Innovation Examples for Ecological Vehicles based on Aerospace Research

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***Abstract*—In this paper innovative technologies from the aerospace research are presented, which are usable for a successful electric mobility of the future. They represent a selection of the German aerospace center research projects, where synergies between space and aviation applications as well as between rail and road traffic applications are used. The work relates to the fields of vehicle-energy concepts, alternative energy converters and lightweight design. Within the individual development projects hardware demonstrators were created and are shown here.**

Keywords*—thermal management; cabin air conditioning; fuel cell; free piston linear generator; range extender; thermoelectric energy conversion; wheel hub motors; micro gas turbine; lightweight design

I. Introduction

On the way to an affordable mobility for all people the development of an all vehicle systems relevant electric mobility has a high priority. In the aviation and space research field there are system-related technologies already existing, where their advantages can be transmitted to ground operation vehicles. In addition, the German Aerospace Center (DLR) is working on independent traffic issues to improve the efficiency, security and affordability of new vehicle concepts. The activities mostly relate to alternative drive technologies, as well as to the reduction of rolling resistances, both have the intent to increase the energy efficiency of vehicles. A further issue is the usage of new energy carriers as hydrogen or different alternative fuels. In this paper some examples of innovative technologies from both areas are presented that are available for electric vehicles in the future. They are restricted to technical components and are focused to increase the total efficiency of ecological vehicles.

The German Aerospace Center is able to use a wide spectrum of research infrastructure. There are synergies to the space field, the aeronautic field, the energy sector as well as to the transport field. Furthermore it can use the research test equipment like a vehicle roller test bench, a drive simulator, a dynamic crash test bench, wind channels or a test setup for cabin air conditioning studies, see fig. 1. A fleet of test vehicles completes the research infrastructure. The experiences and the knowledge made in the areas of aerospace are transmitted here beneficial for the development of new vehicles. In the following chapters individual topics are described which have a close connection on the synergies to the field of aerospace.

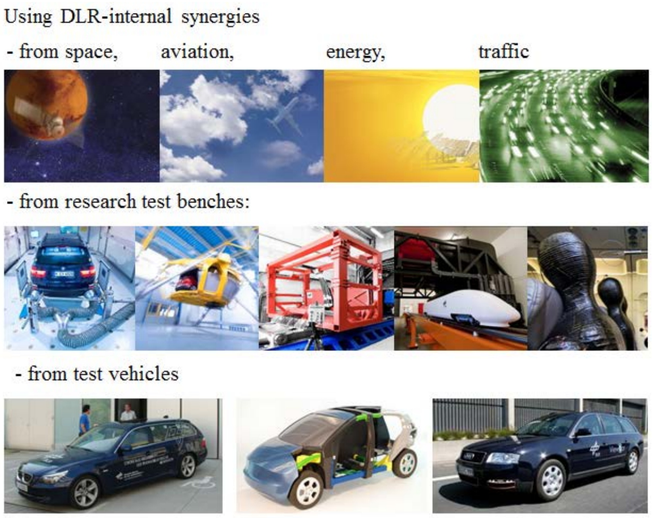

Fig. 1. *Using the synergy potetial from the research infrastructure*

II. Vehicle Energy Concepts and Alternative Energy Converters

A. Thermal Management

Particular attention is due to the thermal management of electric vehicles. Air management already exists in aircrafts, simulation and test procedures used in the aviation branch are applied to the cabin air conditioning system of electric vehicles.

In the area of aircraft cabin air conditioning flow simulation and verification methods are applied using a multi colour laser three dimensional layer visualization. Therefore a large number of heated dummies are placed in the cabin as shown in fig. 2. This setup is used to investigate different kinds of air streaming concepts to reduce the power consumption for the air conditioning of the cabin. This research method is transferred to road vehicles where a vehicle cabin mock-up is designed. With this mock-up various concepts for air conditioning can be tested, for example large-scale introduction of heat at a low temperature level, infrared radiation heating, the use of coated windows or the applicability of thermal storage.

