

# Kinetic energy recovery systems in motor vehicles

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**Abstract.** The article draws attention to the increasing environmental pollution caused by the development of vehicle transport and motorization. Different types of design solutions used in vehicles for the reduction of fuel consumption, and thereby emission of toxic gasses into the atmosphere, were specified. Historical design solutions concerning energy recovery devices in mechanical vehicles which used flywheels to accumulate kinetic energy were shown. Developmental tendencies in the area of vehicle manufacturing in the form of hybrid electric and electric devices were discussed. Furthermore, designs of energy recovery devices with electrical energy storage from the vehicle braking and shock absorbing systems were presented. A mechanical energy storing device using a flywheel operating under vacuum was presented, as were advantages and disadvantages of both systems, the limitations they impose on individual constructions and safety issues. The paper also discusses a design concept of an energy recovery device in mechanical vehicles which uses torsion springs as the main components of energy accumulation during braking. The desirability of a cooperation of both the mechanical- and electrical energy recovery devices was indicated.

## 1. Introduction

The increasing environmental pollution causes the tightening of emission standards. In order to meet their requirements, car manufacturers seek various methods of reducing emissions of harmful and toxic substances, which are produced during the process of fuel combustion in internal combustion engines. This is achieved via improvement of the power unit's efficiency and fuel consumption reduction, the use of innovative systems of exhaust gas recirculation, particle filters and other systems. The most popular methods of reducing fuel consumption include:

- "downsizing" the internal combustion engines by reduction of the stroke volume while maintaining or improving its performance;
- "economy" modes of automatic transmissions, which allow the engine to work in the most economic rotation speed range;
- "start-stop" systems, which allow the engines to shutdown automatically, for the time of stoppage, and then start-up automatically;
- hybrid material frames, built with composite and aluminium materials, to reduce the vehicle's weight;
- hybrid drive systems, which use internal combustion engines and electric motors to power vehicles;
- improvement of vehicle's aerodynamics;
- the use of "low rolling resistance" tires.

Recently, car manufacturers increasingly use hybrid drives with energy recovery systems to lower the vehicle fuel consumption. These systems most often use the braking phase to recover the momentum from the crankshaft, drive shaft or the car's axles and then store it in the form of different types of energy



(electric one, kinetic one or compressed air). The most popular energy recovery methods include the use of[1]:

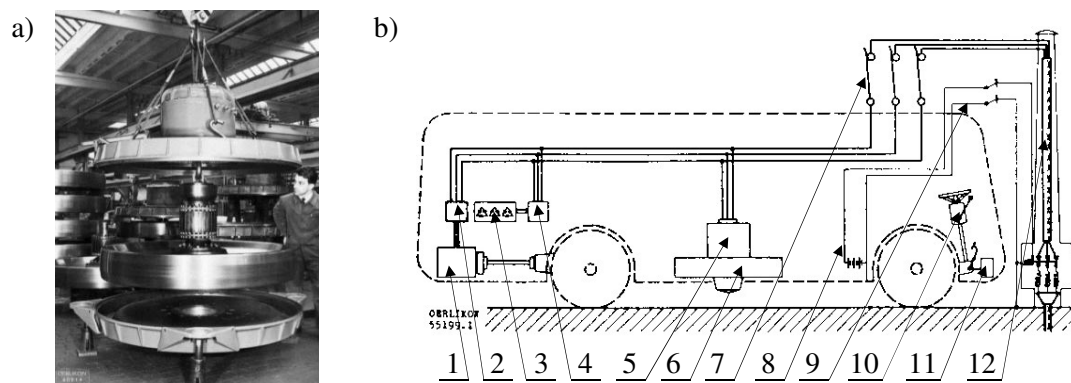
- electric motors, converting the kinetic- to electric energy and storing it in battery packs,
- flywheels, storing kinetic energy.
- compressors, converting the kinetic- to compressed air energy and storing it in hydraulic accumulators[2].

The recovery of kinetic energy in motor vehicles is achieved mostly in three phases. In the first, the energy from the moving vehicle is converted, in the second – it is stored, and in the third, the stored energy is used to power the vehicle.

## 2. Historical design solutions of energy recovery systems

In the past, most interests in terms of energy accumulating were focused on kinetic accumulators. Devices using flywheels to store kinetic energy were used in hybrid buses, trams and cars. In 1946 a hybrid drive system was developed, consisted of electric motors and a flywheel module, allowing short distance travels. It was used in the industry and public transport. The concept was to use a centrally placed flywheel module, with a flywheel weighing 1.5 t and of a 1.6 m diameter. The hermetic flywheel module was filled with hydrogen, for the air friction lowering, allowing the flywheel to rotate at a speed of up to 3000 rpm.

