2014

Comparison and Evaluation of a New Innovative Drive Concept for the Air Conditioning Compressor of Electric Vehicles

Joerg Aurich
IAV GmbH, Germany, joerg.aurich@iav.de

Rico Baumgart
IAV GmbH, Germany, dr.rico.baumgart@iav.de

Christoph Danzer
IAV GmbH, Germany, christoph.danzer@iav.de

Jan Ackermann
IAV GmbH, Germany, jan.ackermann@iav.de

Comparison and Evaluation of a New Innovative Drive Concept for the Air Conditioning Compressor of Electric Vehicles

Joerg AURICH[1]*, Rico BAUMGART[1],
Christoph DANZER[1], Jan ACKERMANN[1]

[1]IAV GmbH
Chemnitz, Germany
joerg.aurich@iav.de
+49 (0)371 237 34917

* Corresponding Author

ABSTRACT

The development of energy efficient air conditioning systems for electric vehicles is an ever increasing challenge, because the cooling as well as the heating of the passenger compartment reduces the cruising range dramatically.

Almost always the compressor of the air conditioning system in electric cars is a scroll compressor with a separate electric motor and appropriate power electronics. However, this solution is critical in terms of the installation space, the weight and also the costs. Therefore, IAV is developing an innovative and energy efficient drivetrain structure for electric vehicles, which integrates the motor of the air conditioning compressor directly into the drivetrain of the vehicle.

Thus it is possible to switch off the compressor motor and to use the main motor for the drive of the air conditioning compressor at certain driving situations. As a result, the operating point of the main motor can be shifted to a better efficiency. This leads to a reduced power loss and an enhanced cruising range. In addition, the compressor motor can be used to contribute to the powertrain of the vehicle, as well, if the efficiency of the compressor motor is higher than the efficiency of the main motor, e.g. in urban traffic. Thereby the efficiency and the cruising range of the vehicle can be increased.

This contribution presents a new powertrain concept which realizes the above mentioned mechanical coupling of the main motor and the compressor motor. Moreover, the simulation models developed for the air conditioning system, the passenger compartment and the drivetrain of electric vehicles are introduced. These models were used to compare an electric vehicle equipped with the new powertrain concept with a common electric car with a separate scroll compressor. Both systems are evaluated by means of the achievable cruising range for different driving cycles and environmental conditions.

1. INTRODUCTION

The high acquisition costs and the limited cruising range are major barriers for a wide diffusion of electric vehicles. The air conditioning system, which is standard equipment for almost all new vehicles by now, has a significant influence on the energy consumption and thus on the cruising range. However, the drive concept of the air conditioning compressor of electric vehicles is fundamentally different to conventional cars.

With conventional vehicles the compressor is driven by the internal combustion engine. Thus, the compressor speed depends on the engine speed. In order to adjust the refrigerant mass flow rate to the cooling demand, externally controlled axial piston compressors with a variable displacement are used.

Contrastingly, with all known drivetrain structures of electric vehicles the air conditioning compressor has no mechanical connection to the main motor. The compressor is equipped with a separate electric motor and with its own power electronics. Thus the compressor speed can be controlled independently of the main motor speed. Therefore, scroll compressors are usually used.

However, both concepts have specific disadvantages: The axial piston compressor has a significant reduced efficiency at low displacements. The common drivetrain structure of electric cars with a separate electric motor for the compressor is critical in terms of the installation space, the weight and the costs.

Therefore, it is worthwhile to combine the advantages of both concepts to a new powertrain structure for electric vehicles.