Test vehicles are used for verification of the simulation models. The heating-up of the cabin is assessed with thermographic images. They help to verify the calculation models and show the characteristics of individual factors such as the thermal conductivity of the windows, but also the air flow through seals or openings as well as additional thermal insulation by attaching parts.

Fig. 2. *Thermal management in vehicles based on experiences in aircraft cabin climate management*

Another research focus in the area of thermal management is to investigate the usability of thermochemical reactions on the basis of hydrogen storage [1]. Hereby, it is possible to store chemical energy for long periods without loss and to produce heat on one side and on the other side the reactant cold at a later time by selectively turning on the chemical reversible reaction. The advantage of this storage technique is to get high energy densities compared to those as with sensitive or latent heat. This difference can be expected to factor 10. This can be used for more rapid heating of the cabin or to warm up the battery.

Thermal management is essential and necessary for the operation of fuel cells which are combined with hydride storages. Because the storage cools down during unloading and the fuel cell heats up, a thermal coupling between the two components is obvious for the optimization of the operation. Fig. 3 shows a thermal circuit simulation model for cooling and heating the cabin, the electrical drive train components and the combination of fuel cell and hydride storage of a future car. It is also suitable to calculate the behavior of high temperature PEM fuel cells in which the heating phase plays an important role.

The simulation model is used to minimize the energy effort for starting the drive system as well as to minimize the cold start period of the fuel cell system. The simulation model is implemented in Dymola/Modelica as the simulation language [2]. Within a model library called AlternativeVehicles the mechanical, electrical and thermal energy flows of complete vehicles can be calculated.

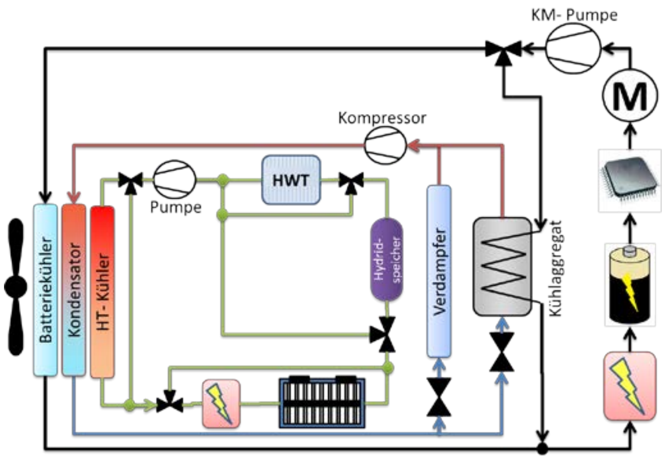

Fig. 3. *Thermal circuit of a high temperature fuel cell vehicle including the combination of fuell cell and hydride storage, AC-circuit and climatisation of the technical components*

B. *Fuel Cells*

The use of hydrogen as an energy carrier is well known from spacecraft applications. Fuel cells have been studied and developed since the early days of space travel. They had systemic advantages in relation to their weight in comparison to batteries, and they were able to use the fuel hydrogen of the spacecraft. A further advantage is their ability to produce water and heat, usable by the crew or for heating up the refrigerated fuel. The Gemini, Apollo and Space Shuttle programs exploited these advantages to benefit.

Vehicles moving in the earth's atmosphere do not have to carry the oxygen with it and they do not have to warm it up. Here we use advantageously air breathing systems. In the aviation sector the oxygen-depleted air, the exhaust gas of the fuel cell, would be also used to fill the kerosine tanks of the aircraft to reduce the risk of explosion.

In the traffic field fuel cells offer the possibility to use renewable produced hydrogen to run longer distances without emissions. The fuel cell can be used as a range extender, where it can be also used as an auxiliary heater. A great advantage of the fuel cell is in the provision of heat, which does not have to be teken as electrical energy from the battery. The fuel cell has a great development potential for future vehicles. Changing requirements make the applicability of fuel cell technology over and over again in question. While the dynamic characteristics of the fuel cell are behind those of batteries or capacitors, their stationary use such as a range extender for electric vehicles is ideal. This is especially true for vehicles that are operated in urban areas, because the average power in the city traffic is about the performance of the steady state operation of the range extender unit. Depending on the size of the range extender unit, the question of range is then only depending on the size of the tank. Fig. 4 shows a DLR invented car which was equipped with a fuel cell powered drive train.

