

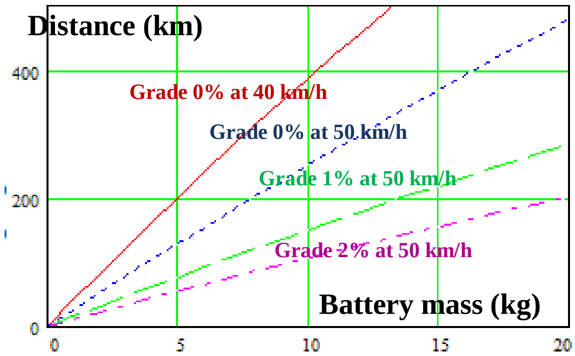


Fig 2: Autonomy vs. battery mass for different average speeds and average grades with a 10kg electric motor

From the above equations, the lighter a vehicle is the less it will consume. But to make an objective comparison, the number of passengers must be taken into account, as in the following figure.

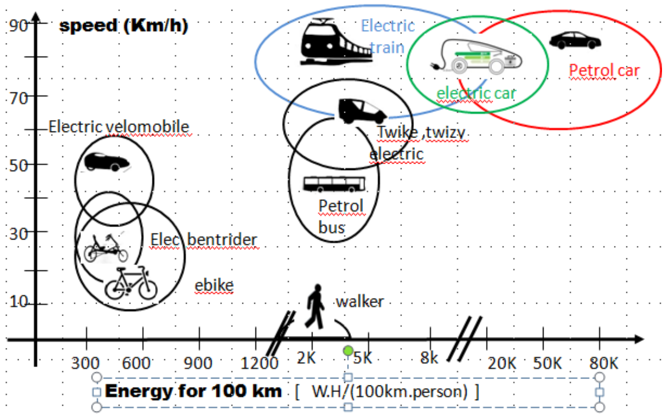


Fig 3: Average speed depending on the energy consumption per 100 km per person [2, 3, 4]

The previous figure demonstrates that only light vehicles allow low energy consumption. Therefore, the faired trike (called velomobile) enables low power consumption with reasonable speeds despite a full fairing of 20 kg. This fairing minimizes the aerodynamic coefficient and overcomes inclement weather. Human pedaling power (100W to 300W) is used in addition to the electric motor to consume less electrical energy and have a physical activity.

But the 20kg fairing increases consumption when the road rises. So how much motor power is required based on the weight of the vehicle and the road elevations?

3 SELECTION OF MOTOR CHARACTERISTICS AND BATTERY

First, we will size the motor power, then check that the battery can deliver this power without being damaged or minimizing the number of battery life cycles. To gain volume and simplify the mechanical transmission, an e-bike uses an outrunner brushless motor in the wheel (hub motor). These motors have a rotational speed of about 600 rpm. Therefore they have many pole pairs (16 to 24). The choice of the number of pole pairs allows more torque or speed for the same power rating. But how do we choose the motor power?

To do this, we must answer the following questions:

- How much motor power will be required to ride up a 10% grade based on the mass?
- How much motor power will be required based on the desired acceleration?

When the grade of the road is high (10% to 15%), the motor power will correspond essentially to the following equation:

$$P_{resistive}(W) \cong M_T \cdot g \cdot slope(\%) \cdot S(km/h)/3600 \qquad (14)$$

Therefore, the maximum power of the motor is proportional to the mass. Considering the tricycle in Table 2 at a speed of 45 km/h on a 10% grade, engine power must correspond to the following value:

$$P_{motor}(W) \cong (50+80) \cdot 9.8 \cdot 0.1 \cdot 45(km/h)/3.6 = 1600W$$

It will add the equivalent of 400W power in aerodynamics and rolling resistance. If the motor needs to accelerate the vehicle at about 3 m/s^2, like a car, in order to blend into a city, its power can be determined by the following equation:

$$P_{motor}(W) = M_T \cdot S(m/s) \cdot \frac{dS}{dt} \qquad (15)$$

To meet this acceleration for a faired trike, the power required will be 4.8KW at a speed of 45 km/h.

But will the battery accept the discharge rate during acceleration and the grade of the road?

