



# Flywheel energy storage retrofit system *for hybrid and electric vehicles*

Jan Plomer, Jiří First

*Faculty of Transportation Sciences  
Czech Technical University in Prague, Czech Republic*

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# 1. Introduction

- Means of transport can be characterized according to different parameters. One of the most important parameter is the energy demands.
- This parameter along with safety and environmental-friendly request are characteristics of great importance and they are expected to become indicators of the highest priority in the near future.
- Two types of transport vehicles, from point of view of an energy delivery into the systems:
  - dependent propulsion - with a stable connection to an energy source (Trolleybuses or EMUs, ...)
  - independent propulsion - energy is stored “on board” directly in a vehicle (electric and hybrid cars, ...)



# 1. Introduction

- The main advantage of vehicles with an onboard storage system is their independence on the track, which increases their mobility.
- To assess energy storage systems, several physical properties can be exploited, e.g.:
  - **Specific mass energy** – a capacity in relation to its weight

$$\varepsilon_m = \frac{A}{m} \left[ \frac{kJ}{kg^{-1}} \right]$$

- **Specific volumetric energy** - a capacity of energy in relation to a volume of the storage,

$$\varepsilon_v = \frac{A}{V} \left[ \frac{kJ}{m^3} \right].$$



# 1. Introduction

- **Specific mass power** – an indicator of dynamic capabilities in relation to its weight

$$\pi_m = \frac{P}{m} \left[ \frac{kW}{kg} \right]$$

- **Specific volumetric power** - is an indicator of dynamic capabilities in relation to its volume

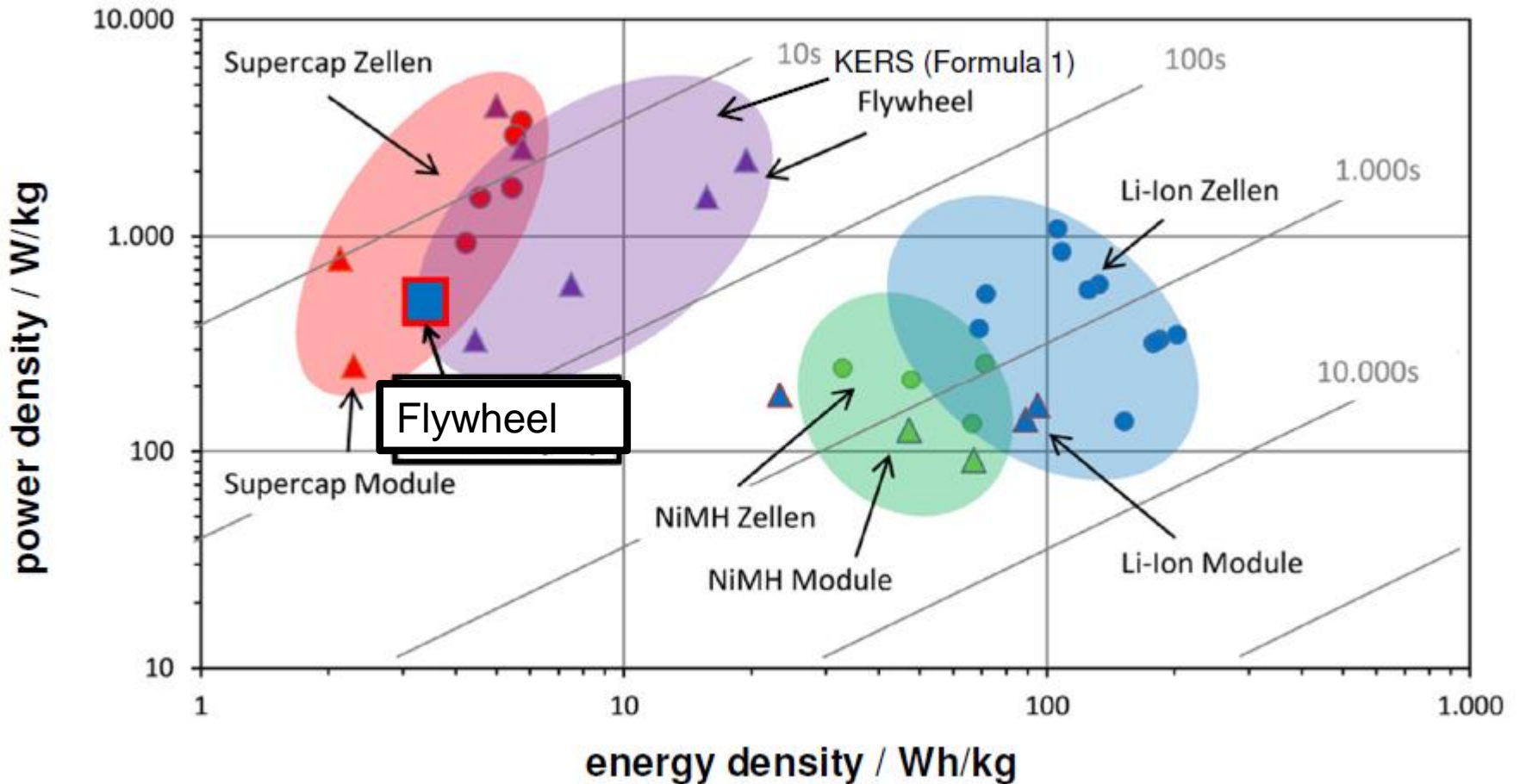
$$\pi_v = \frac{P}{V} \left[ \frac{kW}{m^3} \right]$$