The Gyrobus power principle (Figure 1) involves powering the electric motor 5, from overhead power lines. The motor spins-up the flywheel 6, on bus stop. It causes the flywheel to accumulate kinetic energy. During the later stage, that is the acceleration and travel, the energy accumulated in the flywheel is transferred through the shaft to the electric motor 5 acting as a generator, converting the kinetic- to the electric energy. The electric energy produced charges the electric motor drive 1 which accelerates the bus. To sum up, the Gyrobus's energy recovery system's purpose was to recover the kinetic energy from the flywheel and convert it to electric energy.



**Figure 1.** Gyrobus's flywheel module (a) and Gyrobus's system's components (b)

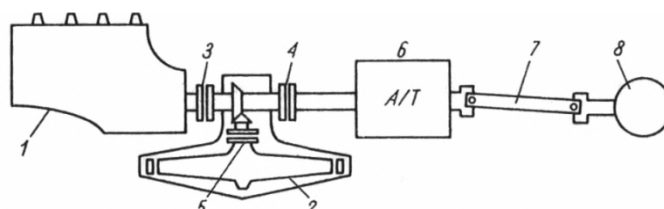
[[www.photo.proaktiva.eu/digest/2008\\_gyrobus.html](http://www.photo.proaktiva.eu/digest/2008_gyrobus.html)]

1 – electric motor drive, 2 – speed control, 3 – capacitors, 4 – traction control,  
 5 – electric motor, 6 – flywheel module, 7 – pantograph, 8 – batteries, 9 – on-switch  
 and grounding, 10 – traction control steering, 11 – speed control steering, 12 – charge mast.

The Gyrobus bus line had charging stations every 5 km. There, a 5 minute spinning-up of the flywheel took place. The flywheel spin-up from standstill to operational rotation speed took about 40 minutes. The kinetic energy accumulated in the flywheel allowed the acceleration of a bus up to 55 km/h. Limitations of technology, large dimensions and weight of the flywheels used in that epoch caused the project shutdown and the design did not to come into everyday use.

In the 70s in the United States of America a number of car concepts were created equipped with hybrid drives with mechanical energy recovery systems. They consisted of internal combustion engines and

kinetic accumulators. The use of a flywheel module for energy recovery purposes requires a complicated powertrain control system with an automatic transmission. The reason for this is the need to ensure smooth torque transfer between the system's flywheel and the drive shaft, during both acceleration and braking, when the car's kinetic energy is being recovered. An example of a hybrid drive with a flywheel acting as an kinetic accumulator and an automatic gearbox is shown in Figure 2[3].

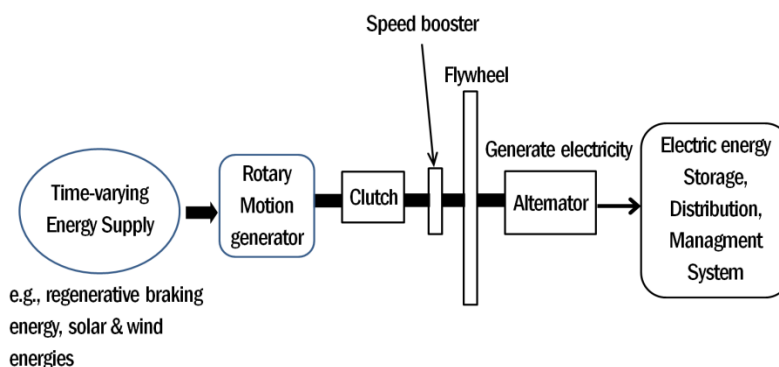


**Figure 2.** Hybrid drive with a mechanical energy recovery system [3]

1 – internal combustion engine, 2 – flywheel, 3, 4, 5 – clutches,  
 6 – automatic transmission, 7 – Cardan drive shaft, 8 – driveline.

During travel the internal combustion engine 1, through clutches 3 and 4 and automatic transmission 6 powers the vehicles driveline 8. Clutch 5 is disengaged and the flywheel 2 is in standstill. While braking, in kinetic energy recovery phase, clutch 3 is disengaged and clutch 5 engaged which causes the flywheel 2 to spin-up. Afterwards, during the vehicle's acceleration the torque gathered in the flywheel 2 is being transferred to the driveline 8.