To avoid not having battery current, constant power control is used, which limits the battery discharge rate to a desired value [2, 6, 7]

Lithium batteries have a density and relatively high specific energy capacity. LiFePo batteries are a bit heavier than Lipo batteries, but they are less expensive and less affected by bumps and vibration.

But LiFePo cells will be required compared to Lipo to achieve the desired voltage, because the nominal voltage is slightly different between the LiFePo (3.3V) and the Lipo (3.8V) batteries.

If the mass is important to have some autonomy on an e-bike, the volume and price are also crucial.
In addition, since the vehicle vibrates, the battery's mechanical protection code (IP) should be taken into account. The following table summarizes the main characteristics depending on the battery technologies:

Kinds of batteries	Resist Ω 25°C	Price / cell	mass/ cell	Kg/ 1000 Wh	cm^3/ 1000 Wh	€/ 1000Wh	€/Ah	IP Code
LiFePo A123 20A.H [17]	0.0033 Ω	€25	0.5 kg	7.5	4076	300	1.25	low
LiFePo Sinopoly 17A.H	0.00735	€32	0.75 kg	11.1	8075	300	1.88	high
LiFePo Headway 40152 15A.H	0.004	€29	0.48	9.6	6202	580	1.93	high
Lipo 20 A.H	0.001	€50	0.4	5.2	3030	700	2.5	low
Lipo Zippy 16A.H	0.002	€35	0.415	6.5	2531	540	2.18	medium
1.5m^2 solar panel 300W 1500 Wh per day		€2000	6kg	4	5936	1333		medium

Table 3: Comparison of different types and battery technologies in 2015

The charging rate for all the cells is 1C, thus the charge can be completed in 1 hour. Consequently, for a 72V 20A.H battery, 1440W is required so the battery can be charged in 1 hour. Consequently, 2 velomobiles can be charged on a single-phase circuit breaker on a conventional socket (220V/16A). The discharge rate should be less than 3C for correct battery dependability [5, 17].

However for a controller-limited power of 3000W, and a voltage of 48V, the discharge rate is 3C with 20A.H cells. Therefore, it is preferable to use a voltage of 72V (21 LiFePo cells). The battery management system (BMS) is made for 6 to 7 cells (approximately €70), so there will be an additional printed circuit compared to a 48V battery.
A daily range of 200 km is reasonable for a cyclist. From Figure 2, a 10kg 1440Wh battery is

necessary for a faired trike. A good compromise for the battery and the controller transistors is to select a voltage of 72V and an energy capacity of 20Ah. The measurements presented hereafter were made based on this energy capacity and voltage.
Moreover, it is recommended to not fully discharge a lithium battery to avoid decreasing its lifespan. A reserve of 20% of the energy capacity is recommended, which reduces the autonomy by the same percentage.

Fig 4: Different prototypes of electric velomobile (from 50kg to 85kg) [9, 10]

Velomobiles' top speed can reach 80 km/h on the flat with electrification and 100 km/h on some descents. At this speed, you need brakes and tires that allow a relatively short stopping distance and that can dissipate the braking energy.
A motor hub and 3KW 72V controller weighs about 8 kg at a cost of €500 and a motor hub and 6.5KW controller weighs 12kg at a cost of €1100.
But how efficient is this type of motor?
Because this efficiency will impact the vehicle's energy consumption.
Electric motor hubs have an efficiency of 80% to 90%. Motor performance can be plotted versus the speed with a power limitation. In the following figure, the resistive power and motive power curves are shown based on the speed.
The intersection of these two curves represents the vehicle's steady state speed. The efficiency and torque based on speed are also plotted. For the speed operating point, the simulator also gives the motor losses, consumption in Wh/km and autonomy as shown in the following figure. Therefore, the energy consumption will be decreased by the motor losses, on the order of 10% to 20%.