The challenges for fuel cells in the automotive technology are in the development of their efficiency by increasing the operating temperature and in the provision of an appropriate charging and refueling infrastructure. The further development is strongly linked to the thermal management methods as mentioned in the chapter before.

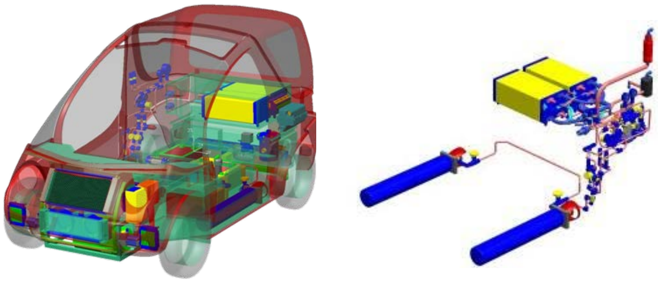

Fig. 4. *Electric vehicle equiped with a fuel cell powered drive train*

C. *Free Piston Linear Generator*

A special energy converter to generate electrical energy represents the free piston linear generator [3]. It converts the kinetic energy from the purely linear movement of the piston of a combustion process with a linear generator [4] directly into electrical energy, working without a rotating crankshaft. The piston is flying in a free movement against a gas spring. He carries permanent magnets, which induce a voltage in an electrical coil. The complete system thus represents a high integration of a combustion linear engine and an electrical linear machine, see fig. 5.

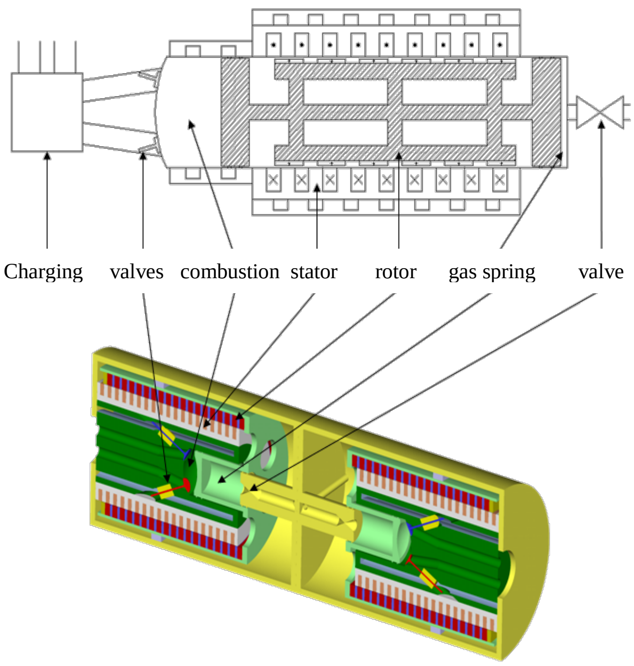

Fig. 5. *Schematic design of the free piston linear generator(upper figure) and design of two opposing systems (lower figure) to minimize vibration*

The piston stroke is adjustable. This increases the efficiency of the total system compared to one with a conventional internal combustion engine especially under part load condition. The electrical energy for hybrid vehicles or range extender vehicles is generated with a higher efficiency. In addition, the free piston linear generator offers the possibility to use different fuels due to its adjustable compression. Due to its compact and modular design it offers more installation options.

Fig. 6 shows the test bench of the free piston linear generator developed at the German Aerospace Center, consisting of the separate components gas spring, linear generator, a hydraulic actuator to simulate the movement of the piston and the combustion chamber with a variable electromagnetic valve unit. The gas spring is used to control the way of the piston or the pressure in the cylinder. With the linear electric machine the system can be started and the electric energy can be coupled out. The hydraulic actuator is only used during test procedures. In case of a failure the hydraulic actuator can catch up the mechanical force to avoid damage of the parts, especially of the valves. The inlet and outlet valves are moved by electromagnetic actuators.