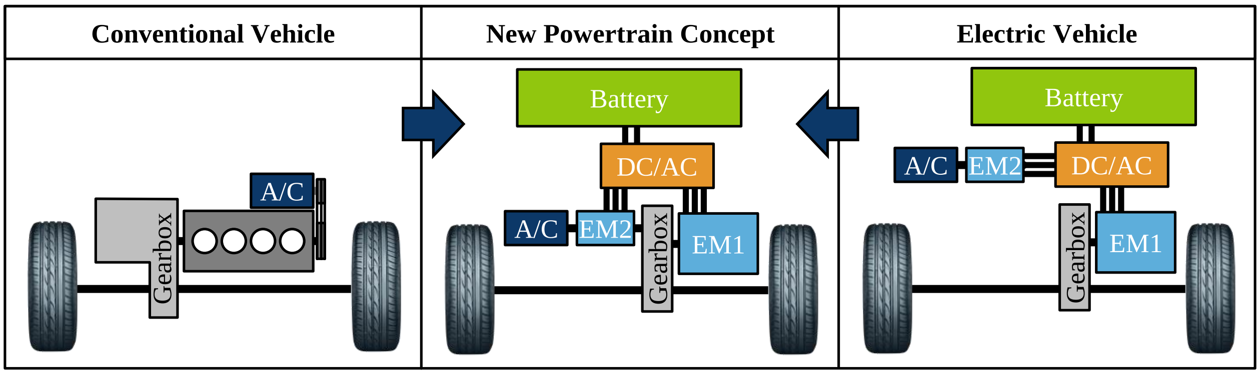

Figure 1: Powertrain structures (schematic)

The new powertrain concept, which is illustrated in Figure 1, uses an externally controlled axial piston compressor. This compressor is equipped with an electric motor (EM2) and a mechanical coupling to the gearbox and the main motor (EM1) respectively.

Thus it is possible to switch off the compressor motor (EM2) at certain driving situations and to use the main motor (EM1) for the drive of the air conditioning compressor. As a result, the operating point of the main motor can be shifted to a better efficiency. This leads to reduced power losses and an enhanced cruising range. In addition the compressor motor (EM2) can be used to drive the vehicle, if the efficiency of the compressor motor is higher than the efficiency of the main motor (EM1), e.g. in urban traffic. Thereby the efficiency and the cruising range of the vehicle can be increased as well.

The following chapter introduces the structure and function of this new powertrain concept. Afterwards the simulation models, which were used for the investigations, are specified. Finally, the modes of operation of the powertrain concept are detailed for different driving cycles and environmental conditions. In addition, the energetic advantages in comparison with an electric vehicle with a conventional powertrain are evaluated.

2. POWERTRAIN CONCEPT

The powertrain concept “Efficient Synergy Drive” (Danzer *et al*., 2012) makes it possible to use the compressor drive for the climatization and also for the drive of the vehicle at partial load. The coupling of two electric motors with the gearbox allows the best possible efficiency at any driving situation, because the required power for the A/C compressor and for the vehicle can be distributed between both motors. The improvement of the operating point reduces the power losses and finally increases the cruising range. Additionally, the two-motor-concept allows an active synchronized two-speed transmission without traction interruption. Thus, this powertrain concept does not require multiple disk clutches and complex hydraulics, which leads to an increased efficiency of the transmission and the whole system.