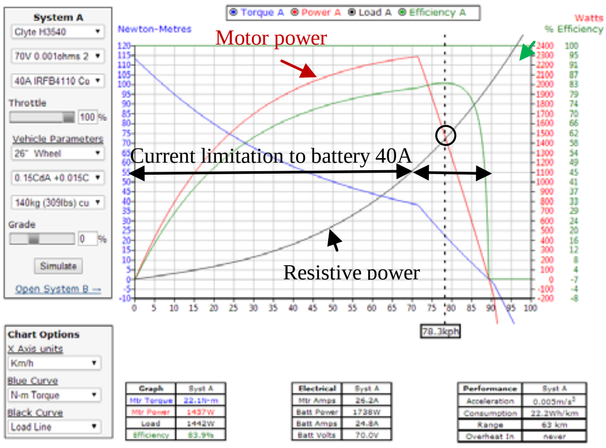
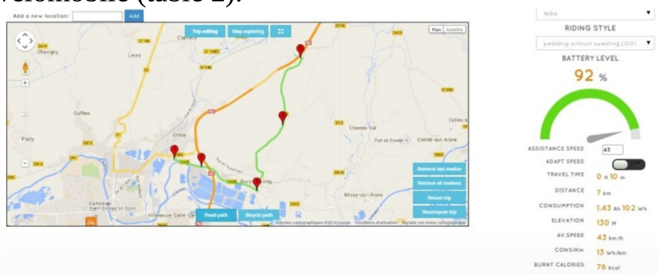


Fig 5: Simulation of a Crystalye HS3540 motor operating at 70V for a velomobile (140kg, kaero 0.0015 W/(km/h)^3) [15]

From the above equations, what average speed should we choose to ride a desired route for a given battery energy capacity?

4 ESTIMATED CONSUMPTION ON A GIVEN ROUTE AND VEHICLE PERFORMANCE

With a 3000W motor and voltage of 72V, the motor used can reach a speed of 80 km/h and climb 10% grades at 50 km/h. But at 80 km/h, consumption will increase significantly due to the aerodynamic coefficient. Furthermore, autonomy will drop significantly, especially if the average grade slope is relatively steep.
Since 2012, many websites (e.g., google.maps, open runner, etc.) let users trace a route, identify the elevation gain on the road and therefore calculate the average grade over the road.
From equation (7) and the average motor efficiency, the average speed can be determined based on the battery energy.
To check a vehicle's consumption, an online estimator has been developed ebikemaps.com [16]. In the following figure, we can see the consumption estimator with its battery gauge based on the route and the average speed of the velomobile (table 2).



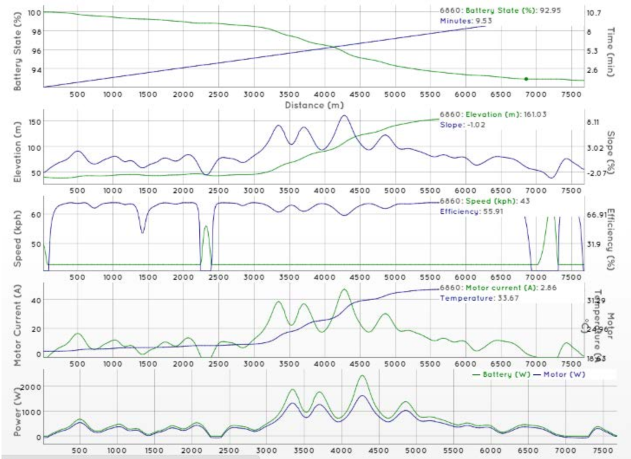


Fig 6: For velomobile: estimation of energy consumption based on a route and an average speed fixed. The resistive power and the motor temperature are estimated also. [16]

All of our prototypes have recording instrumentation that can check the estimator and the energy consumption in real time, based on speed and altitude.

In the following figure, we can see the consumption and power measurements for the previous route, which confirms the estimator.