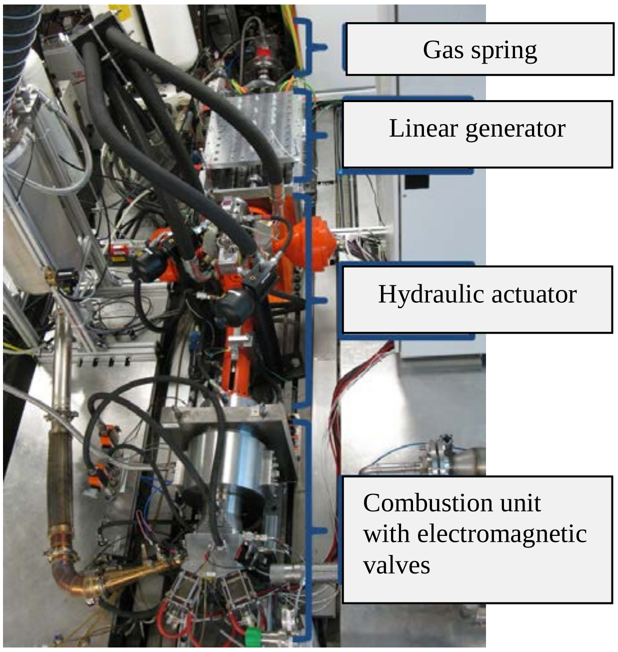

Fig. 6. *Free Piston Linear Generator on the test bench*

While in the past the main focus of the research project was to study the three components gas spring, linear alternator and combustion process separately, at the end of 2012 it was worldwide the first time that such a system operated in a stand-alone operation. This means that the control of the combustion process and the control of the generator have worked without additional protection. The challenge is to control the system and there are a lot of system parameters which could be used: the parameters of ignition and combustion, the parameters of the electrical machine and the parameters of the adjustable gas spring.

D. *Micro Gas Turbine*

From aircraft propulsion technology as well as from the energy sector gas turbine technologies are well known, fig. 7. Their application to stationary usage or to automotive applications on a smaller power range also offers an opportunity for range extender concepts. Another advantage is the ability to use natural gas for a better CO_2-behaviour.

Maximum temperatures and the shapes of the metallic turbine blades still limit the mechanical efficiency of small gas turbines today. With a thermal or thermoelectric recuperator the efficiency can be raised. The disadvantages of the limited efficiency can be balanced by the benefits of running and reliability because the turbine has only one continuously rotating shaft. Another advantage is the ability to operate with different fuels such as using the free piston linear generator.

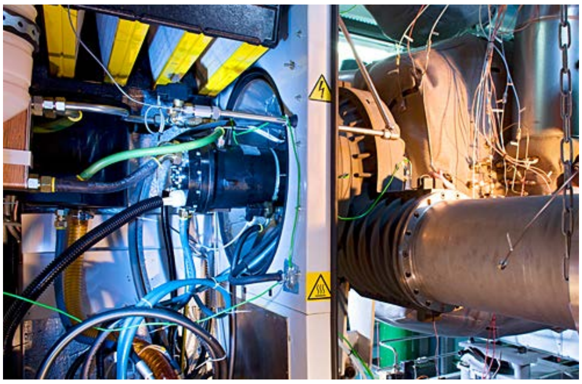

Fig. 7. *Micro gas turbine on the test bench*

Development potential of the micro gas turbine consists in increasing the electrical efficiency and in the development of innovative combustor concepts for further reduction of emissions and increasing the fuel-flexibility.