- The assessment of storage systems according to described parameters is not sufficient. Additional properties have to be considered as well, e.h. energy transfer or energy transformation



# 1. Introduction

## Comparison of different energy storage systems



## 2. Flywheel history and future potential



- For centuries, flywheels have been used in smooth running rotated mechanisms.
- The flywheel currently forms an integral part of any combustion engine, in which it balances uneven rotations of the engine.
- Flywheels have nowadays much more advanced designs to allow more complex functions (Lee et al., 2011; Plomer, 2010; Plomer, 2011; Yang, 2012)
- Flywheels are currently employed as short-term energy accumulators, whose energy can be reused later. In the future, applications are extensive and could include, e.g. hybrid and electric vehicles (Plomer, 2013), or voltage stabilization in electric distribution networks.

# 3. Gyrobuses in Switzerland



- In the past, the flywheel had been used as a source of energy for gyrobus drives, e.g. in Switzerland, Belgium, Congo, Sweden and China.
- A Swiss company Maschinenfabrik Oerlikon (ABB today) had 19 such gyrobuses in total.

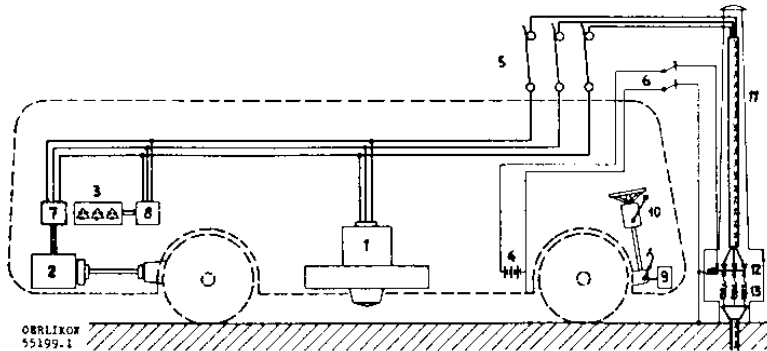


Abb. 6. Anordnung im Gyrobus. 1 Elektrogyro; 2 Triebmotor; 3 Kondensatoren; 4 Hilfsbatterie; 5 Dachkontakte; 6 Einschalt- und Erdungskontakt; 7 Geschwindigkeits-Regulierschalter; 8 Zugkraft-Regulierschalter; 9 Antrieb zu 7; 10 Antrieb zu 8; 11 Lademast; 12 Einschalt-hüpfel; 13 Ladedrossel





# 3. Gyrobuses in Switzerland



- **Advantages:**

- zero emission operation, because there was no internal combustion engine in the vehicle at all.
- the vehicle in operation was substantially quieter.
- no need to build and maintain overhead contact lines between individual stops.

- **Disadvantages:**

- maximum rotation speed was significantly limited (app. 3.000 1/min).
- worse handling characteristics due to the higher weight and the gyroscope torque had negative effects on the turning ability.



## 4. Existing applications of flywheel battery

Some examples of flywheel battery:

- **Small flywheel systems for short-term voltage balancing in the power grid.** These systems have relatively small specific density, since the volume and weight are limited. On the other hand, a high specific output power can be achieved.
- **Usage of the flywheel to balance the peak voltage of electric vehicles.** The aim is to reduce significantly high currents from the original battery power for the traction engine. The battery life is significantly prolonged by reducing the peak current.
- **Flywheel for photovoltaic systems.** Incorporating flywheels into a photovoltaic system, the extension of the energy supply up to approximately 30% can be achieved.



## 5. Energy storage in flywheel

- Advances in material technology, magnetic bearings and power electronics have led to successful applications of flywheels in a short-term storage of energy.
- Modern flywheels work with high power and thanks to the composite materials, the flywheels reach high angular speed with power density higher than is the power of chemical batteries.
- Exploiting magnetic bearings significantly reduces internal losses (Kamf, 2012)
- Since the accumulated energy is proportional to the square of the speed and only linearly to the flywheel mass, the high speed flywheel rotation is essential for accumulating a large amount of energy.