Currently similar kinematic systems of flywheel based energy recovery are used. The difference, when compared to the historical ones, lies in the use of advanced electronic control systems, the high-strength multi-material design and the complexity of the construction. A schematic of a 2013 developed system for energy recovery and storage during braking motion with intermittent rotary velocity for e.g. hybrid vehicles is shown in Figure 3.



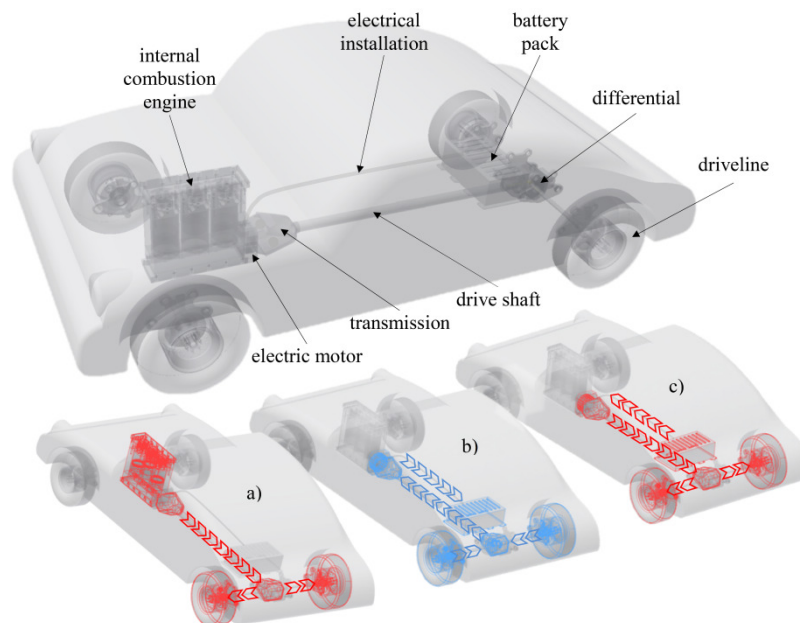
**Figure 3.** Major components of a regenerative braking system[4]

### 3. The principle of operation of energy recovery systems

Kinetic energy recovery from a moving vehicle is being initiated mostly during a vehicle's braking phase. In order to do so, the shaft of an energy recovery system must be included in the powertrain, most often connected to a crankshaft or to one of the axles. The first phase of the energy recovery process is the conversion of the energy from the moving vehicle. During the vehicle's slowing down, energy recovery devices (electric motor, flywheel or compressor) are being coupled through transmission to the driveline. This results, dependent on the system, in spinning-up of the flywheels, carrying out work by the electric motors or compressors in order to convert the kinetic- to electric- or hydraulic energy. The next phase is the accumulating of the energy, which is achieved with the use of flywheels, battery packs or hydraulic accumulators. The third and the last phase of the energy recovery process is the utilization of the energy gathered to accelerate the vehicle or to power the vehicle's electric consumers. By that

means the energy, which in normal conditions would be lost in the braking process in the form of generated heat, is being recovered and utilized.

The principle of operation of an energy recovery system with the use of an electric motor, converting the kinetic- to electric energy and storing it in a battery pack is shown in Figure 4. The arrows in the diagrams a), b) and c) show the flow of the energy between the vehicle's engine, driveline and the energy recovery system's components.



**Figure 4.** Principle of operation of an electric energy recovery system [own work]  
 (a) accelerating of the vehicle with the use of an internal combustion engine,  
 (b) energy recovery during the vehicle's braking and its storing in the battery pack,  
 (c) accelerating of the vehicle with an electric motor.

#### 4. Contemporary design solutions of energy recovery systems

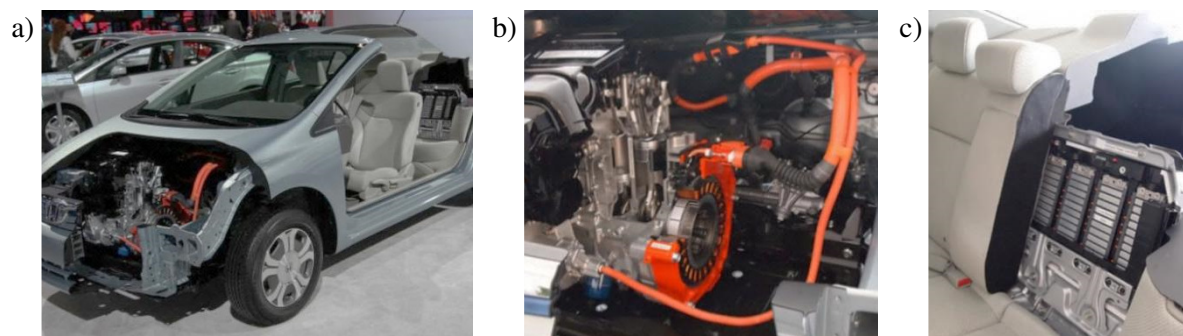
Currently, electric energy recovery systems are most often used in the motor industry. It is due to the World's development trends and the fact that electronics plays a dominant role in motorization for the sake of increasing the user's comfort. Hybrid electric, electric devices and fuel cells are more often used by the car manufacturers. Table 1 shows the selected experimental car models and the mass produced ones, with hybrid drives installed.