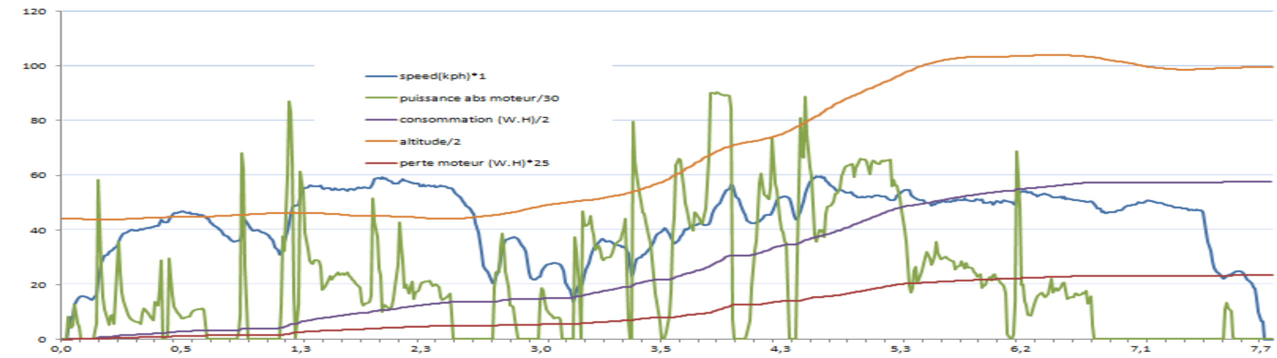


Fig 7: Recording: speed (km/h), power battery (W), energy (Wh), altitude (sum of elevation gain) (m) and loss power motor

The estimation accuracy is on the order of 5% to 10%, knowing that it doesn't take into account the electricity generated by regenerative braking, the granulometry of the road surface, the wind or the consumption due to accelerations.

It can be noted in the previous figure that the power is chopped significantly because there are many accelerations on a route, while the estimator filters these accelerations.

Acceleration is especially predominant in urban areas or during challenges because there are many turns. On 100 km to 200 km routes, the kinetic energy in the acceleration is recovered during deceleration while freewheeling. In this case the acceleration may be neglected

But how much energy is used during acceleration?

5 VEHICLE CONSUMPTION DURING ACCELERATIONS

The consumption for each acceleration corresponds to the following equation:

$$E_{Kinetic}(J) = \frac{M_T}{2} \cdot (\text{Speed}_{final}^2 - \text{Speed}_{initial}^2) \quad (16)$$

The kinetic energy is proportional to the mass of the vehicle.

To test the consumption due to vehicle accelerations, a reproducible travel profile can be defined on a circuit for some challenges [12, 13, 14]. Indeed, the objective of these challenges is to test different types of vehicles in real conditions and to compare their performance.

The circuit presented here is the 2014 Chartres Solar Cup [14], 1.6 km long with an elevation difference of 11m and therefore an average grade of 0.7%.

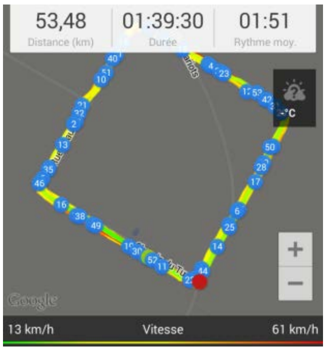


Fig 8: Smartphone solar cup circuit with measurement of speed & altitude every 1s. (4 right angle turns and 1 roundabout), measurement of distance & average speed plus an estimate of consumption, total altitude gain and vehicle performance.

In the following figure, one can see the power of the accelerations after each turn, the speed and the energy.

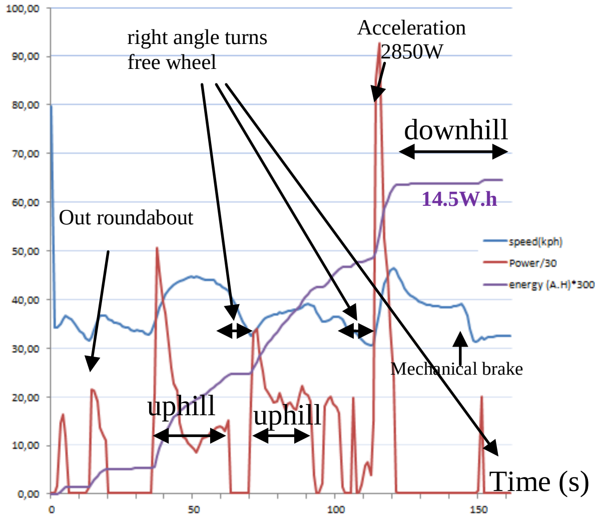


Fig 9: Power speed and power versus time for a ride without pedaling 1.6 km (Chartres solar cup)

Without pedaling, the velomobile consumed 9Wh/km for an average speed of 40 km/h.

From equation (7), the theoretical resistive power at 40 km/h is 256W and the theoretical consumption is 8.83 Wh/km, so there was little difference between the theoretical and practical consumption despite the acceleration.