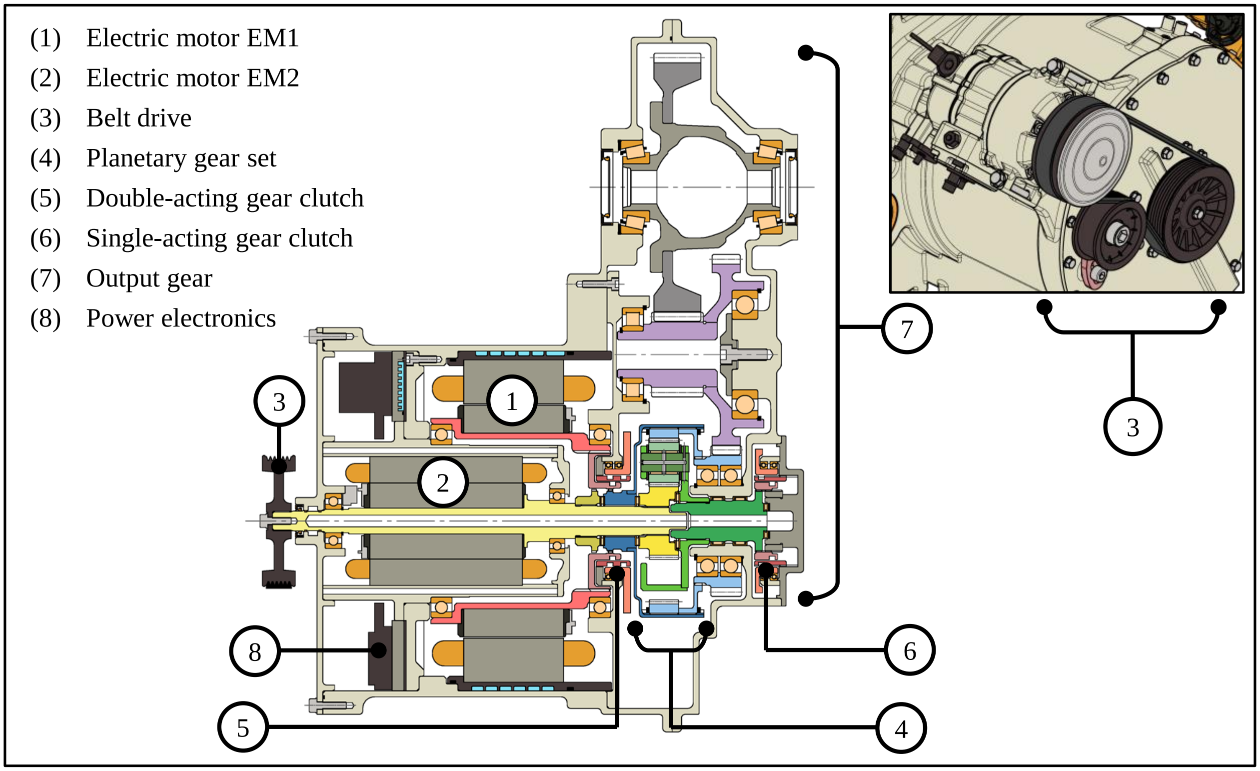

Figure 2: ESD-concept (2D-Draft Construction)

Figure 2 illustrates a draft construction of the ESD-concept. The main motor (EM1) is located on the left side of the housing (1). The compressor motor (EM2, 2) is integrated coaxially inside the rotor of EM1. The air conditioning compressor is driven by a belt drive (3) that is mounted on the motor shaft of EM2. Alternatively, the compressor can be connected directly to this motor shaft.

In the middle of the gearbox the planetary gear set (4) is positioned, which allows the power distribution between the electric motors. The gear set is actuated by a double-acting gear clutch (5) and a single-acting gear clutch (6). The planetary gear set is followed by the output gear (7). Furthermore, the power electronics (8) are integrated in the gearbox housing.

In the following, the functioning of this new powertrain concept will be explained for an exemplary motor configuration at a typical urban driving situation: The speed of the vehicle is 50 km/h and the acceleration is 0.25 m/s^2. Considering the vehicle parameters (Table 1) the required driving power is 7.5 kW. In addition, the required power for the A/C compressor is 0.5 kW, e.g. on a mild summer day after the cool down phase.

With the conventional powertrain structure of an electric car the main motor operates at a partial load of 7.5 kW to drive the vehicle. The compressor motor operates at 0.5 kW. However, both motors are working at inefficient operating points, as can be seen in Figure 3 (gray points). This leads to high power losses and a reduced cruising range of the vehicle.

Contrastingly, with the new powertrain concept the main motor (EM1) can be stopped and the compressor motor (EM2) can be used to drive the vehicle. Thus, the power and also the power loss of the main motor is 0 kW. The compressor motor operates now at 8 kW, which leads to a better efficiency, as can be seen in Figure 3 (black points). Finally, this increases the cruising range of the vehicle.