**Table 1.** Makes and models of vehicles that have forms of energy recovery systems installed.

Manufacturer	Model
Citroen	XsaraDynactive
Dodge	Durango Hybrid
Fiat	Multipla Hybrid Power
Ford	Escape Hybrid SUV
Honda	Civic Hybrid, Insight
Nissan	Leaf
Toyota	Auris Hybrid, Prius
Volvo	V60 Plug-In Hybrid

##### 4.1. Electric energy recovery systems

As was already mentioned, the motor industry largely prefers the electrical energy recovery systems. These systems are frequently based on electrical motors coupled with internal combustion engines through crankshafts with the battery packs placed in the rear part of the vehicle (Figure 5). This allows the electric motor to work as a "generator" during the vehicle's slowing down and a "starter" during the vehicle's acceleration/travel. The energy stored is utilized automatically to power both the car during acceleration and the electric consumers during stoppage when the engine's shut down (through the start-stop system). In the case of low battery power, the internal combustion engine, through the electric engine, powers the battery pack to ensure their suitable efficiency.

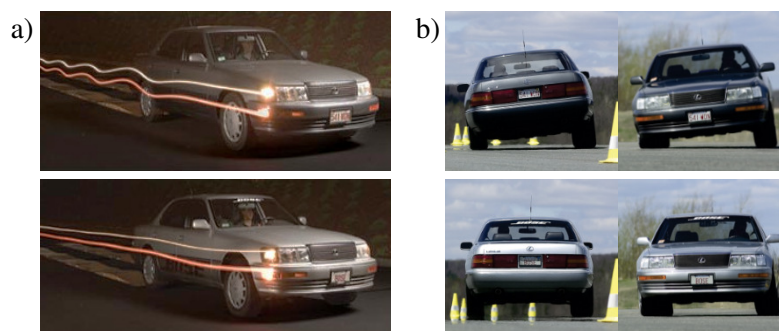


**Figure 5.** Honda Civic hybrid (a) drive components cut through (b) and battery pack placed in the rear seat's backrest (c) [[www.theexpensivecars.com/2012-honda-civic-hybrid.html](http://www.theexpensivecars.com/2012-honda-civic-hybrid.html)].

Among the electric energy recovery systems not all devices use the braking phase of the vehicle to recover energy. An example of such a system is the Bose's electromagnetic suspension (Figure 6) [[www.bose.com/controller?url=/automotive/bose\\_suspension/index.jsp](http://www.bose.com/controller?url=/automotive/bose_suspension/index.jsp)]. This device converts the reciprocating motion, accompanying the vehicle's shock absorbing during travel through uneven terrain, into electric energy. This system uses the obtained energy to raise the user's comfort by the horizontal stabilizing of the vehicle. The results of tests with vehicles equipped with conventional and Bose's suspension show that the Bose system is more effective with the car displaying lesser tilt and better shock absorbing (Figure 7).



**Figure 6.** Bose suspension



**Figure 7.** Motion (b) and turning (c) of vehicles equipped with conventional (upper figures) and Bose suspension (lower figures)

The advantage of an electric energy recovery system's construction is that it's reliable and maintenance free. When in use, it reduces the wear of the conventional braking system's components. Tests performed on a hybrid-electric car resulted with an energy recovery ratio ranged from about 16 % to 45 % [5] depending on the degree of use of the conventional braking system. Electric energy recovery systems are also relatively safe with installed current protections and battery packs sealed off. However, it should be noted that there is a potential danger from the battery packs, for the health of the user and the environment, especially during road accidents. Lifetime of battery packs still depends on