E. *Thermoelectric Energy Conversion*

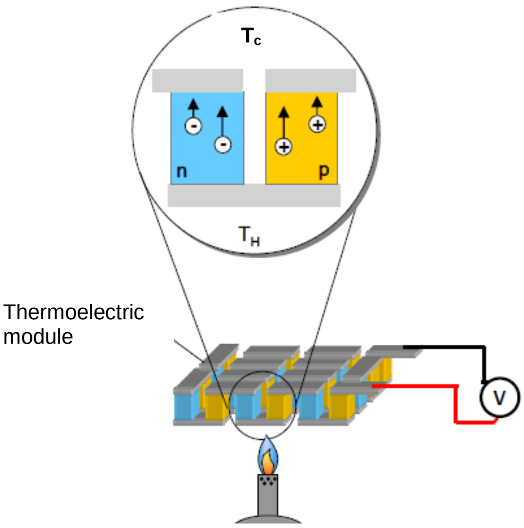

Fig. 8. *Thermoelectric energy conversation based on Seebeck-effect, T_c is the temperature at the cold side, T_h the temperature at the hot side*

In all cases where waste heat is produced at a high temperature level, for example from combustion processes such as electric vehicles with range extender, the use of thermoelectric energy conversion is possible. The technology is well known from satellite energy supply. The basis is the use of the Seebeck effect, which states that a thermoelectric material generates an electric voltage when it is subjected to a temperature difference, fig. 8. According to its internal electrical resistance, the voltage source may provide electrical power. The voltage produced by the temperature difference is

$$U = S \cdot \Delta T, \qquad (1)$$

where S is the Seebeck-coefficient. Thermoelectric materials are characterized with the ZT-value as a dimensionless number which includes the quality of Seebeck constant *S* and the application temperature *T*.

$$ZT = S^2 \times \frac{\sigma}{\kappa} \times T \qquad (2)$$

It is important to recognize the opposite requirement in itself to the material, to have a good electrical conductivity σ at the same time with a poor thermal conductivity κ. These characteristics have semiconductor materials which are optimized by means of doping processes. Their mechanical behaviour is similar to that of ceramic.

The efficiency results in an equation which depends on a high carnot efficiency and on a high ZT-value:

$$\eta = \frac{P_{el}}{Q} = \frac{T_h - T_c}{T_h} \cdot \frac{1}{\frac{1}{4ZT} + 2 - \frac{1}{2}\frac{T_h - T_c}{T_h}} \qquad (3)$$

P_{el} is the electric power, Q the thermal Power, T_h the temperature at the high side and T_c the temperature at the cold side. Fig. 9 shows the ZT-values of typical thermoelectric materials. For the demonstrators in the automotive branch PbTe and Bi_2Te_3 are the most used materials.

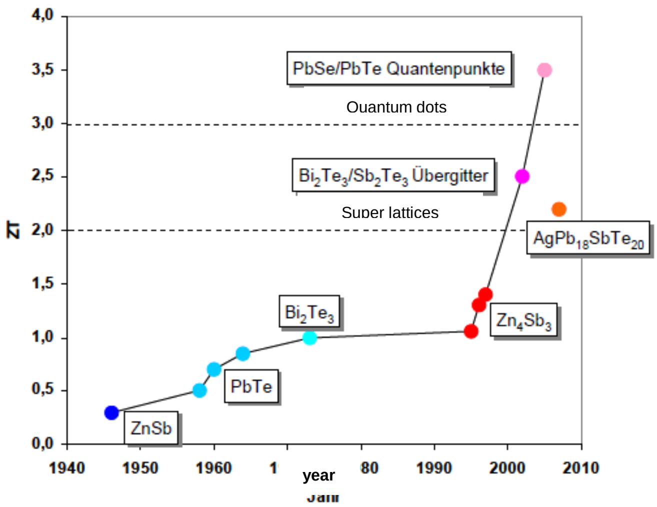

Fig. 9. *Thermoelectric materials characterized by their ZT-value*

Fig. 10 shows the mechanical design of a thermoelectric generator for use in a vehicle. The thermoelectric modules (yellow) are disposed between heat exchangers for the exhaust gas (red) and the cooling medium (blue). The thermoelectric generator is installed in the exhaust line of the vehicle, connected to the cooling circuit and to the electric board net.