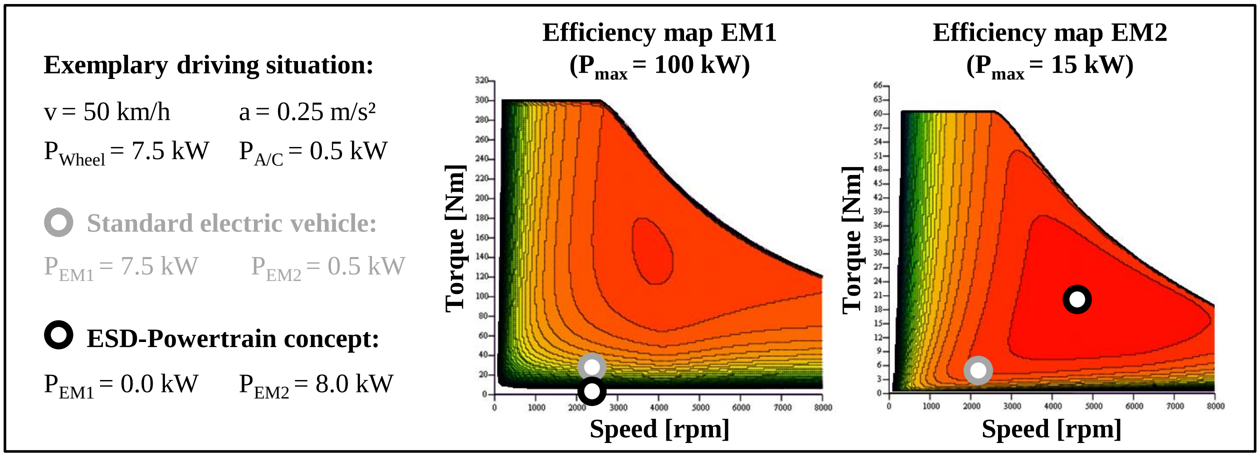

Figure 3: Operating points for an exemplary driving situation and motor configuration

3. SIMULATION MODEL

For the following detailed investigations simulation models for

- the powertrain of electric vehicles,
- the air conditioning system and
- the passenger compartment

were developed (Baumgart, 2010). All these models consist of different submodels. For instance, the simulation model for the air conditioning system includes geometry and process based models for

- the A/C-compressor (axial piston compressor and scroll compressor),
- the heat exchangers (condenser and evaporator) and
- the thermostatic expansion valve.

All simulation models were validated in detail with the help of measurements.

The priority here is a short description of the scroll compressor model. This simulation model is exclusively based on the geometry of the compressor parts and the working physical processes. The input parameters are the scroll geometry and some other geometrical measurements and the operating point, of course, which is characterized by the compressor speed, the inlet and the outlet pressure, the superheating at the compressor inlet and the ambient temperature. Some exemplary results of the model are:

- the refrigerant mass flow rate,
- the driving power and torque,
- the efficiencies of the compressor and
- the pressures and temperatures for any compressor chamber.

The diagram in Figure 4 shows the pressure profile depending on the driving angle for the different compressor chambers. For the used scroll geometry a small leakage path occurs between the fixed and the orbiting scroll at a certain driving angle. This leads to a pressure equalization process between the discharge chamber and the compression chambers (cf. Fig. 4).

Further considered effects of the scroll compressor model are for example the wall heat transfer, the dynamic valve behavior of the outlet valve and the leakage between the compressor chambers.