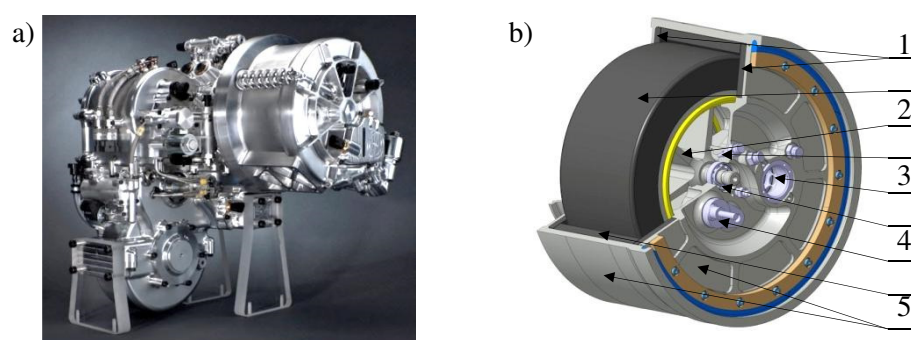


the continuity of the user's vehicle usage. The lack of the vehicle's regular use causes the lowering of the battery pack power and efficiency. The lifetime of a battery pack varies from 3 to 10 years.

#### 4.2. Kinetic energy recovery systems

It's in the past that kinetic energy recovery systems were equipped with flywheels of great weight and large diameter to ensure a proper moment of inertia. In 2009 Flybrid Systems designed a hybrid kinetic accumulator for the Formula 1 race cars allowing the flywheel to work in the speed ranges of up to 60.000 rpm. It's steel and carbon-fiber construction weighed 25 kg and was rated at 60 kW.

Since then Flybrid worked with Jaguar and Volvo on developing a reliable system for everyday use. Applications of Flybrid's system for passenger cars feature long life and maintenance free work with the automated process of recovering and utilizing of the gathered kinetic energy. It's design consists of a flywheel locked in an airtight housing (Figure 8.b). By creating a vacuum it was possible to minimize friction losses.



**Figure 8.** Volvo-Flybrid kinetic energy recovery system with transmission (a) and Flybrid flywheel module cut through (b): 1 – Containment Disks, 2 – Flywheel rim, 3 – Flywheel hub, 4 – Vacuum seals, 5 – Vacuum port, 6 – Flywheel bearing, 7 – Speed sensor, 8 – Containment Ring, 9 – Flywheel housing  
 [www.media.volvocars.com/global/en-gb/media/pressreleases/48800].

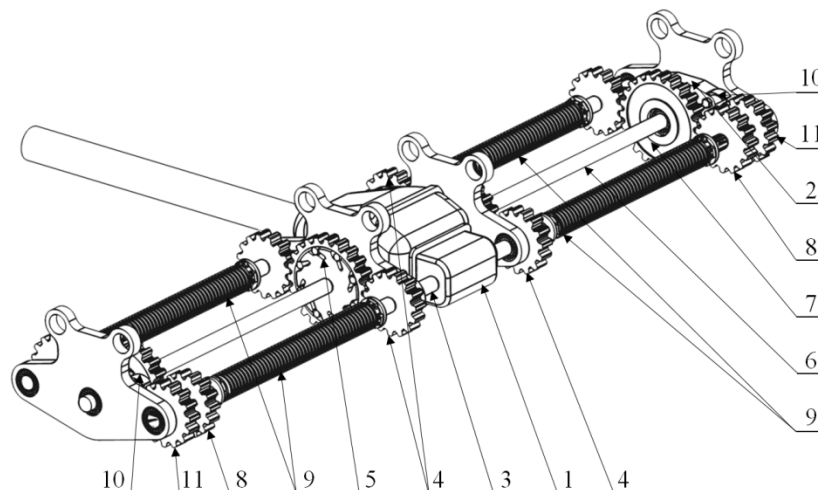
The advantage of the presented kinetic energy recovery system's construction is its small size and weight. Kinetic accumulators have a longer life cycle, relative to electric devices, because of the lack of the negative impact of low temperatures on its lifetime. The production and disposal process of such a system is not as potentially harmful for the environment as the one of an electric system, which includes the need to use electrolytes for batteries.

The disadvantage of kinetic energy recovery systems based on flywheels, is the need to ensure high rotating speeds of its working unit. It poses a health threat for the user and passers-by in the case of its damage and detachment of its components. In the 90s, safety issues caused the shutdown of a Chrysler hybrid race car project, code-named "Patriot". Its kinetic accumulator system included a 61 kg flywheel, rotating at up to 58.000 rpm[5].