With pedaling and still at 40 km/h on this circuit, the actual consumption decreases to 6.25 Wh/km while in theory with a human power of 100W, the theoretical consumption is 6.33 Wh/km. Therefore, the human power was indeed around 100W.

During this challenge the velomobile covered 172 km at an average speed of 37 km/h and consumed 1200 Wh for an average consumption of 7 Wh/km. Our vehicle's best average speed around the circuit was 51.3 km/h. During the 4¾ hours race, measurements were taken pedaling 90% of the time and the remaining 10% was used to study the consumption at different speeds without pedaling for comparison purposes.

In Table 3, when the sun shines, the solar panels can produce significant energy for a relatively small mass compared to the batteries. However, solar panels are relatively expensive compared to batteries.

From the above equations, it is possible to compare the consumption of different vehicles based on their mass and their comfort and to know the vehicle's consumption ratio, its price and its obsolescence.

6 COMPARISON OF DIFFERENT ELECTRIC VEHICLES

From equation (9), the consumption ratio will depend on the ratio of the masses and consumption coefficient k_{conso} for vehicles 1 and 2:

$$\text{consumption ratio} = M_1 \cdot K_{consu1} / M_2 \cdot K_{consu2} \qquad (16)$$

When the average grade is predominant compared to the coefficient of the tires' Cr, the k_{conso} coefficient will be the same for 2 vehicles. Therefore, the consumption ratio corresponds to the relationship of the masses.

Similarly, the motor power ratio for an uphill grade or acceleration corresponds to the ratio of the masses.

$$\text{motor power ratio} = \frac{M_1 \cdot g \cdot \text{grade} \cdot S(m/s)}{M_2 \cdot g \cdot \text{grade} \cdot S} = \frac{M_1}{M_2} \qquad (17)$$

But it is difficult to compare a 1480kg electric car with a 130kg velomobile. Indeed, 5 people can be transported in a car while the velomobile is an individual alternative mode of transportation. Moreover, comfort factors (protection against rain, protection from the cold, good ergonomics, etc.) are important parameters.

The following table gives the required energy and price for a distance of 100 km at an average speed of 50 km/h and an electricity price of 0.12 € / kWh. This table gives an idea of the cost of travel including vehicle depreciation over 4 years at an average distance of 1500 km per month. The cost per month is split in two.

Obviously, the longer your car lasts, the more its cost will be amortized (thus the product quality and maintainability are very important).

On a flat road, an electric car has a rolling coefficient 40 W/(km/h) and aerodynamics of $0.015W/(km/h)^3$ compared to a velomobile with 3.5 W/(km/h) and $0.0015W/(km/h)^3$. This gives a ratio of 1:10 for the rolling and aerodynamic coefficient between these 2 vehicles.

But regardless of the mass, consumption coefficients are very close numerically.

On the flat the consumption ratio between an electric car and an electric velomobile is 1:10 at 50 km/h with an average grade of 2%

However, as soon as the speed is increased the gap widens substantially due to the aerodynamic coefficient ratio of 1:10 between the vehicles.

The table above compares the consumption and cost of electric vehicles and shows that they are closely related to the vehicles' mass and power.

	e-bike 25 kg + 80kg	Electric Velomobile 50kg + 80kg	Electric car 1400kg + 80kg
K_{aero} and Cr	0.0065 W(/km/h)^3 0.01	0.0015 W(/km/h)^3 0.01	0.015 W(/km/h)^3 0.01
Coefficient k_{consu} Wh/(km.kg)	Grade 2% => 0.217	2% => 0.095	2% => 0.107
Resistive power (W)	Grade 2% => 1150W	2% => 618W	2% => 7950 W
Energy Wh for 100 km	Grade 2% => 2.3K Wh	2% => 1236 Wh	2% => 15.8k Wh
Mass and price of battery for autonomy of 100 km	2% => 17.5 kg €690	2% => 9.2 kg 370€	2% => 120 kg €4740
Cost of the vehicle	€2,000	€6,000	€14,000 with €6,000 bonus
Cost consumption + cost obsolescence battery 4 years	(€0.27 + €0.95)/100 km	(€0.14 + €0.41)/100 km	(€1.9 + €6.6)/100 km
Cost / month over 4 years (consumption + obsolescence vehicle)	(€18.3 + €41)/month	(€8.5 + €125)/month	(€127.5 + €291)/month
Comfort and ergonomics	+ / Traditional bike	+++	++++

Table 4: Different vehicle consumption compared to **50 km/H** for 100 km
For an average grade **2%** with battery **7.5kg/kWh** and **€0.3**/kWh for **1500 km** by monthly

At 1500 km per month, 15 charges would be required per month with a battery that provides a range of 100 km, which equates to 720 charges in 4 years.