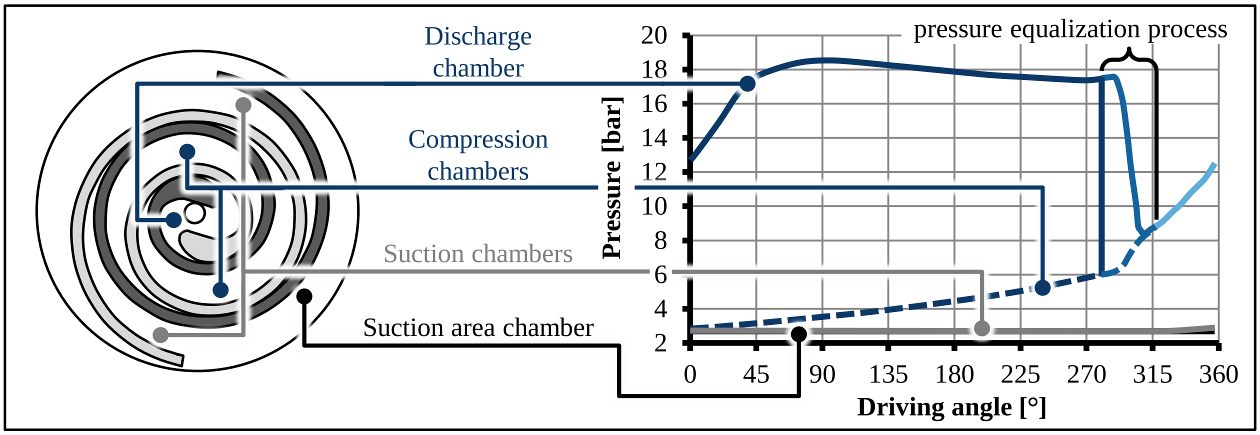

Figure 4: Scroll compressor model: pressure profile for the different compressor chambers

4. SIMULATION CONDITIONS AND ASSUMPTIONS

For the simulations an exemplary electric vehicle was used. Table 1 details the most important parameters of this car.

Table 1: Vehicle parameters

Vehicle parameter	Value	Vehicle parameter	Value
Class	Medium-sized	Air density	1.21 kg/m^3
Weight	1,450 kg	Wheel diameter	0.625 m
Frontal surface area	2.13 m^2	Rolling resistance coefficient	0.009
Drag coefficient	0.33	Battery capacity	25.0 kWh

The simulated car was equipped with a lithium-ion battery with a usable capacity of 25 kWh. The car was driven by a permanent-magnet synchronous machine (EM1) with a maximum output power of 100 kW.

For the reference simulation with a common powertrain structure a conventional electric driven scroll compressor with a displacement of 34 cm³ was taken as a basis.

For the simulation of the new ESD-powertrain a standard externally controlled axial piston compressor with a maximum displacement of 140 cm³ was combined with a permanent-magnet synchronous machine (EM2) with a maximum output power of 5.3 kW.

To achieve comparable simulation results between the standard electric vehicle and the vehicle with the ESD-concept, the functionality of the ESD-concept was slightly reduced: The main motor (EM1) was used to drive the vehicle and, depending on the driving situation and the cooling demand, for the drive of the A/C-compressor. The compressor motor (EM2) was only used for the drive of the A/C-compressor, but not for the vehicle drive. Furthermore, the ESD-concept was used only as a single-speed transmission.

The investigations were based on two different driving cycles: The New European Driving Cycle (NEDC) with its moderate power demand and a maximum speed of 120 km/h (Figure 5a) and the Artemis-Cycle with significant higher power requirements and a maximum speed of about 150 km/h (Figure 5b).