#### 5. Design concept of a kinetic energy recovery system

The Military Institute of Engineer Technology in Wroclaw submitted a patent application for "A device for recovering energy of a motor vehicle" to the Polish Patent Office (application no. P.409589) and to the European Patent Office (application no. 15169299.3) [7]. The concept comprises torsion springs as the main components of kinetic energy storage during a vehicle's slowing down phase. The system's increased lifetime will mainly be due to a simple design and a decreased amount of electronic components for steering purposes only. Ultimately the device should be installed on the vehicle's rear axle, to balance its centre of gravity, but it's possible to install the spring-modules alongside of the vehicle's axis of symmetry in a circular or rectangular pattern. These modules could be engaged in the system with additional gears or clutches to allow for sequential utilization of the stored energy. The principle of operation of this concept relies on the operation of five clutches: a friction clutch (1), two

claw clutches (2), two one-directional clutches (5) and two locking mechanisms (10) (Figure 9). The figure shows a concept of an energy recovery system with the turned off view of housings, to illustrate the connections between clutches, torsion springs and gears.

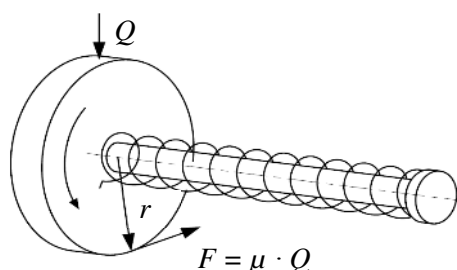


**Figure 9.** A device for recovering kinetic energy of a motor vehicle [7],

1 – friction clutch housing, 2 – claw clutch engagement mechanism housing,  
3 – fourth shaft, 4 – fourth gear, 5 – one-directional clutch, 6 – drive shaft, 7 – first gear,  
8 – third gear, 9 – torsion spring, 10 – locking mechanism, 11 – second gear.

The friction clutch (1) stops the fourth shaft (3) alongside with fourth gears (4) and the cooperating one-directional clutches (5). The claw clutches (2) transfer the torque from drive shafts (6) to first gears (7) causing the rotation of third gears (8). The difference in rotation speeds between the fourth gears (4) and the third gears (8) causes the twisting motion of the torsion springs (9). When the desired angle of rotation of torsion spring fronts (9) is reached, the claw clutches (2) disengage, and the locking mechanisms (10) engage, leaving the cooperating second gears (11) third gears (8) and first gears (7) in standstill. The disengagement of the friction clutch (1) causes the utilization of the stored in the torsion springs (9) torque, through the fourth gears (4) and the one-directional clutches (5) to the drive shafts (6). When the angle between the torsion spring fronts (9) reaches zero degrees, meaning all of the stored torque is used, the locking mechanisms (10) are being disengaged leaving the device in standstill.

Using the torsion springs to recover energy allows for smooth torque transfer between the driveline and the energy recovery device, as well during the vehicle's braking and acceleration without the use of complicated transmissions. This is mainly due to the work characteristics of torsion springs. During a vehicle's slowing down phase, a steady rise of torque occurs, from near zero to maximum, limited with the vehicle's wheel friction to the road surface (Figure 10).

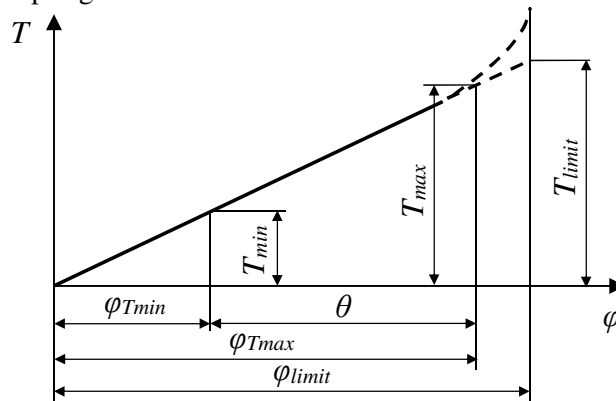


**Figure 10.** Distribution of forces on a vehicle's wheel during braking while recovering energy through a torsion spring.