A LiFePo battery can last from 1000 to 1500 charge and discharge cycles, but after 4 years the battery will no longer work because these poles will be oxidized. So to optimize the battery one should travel about 3000 km per month.

At 50 km/h over 100 km, the required pedaling energy is 200 Wh, which is small compared to the energy required by most vehicles except for the velomobile. Consequently, at more than 45 km/h, the electric bike is more an electric scooter than a bicycle.

To date velomobiles are handcrafted and therefore relatively expensive, but prices should drop with industrialization.

If the mass induces greater consumption, it will also affect the center of gravity and consequently the vehicle's handling and the braking design. We will present these interactions.

7 VEHICLE DRIVING STABILITY

The mass of the batteries and motor will change a tricycle's center of gravity, thus limiting the vehicle's maximum speed in turns so it doesn't tip over or drift. To know a vehicle's center of gravity, we can use a scale to measure the forces on each wheel on the flat, with the rider in the vehicle. This provides G_x. We then lift the vehicle 30 cm as shown in the following figure and redo the measurements to know G_y [10]. We can then determine the best position of the masses in the vehicle algebraically or with software such as Solidworks.

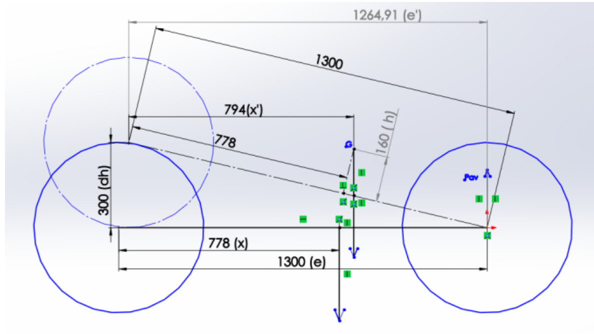


Fig 10: Study of the tricycle center of gravity from the masses added in Solidworks [10].

The maximum speed based on the turn radius (R in meters) and the width of the vehicle's track geometry (TG) is given by the following equation:

$$S_{max\,i}(km/h) = 3.6\sqrt{\frac{R}{mass_T}\cdot\frac{TG(m)\cdot mass_{front}\cdot 9.81}{2\cdot \text{height center of gravity}}} \quad (18)$$

The wider a vehicle's tracks are or the lower its center of gravity is or the higher the ratio is between the mass in the front and the total mass, the higher the maximum speed in turns will be. Likewise, the closer the center of gravity is to the two front wheels, the higher the maximum speed in turns will be. But during emergency braking on the front wheels of a tricycle, there is a risk of "jackknifing." Therefore, the placement of the battery and rider masses in the chassis must be planned in advance.

A low center of gravity minimizes mechanical braking before curves and entails less energy loss. Furthermore, the vehicle's steering safety is more important. But the weight of the battery and the motor will cause additional thermal heating of the brakes, which therefore have to be sized accordingly.

8 BRAKING AND THERMAL HEATING

During an emergency stop, the mechanical stop distance is proportional to the mass. It corresponds to the following equation:

$$\text{Distance}_{\text{Brake}}(m) \approx \frac{\text{Mass}}{2 \cdot F_{\text{Brake}}(N)} \cdot \frac{\text{speed}^2}{3.6^2} \quad (19)$$

Two 160 mm Avid BB7 mechanical disc brakes have a braking force of about 900N. The disk's thermal capacity (C_{TH}) is 450 J/°C and the thermal resistance (R_{TH}) is 0.1W/°C at 40 km/h [10].