## 5. Energy storage in flywheel

- The benefits of flywheel applications (Bolund et al., 2007) for energy accumulation stems from basic properties of the flywheels, namely from:
  - High power density;
  - Capacity of being independent of the depth of discharge and the number of charging cycles;
  - Simple measurability of a charge status, which is given simply by the angular speed of the flywheel;
  - Very short charging period;
  - Very low maintenance requirements during flywheel operation.



## 5. Energy storage in flywheel

- One of the most important advantages of flywheels is their ability to handle high-level power. This property is required for example in vehicles if a high power is needed during vehicle acceleration.
- If a traction electric engine is used in the generator mode as a brake, the braking of the vehicle generates a large amount of energy in a short time interval and the breaking energy can be accumulated in the flywheel battery. It is evident that in such regime, energy is used more efficiently, which results in reducing fuel consumption and thus also in reducing  $CO_2$  emissions.



## 6. High speed flywheel battery

- Due to the dependence of the amount of the stored energy in a rotating mass on the square of the angular velocity, the highest possible angular velocities of the rotor in the flywheel battery are required.
- However, high rotational speeds greatly increase technical demands on the material properties of the rotor, the bearings and, last but not least, also on decreasing of the additional resistance acting on the rotating flywheel.
- The amount of kinetic energy of a rotating mass is described by the basic equation:

$$E_k = \frac{1}{2}J\omega^2$$

- Moment of inertia (J) depends strongly on a shape of the rotating mass and its weight.



## 6. High speed flywheel battery

- The principal shapes of steel rotors are full cylinders, for which the following equation is relevant:

$$J = \frac{1}{2}mr^2 = \frac{1}{2}\pi a\rho r^4$$

where  $r$  is radius,  $a$  is length of cylinder,  $m$  is weight and  $\rho$  is cylinder density.

- The hollow cylinder is another frequently used shape of the flywheel rotor, for which holds

$$J = \frac{1}{2}mr^2 = \frac{1}{2}\pi a\rho r^4$$

- It is evident from the equations above that achieving the highest angular speeds is decisive for storing the maximum amount of energy in flywheels.



## 6. High speed flywheel battery

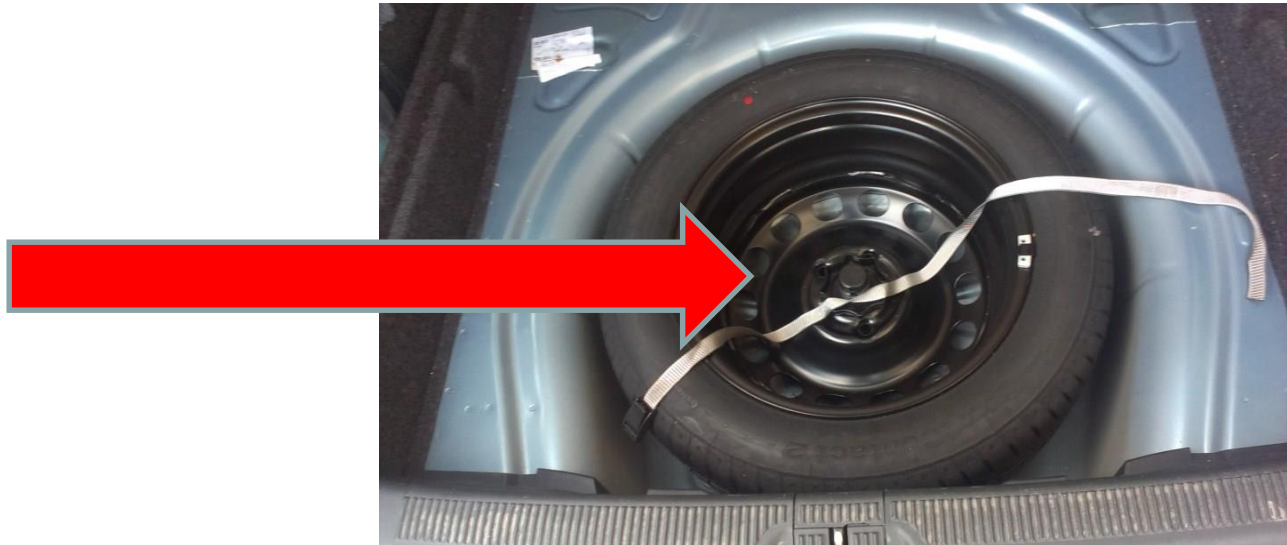
- On the other hand, there are limitations resulting from the material strength  $\sigma$ . Materials with low density and high strength are optimal for constructing flywheels.
- From a technical point of view, there are no obstacles to design the high-speed flywheel battery (e.g. Tang et al., 2012).
- However, from an economic point of view, it is impossible to implement such designs into a serial production and apply them in a broad scale into common cars at present.