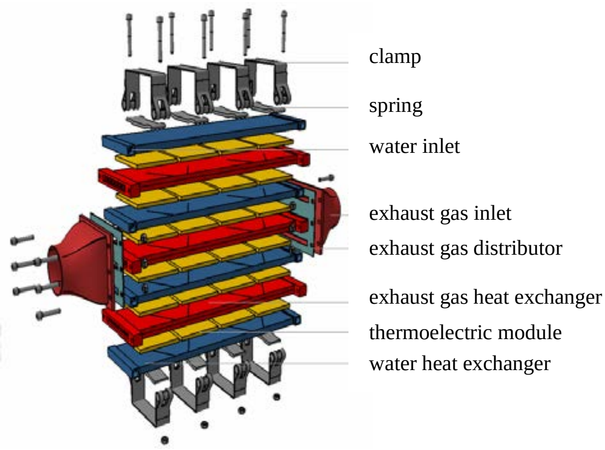

Fig. 10. *Thermoelectric generator for vehicle application*

Electrical energy is generated from the heat of the exhaust gas. This is also applicable on purely internal combustion engine driven vehicles. There is a successful application from the DLR in a road vehicle published first time since 2008 [5], see fig. 11. 200 W of electric power were generated to disburden the vehicles alternator or to feed the vehicles board net. The thermoelectric generator in this application is protected against overheating by a bypass in the exhaust line.

Fig. 11. *Thermoelectric generator integrated in the exhaust system of a car with combustion engine*

F. Wheel Hub Motors

For new vehicle concepts no longer the size of the combustion engine is crucial for the space and the integration of the powertrain components. In special cases it is natural to use the space inside the wheels to accommodate the drive motors. The advantage is the improvement in the driving dynamics of the individually driven and steerable wheels. In the past, these innovative and highly integrated hub motors for moving a passenger aircraft were presented first time in the world in 2011 [6], see fig. 12, and as a conceptional study later on in train applications [7] as shown in fig.13.

Starting from the question of whether a passenger aircraft can move independently on the ground, an electric hub motor has been designed which can be mounted easy on the axle of the nose landing gear of an Airbus A320. The purpose of the development was to demonstrate the feasibility of such a drive. The drive is characterized by its compactness, which was possible because the rotor of the electric machine, which normally forms with its material the magnetic yoke of the permanent magnet excitation, also forms the planet carrier of a two-stage planetary gear. The electric machine has a relatively high number of pole pairs and is designed as a ring machine which provides the space within the rotor for the gear and the clutches. The two motors of the nose landing gear produce a torque up to 11 kNm and may brake away the aircraft and may move the aircraft on a taxiing way with a slope up to 1.5 % [6].

Fig. 12. *High integrated electrical machine in a wheel hub motor based on a project for autonomous taxiing of a passenger aircraft [6]*

Extending the question of whether it is possible to transmit the driving power for a double deck high-speed train with single wheel drives to the rail, a concept for a combined electrically-permanent magnet excited synchronous machine was designed [7]. The electric machine fits into the disk-shaped space of a wheel. It can be controlled by the excitation current from zero to maximum excitation, which is an advantage for the generation of high flux densities during startup, but also for the field weakening at high speeds. Due to the complete de-excitation, the train may roll out without additional losses, which would not be possible in pure permanent magnet excited machines without the use of an additional mechanical coupling.