Disc brakes' setting temperature can easily reach 200°C. Above 250°C (disc brake pads organic), the brake's plastic parts melt, the friction coefficient changes and the braking force decreases substantially (fading) [10]

The average power that the brakes have to dissipate is proportional to the vehicle's mass. It is given by the following equation:

$$P_{\text{average brake}} = \frac{\text{Force} \cdot \text{speed}_{\max}}{2} = \frac{\text{mass}_{\text{vehicle}} \cdot S_{\max}}{2 \cdot \text{time}_{\text{brake}}} \quad (20)$$

The average power to be dissipated depends on the vehicle's mass and the braking time. The temperature rise on the brake discs is given by the following equation:

$$\text{Temperature}_{\text{brake}} = \frac{\text{mass}_{\text{vehic}} \cdot \text{speed}^2_{\max}}{2 \cdot C_{th}} \quad (21)$$

So to stop from a given speed, the average power dissipated is proportional to the mass and the temperature reached by the disc. Therefore, the brake should have a larger diameter in order to dissipate more energy based on the added mass.

Example: if we want to stop a 100 kg vehicle at a speed of 40 km/h with a deceleration of 6 m/s^2 and an ambient temperature of 25°C, then the kinetic energy will be 1.7 Wh, the braking force will be 600N, the stopping time will be 1.85s, the average power will be 3.3kW and the temperature on the brake disks will be 38°C.

However, if the vehicle weighs 140 kg, the braking force will be 840N. The braking time will be the same since the deceleration is the same, while the average power will be 4.6kW and the temperature will reach 44°C.

In the following figure, the temperature can be observed at the end of a descent causing a temperature rise of 86°C following an average power of 700W for 30 seconds.

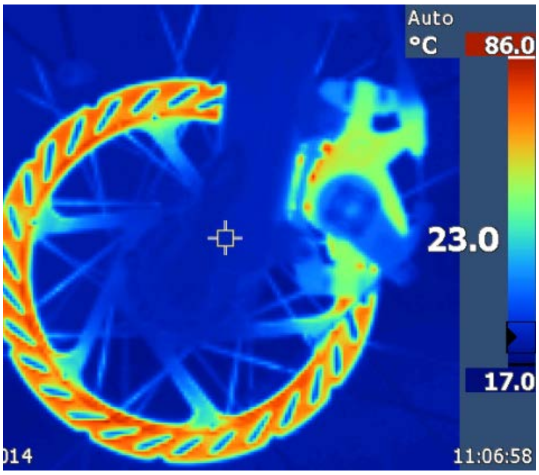


Fig 11: Image of the temperature of the brake disc

These thermal and mechanical characteristics based on the added mass can be used to choose the brakes for a vehicle.

9 CONCLUSIONS

This paper shows that the energy consumption, battery capacity (thus their prices), autonomy and maximum power from the motor depend primarily on the mass of the vehicle. This article determined all of the coefficients proportional to the mass in order to optimize a vehicle and have low energy consumption. The motorization power was determined to satisfy acceleration requirements so the vehicle can be integrated in everyday traffic and uphill grades without obstructing traffic. But this motor oversizing resulted in a motor and battery mass that is penalizing in the search to minimize the vehicle's weight and price.

Since 2011, the prototypes produced and tested at the IUT Electrical Engineering of Soissons (France) have shown that it is possible to produce vehicles with average speeds (50 km/h) and reasonable and sufficient acceleration performance ($3m/s^2$) in most daily uses, with autonomy of 200 km [8, 9, 10, 13, 14].

On a long route with a given battery energy capacity, average speed will depend on the type of route (average vertical gain/loss, frequency of accelerations, etc.). Therefore, an online estimator was developed to determine the average speed and to adjust a vehicle's performance coefficients.

Since the price of electricity is low compared to other energy sources, the cost of consumption will be even lower.

But to know the real cost of these alternative means of transport, the article took into account the depreciation of a vehicle, which depends primarily on the initial investment cost to produce the prototype and consumables, especially the life of batteries. Low energy consumption electric motorcycles are already an alternative means of transportation used daily by some people because the increase in the cost of energy makes them competitive to use. Indeed, these light electric vehicles can compete with petroleum-fueled vehicles even though the cost of the batteries is still expensive. This article has also shown that adding motorization and a battery will also affect the center of gravity and thus the handling and braking. Consequently, it is essential to study the vehicle's chassis in order to optimize the location of the masses in the vehicle. Implementing and testing these prototypes constitute excellent multi-technology learning systems for students.

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