The dependence between the torsion spring's maximum torque  $T_{max}$ , the road surface's friction coefficient  $\mu$ , the wheel's load  $Q$  and radius  $r$  is shown in equation (1),

$$T_{max} = \mu \cdot Q \cdot r \quad (1)$$

Figure 11 shows a graph of torsion springs characteristics in form of the correlation of a spring's stored torque  $T$  and the spring's angular deflection. The torsion spring's smooth torque's transfer is suitable for the vehicle's energy demands. During braking, when a smooth speed decrease is desired for the user's comfort, the torque increase should be linear; from a minimal  $T_{min}$  to a maximal  $T_{max}$  value. During start-up, the energy needed to overcome the car's rolling resistance, mostly related with the vehicle's weight, is high. Therefore the applied torque should also be linear from a maximal  $T_{max}$  to a minimal value  $T_{min}$ , such as that of the torsion spring.



**Figure 11.** Graph of torsion spring's characteristics in form of torque value  $T$  versus angular deflection  $\phi$  [8].

When choosing springs for an application, an important parameter is the torsion spring index. It is dependent on spring's wire diameter  $d$  and the mean spring diameter  $D$ , and it is calculated as in equation (2). The lower the factor, the more exposed to the stress damage the spring's fibres closest to the axis of the spring will be. Therefore using springs of index not lower than 3 or 4 is recommended.

$$C = \frac{D}{d} \quad (2)$$

What is important for the torsion spring's maximum torque  $T$ , is the correlation of the wire's cross-sectional shape and the curvature of the spring's coil which are known as the  $K$  factor. It is defined differently, dependent of the literary source. For example literary source [8] for calculation purposes of the  $K$  factor provides the following equation (3). However, the factor's value is similar, regardless of the formula used.

$$K = \frac{4C-1}{4C-4} \quad (3)$$

For design assumptions, an exemplary 1H18N9 steel will be used of tensile strength rating  $R_m = 1500 \text{ N/mm}^2 = 1500 \cdot 10^6 \text{ N/m}^2$  and allowable stress in bending as in equation (4) [9]. The torsion spring's maximal torque as in [8] is dependent on the spring's material, in the form of the allowable stress in bending  $k_g$  [ $\text{N/m}^2$ ], the spring's wire diameter  $d$  [mm], and the  $K$  factor. For a spring with mean diameter of  $D = 30 \text{ mm}$ , the wire's diameter of  $d = 6 \text{ mm}$  and  $n = 35$  number of coils, the maximal achievable torque can be calculated from an equation (5).

$$k_g = \frac{R_m}{x_{Rm}} = 0.7 \cdot R_m = 0.7 \cdot 1500 \cdot 10^6 = 1050 \cdot 10^6 \frac{\text{N}}{\text{m}^2} \quad (4)$$



$$T_{max} = k_g \cdot \frac{\pi \cdot d^3}{32 \cdot K} = 1050 \cdot 10^6 \cdot \frac{3.14 \cdot 0.006^3}{32 \cdot 1.19} = 18.7 \text{ N}\cdot\text{m} \quad (5)$$

The maximal torque can be achieved safe only with an optimal twist angle. The spring's twist angle  $\varphi_{Tmax}$ , dependent of the maximal torque, the spring's material, in form of the Young's modulus  $E$ , the spring's wire diameter  $d$ , the  $K$  factor and the length of the spring  $l$  can be calculated as in equation (6).

$$\varphi_{Tmax} = 114.5 \cdot \frac{k_g \cdot l}{K \cdot d \cdot E} = 114.5 \cdot \frac{k_g \cdot \pi \cdot D \cdot n}{K \cdot d \cdot E} = 114.5 \cdot \frac{1050 \cdot 10^6 \cdot 3.14 \cdot 0.03 \cdot 35}{1.19 \cdot 0.006 \cdot 190 \cdot 10^9} = 292.2^\circ \quad (6)$$

The spring's twist angle  $\varphi_{Tmax}$ , which is dependent of the maximal torque  $T_{max}$ , should be checked for buckling. The spring's limit twist angle  $\varphi_{limit}$ , given safety factor's value 2, can be calculated as in equation (7).

$$\varphi_{limit} = 123.1 \cdot (n)^{1/4} = 299.4^\circ \quad (7)$$

The lesser value of the spring's twist angle  $\varphi_{Tmax}$ , in comparison with the limit twist angle value  $\varphi_{limit}$ , means that the chosen torsion spring can safely produce 18.7 Nm with the spring's twist angle of 292.2°. It should be reviewed whether the spring's project length was correctly assumed and what correlations are there between the spring's length, diameter and twist angle. Therefore, new factors will be introduced:

- the  $\Delta D$  factor, the difference between the spring's mean diameter  $D$ , and the decreased diameter  $D'$  while in twist angle  $\varphi_{Tmax}$ , shown in equation (8).
- the  $\varphi'$  factor, a percentage use of the limit twist angle, a quotient of the spring's twist angle  $\varphi_{Tmax}$  and the spring's limit twist angle value  $\varphi_{limit}$  is shown in equation (9).