## 7. New design of additional flywheel battery 200Wh/20kW/48V

- Efficient flywheel battery, designed with commercially available components.
- The basic idea is based on a possibility of using the free space in spare wheel of a vehicle and integrate an additional flywheel battery with the capacity 200Wh, peak power 20kW and voltage 48V.





# 7. New design of additional flywheel battery 200Wh/20kW/48V

- Electrical engine/generator, as well as flywheel, must be designed from available materials, to keep the development and production costs on the competitive level.
- The Estimation of an amount of theoretical kinetic energy stored in a steel or aluminum rotor is with following parameters: mass = 10.0 kg, moment of inertia  $J = 0.11 \text{ kg} \cdot \text{m}^2$ .

Speed [1/min]	Energy [kJ]	Energy [kWh]	Energy [kWmin]
0	0.0	0.0000	0
1000	24.4	0.0068	0.41
2000	97.4	0.0271	1.62
3000	219.2	0.0609	3.65
4000	389.6	0.1082	6.49
5000	608.8	0.1691	10.15
<b>6000</b>	<b>876.7</b>	<b>0.2435</b>	<b>14.61</b>
<b>7000</b>	<b>1193.3</b>	<b>0.3315</b>	<b>19.89</b>
<b>8000</b>	<b>1558.5</b>	<b>0.4329</b>	<b>25.98</b>
<b>9000</b>	<b>1972.5</b>	<b>0.5479</b>	<b>32.88</b>
<b>10000</b>	<b>2435.2</b>	<b>0.6765</b>	<b>40.59</b>
11000	2946.6	0.8185	49.11
12000	3506.7	0.9741	58.45
13000	4115.5	1.1432	68.59
14000	4773.0	1.3258	79.55
15000	5479.3	1.5220	91.32



## 7. New design of additional flywheel battery 200Wh/20kW/48V

- It is evident from the calculated values of kinetic energy that the accumulated amount of energy between 6.000 - 10.000 1/min is sufficient for an acceleration of a vehicle to approximately 50 km/h solely by exploiting the accumulated energy. This becomes important particularly in urban areas.
- However, the main benefit of this flywheel battery is its ability to support the combustion engine in situations requiring a sudden high power supply from the combustion engine.
- Thus in such model modes, the combustion engine can run in economical mode and the flywheel can be used for a short-term demand of increased power for the vehicle acceleration.



## 7. New design of additional flywheel battery 200Wh/20kW/48V

- Particular design of an additional flywheel battery will depend on vehicle specifications.
- The choice of electric engine, of a standard production on the market, depends on parameters of the flywheel battery. Speed up to ca. 6 000 – 8 000 1/min and storage of the short-term maximum power up to 20 kW for a few seconds are assumed which are commonly used in hybrid transmissions (e.g. ZF 8P automatic transmission).
- To store the energy in a flywheel battery for several minutes, it is necessary to eliminate losses, due to an air resistance acting during the high-speed disc rotation. This can be effectively achieved by placing the flywheel battery in an airtight vacuumed container.



## 7. New design of additional flywheel battery 200Wh/20kW/48V

- The design assumes the flywheel battery could be also connected to a standard 230V outlet. Such configuration allows a quick recovery charging of the flywheel battery with a smaller amount of energy.
- The charging will be sufficient to start the combustion engine in case that the main vehicle battery operating at voltage of 12V would not have sufficient amount of energy.
- Moreover, disconnecting of the standard 12V main battery in dependence on the current situation is assumed. The energy required for the on-board vehicle systems will be delivered solely from the flywheel battery that increases the lifetime of a standard main 12 V battery in the vehicle.

# 8. Conclusion



- Flywheel storage battery is promising technical solution of an additional energy-storage system for common vehicles
- Presented new design does not require any demanding specific development, including e.g. a production of a carbon-fibre rotor.
- In general, high-tech development would increase several times the rotational speed and the amount of stored energy, but from the economic point of view, such solution would have limitations in its wider distribution.



## 8. Conclusion

- Modern trends in technologies emphasize reducing both energy demands, as well as decreasing emissions from the means of transport.
- Therefore, the designed flywheel battery may be a new perspective short-term energy storage system.
- Extensive expansion of such flywheel battery does not seem to be limited by any major technological or economic barriers.

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- Next milestone for CTU, Faculty of Transportation Sciences:

**Building a prototype of flywheel battery for passenger vehicles**



# *Thank you*



## HYBRID CITY DRIVE Summary

- Innovative drive with significant reduction of CO<sub>2</sub> emissions
- Thanks to expected platform modularity (e.g. scaled Power/Torque of combustion engine and electric motors), the Hybrid City Drive is suitable for large amount of different vehicles
- Excellent driving dynamics due to 3 power sources in the drive chain
- Low cost prototype development and integration into demonstrator vehicle (all components are state of art)
- Additional Flywheel battery can be designed as low cost storage system, with limited capacity of energy.