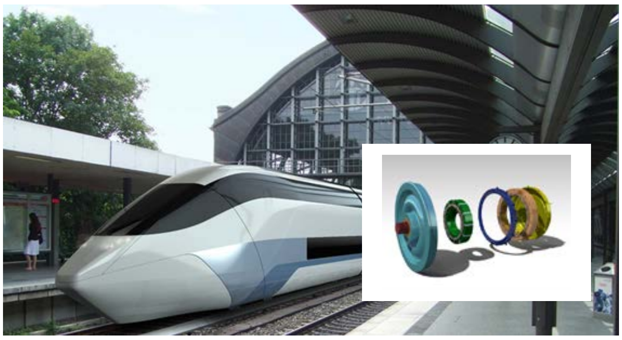

Fig. 13. *Wheel hub motor for a double deck high speed train [7]*

According to this work a wheel hub motor for an electric vehicle was designed as shown in fig. 14. It is part of the concept car which includes the technologies described in this paper and which is shown in fig. 16. Special attention had to be pay to the sealing at a low diameter and the cooling concept of the electrical machine. In all cases, the integration of a mechanical brake is the biggest challenge. In this particular case a drum brake was used advantageously.

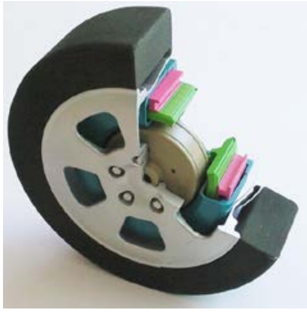

Fig. 14. *Wheel hub motor for electric vehicle concept*

III. LIGHTWEIGHT DESIGN

From the aircraft structure the frame construction is known, advantageous by its modularity and in its mechanical strength while minimizing the weight. The application of this technique to the design of the vehicle's structure also allows the investigation of new types of materials such as fiber composite in relation of its applicability in vehicles.

An example is a circular carbon fibre reinforced plastic (CFRP) rib construction at the position of the b-pillar that creates a light, safe passenger compartment to assure the safety of the passengers as well as the components of an alternative drive train in case of a side crash, see fig. 15. This is associated with the introduction of new energy absorbing structures which allow a safe storage of the powertrain components and ensure sufficient security conditions in frontal as well as in side impact situations [8].

Fig. 15. *Frame chassis construction for new vehicle design based on aircraft design*

IV. CONCLUSION

Different technologies from the areas vehicle energy concepts and alternative energy converters even from the light weight area were shown in this paper. They all are based partly on aerospace research in the past. The results and experiences help to define new vehicle concepts, especially in creating new knowledge about the functional behavior between the technologies. One example of an electric vehicle concept is shown in fig. 16, which includes the wheel hub motors, the frame chassis and a range extender, itself consisting of a free piston linear generator as described above. The range extender could also be a micro gas turbine or a fuel cell system. To increase the total efficiency of the power train it could be helpful to use the thermoelectric energy conversion, depending on the size of the chosen components. The technologies described in this paper could also be part of a Next Generation Car, which includes the main research fields of vehicle concept, vehicle structure, drive train, chassis, thermal management and vehicle intelligence and which is part of the future activities in the German Aerospace Center.

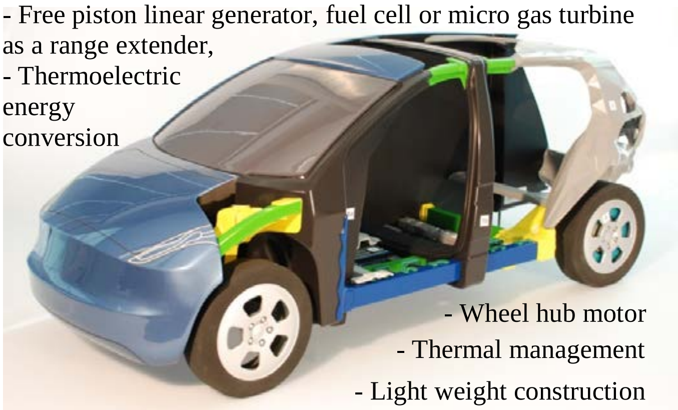

Fig. 16. *Conceptional car including the technologies described in this paper*

ACKNOWLEDGMENT

To investigate this field of technologies many institutes which were not named separately have taken part of it. These are the Institute of Technical Thermodynamics, the Institute of Combustion Technology, the Institute of Materials Research, the Institute of Robotics and Mechatronics and the Institute of Aerodynamics and Fluid Technology.

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