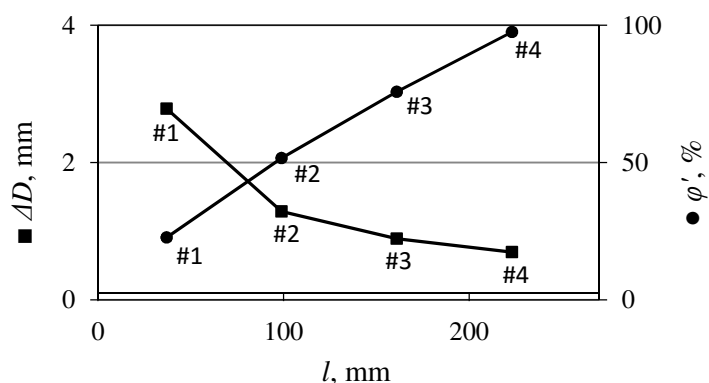
$$\Delta D = D - D' \quad (8)$$

$$\varphi' = \frac{\varphi_{Tmax}}{\varphi_{limit}} \cdot 100 \% \quad (9)$$

The correlations of the spring's length and the  $\Delta D$  and  $\varphi'$  factors for a spring of 30 mm mean diameter, of 6 mm wire diameter, under the load of 18.7 Nm, for 4 sample springs were presented in table 2 and graphically in Figure 12.

**Table 2.** The correlation of the spring's length and the  $\Delta D$  and  $\varphi'$  factors

Parameter	Sample spring number			
	#1	#2	#3	#4
$l$ , mm	37	99	161	223
$\varphi_{Tmax}$ , °	42	125	209	292
$\varphi_{limit}$ , °	184	242	275	299
$\varphi'$ , %	23	52	76	98
$\Delta D$ , mm	2.78	1.29	0.89	0.70



**Figure 12.** The correlation of the spring's length and the  $\Delta D$  and  $\phi'$  factors

The results from table 2 show that with the increase of spring's length the percentage use of the spring's limit twist angle  $\phi_{\text{limit}}$ , increases. However, the  $\Delta D$  factor decreases, which means that the longer the spring, the lower is the diameter reduction during the twist.

Analysing the formula from equation 6 and the results from table 2, the torque obtained is not dependent on the spring's length, which means that the desired torque  $T_{\text{max}}$  could be achieved with a shorter spring with lower twist angle, but with a greater mean spring diameter reduction. However, this would result in earlier deterioration of the spring's characteristics. For the kinetic energy recovery system's reliability purposes, a rather long spring should be used, because of the lower decrease in the spring's mean diameter  $D$  while in twist angle  $\phi_{T_{\text{max}}}$ .

Analysing the results of the above performed calculations, it can be assumed that the proposed concept of the kinetic energy recovery system comprising four torsion springs, would allow great recovery of the vehicle's kinetic energy, which is normally lost during the braking process. It should be noted that the described concept's parameters, such as: dimensions, weight, production costs, energy recovery effectiveness and savings resulting from the system's use are unknown. Nonetheless, the device's advantages, such as low maintenance cost, reliability and no efficiency losses due to the lack of energy conversion, allows the author to believe that it is reasonable to develop a test model of such a solution. Additionally, because of the aforementioned work characteristics of torsion springs, this system would ideally complement the electric energy recovery systems used nowadays. The use of both kinetic- and electric energy recovery systems would greatly raise the effectiveness of energy recovery.

## 6. Conclusions

Recovery of a motor vehicle's kinetic energy, as the most developmental method of reducing fuel consumption, attracts the attention of both car manufacturers and vehicle users. Contemporarily, many car manufacturers use hybrid electric drives, which recover energy during a vehicle's braking phase and utilize it for acceleration- or powering of electric consumers purposes. Kinetic energy recovery systems, e.g. using flywheels as means of energy storage, draw little interest. The proposed idea of a kinetic energy recovery device using torsion springs to store energy, would complement the currently used electric energy recovery systems perfectly. It requires little time to store kinetic energy and it is safe, when comparing to kinetic energy accumulators using flywheels as means of kinetic energy storage. The use of both kinetic- and electric systems alongside each other in order to reduce fuel consumption and thereby lower emissions of harmful and toxic substances in the atmosphere seems very promising.

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