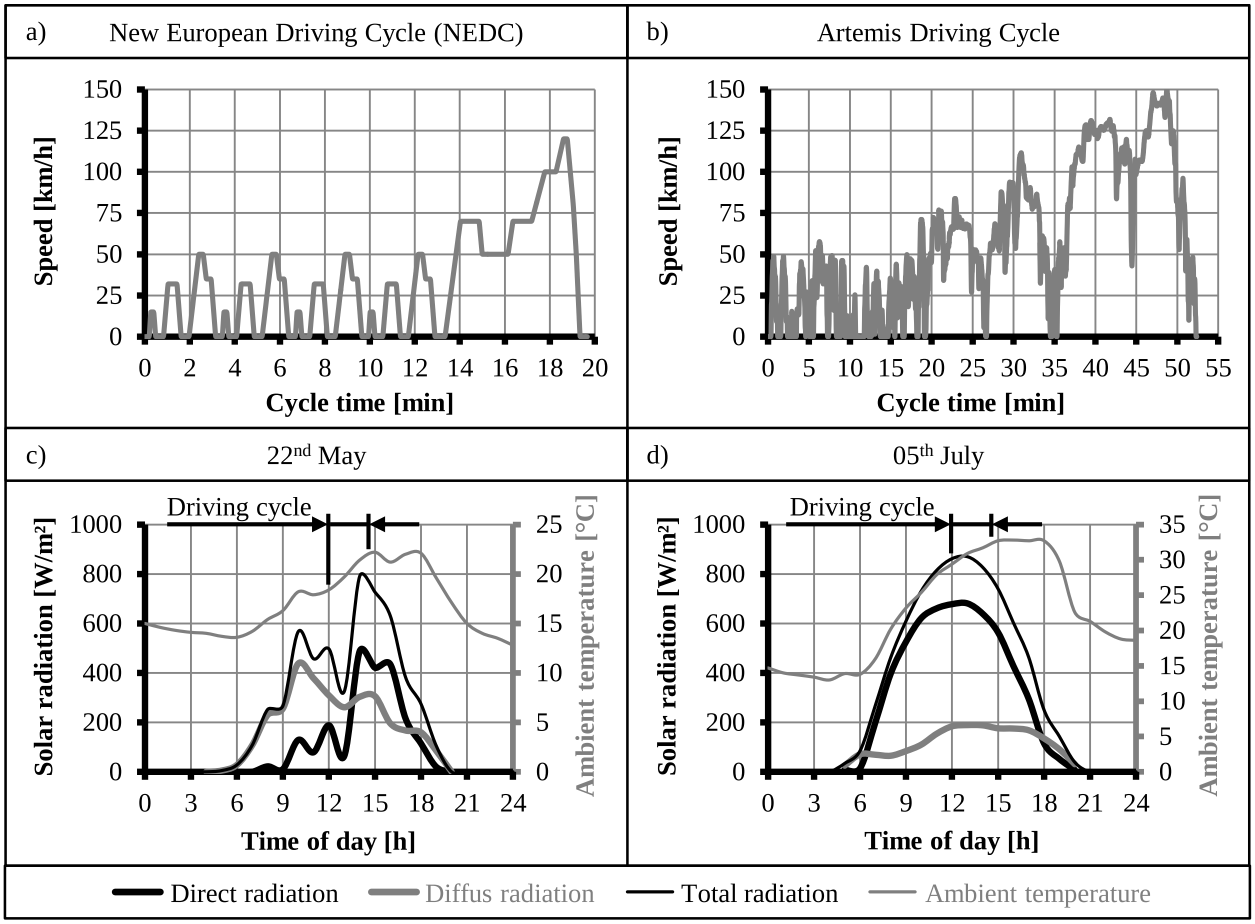

Figure 5: Driving cycles and environmental conditions

The applied weather conditions were taken from the Test Reference Year of the German Weather Service (Christoffer *et al.*, 2004). The simulations have been executed for two different days and were based on the following key values:

- the 22nd May of the Test Reference Year with an average temperature of 21 °C in the investigation period
- the 05th July of the Test Reference Year with an average temperature of 32 °C in the investigation period

The Figures 5c and 5d present the ambient temperature and the solar radiation profile for these two days and the investigation period that started at 12 noon with two hours of parking. The parking period was prefixed onto the cooling down simulation to reach the respective initial temperatures for any component and air zone of the cabin.

The simulation explored the energy consumption of the vehicle during the driving cycle. This result was used to calculate the achievable cruising range with the above mentioned battery.

5. RESULTS

Figure 6a presents the speeds of the main motor and the compressor for a conventional electric car with a separate electric scroll compressor. The results are shown for the Artemis driving cycle and the 05th July of the Test Reference Year. The speed of the main motor correlates with the speed of the vehicle (cf. Fig. 5b) because - as mentioned above - the car was equipped with a single-speed transmission.

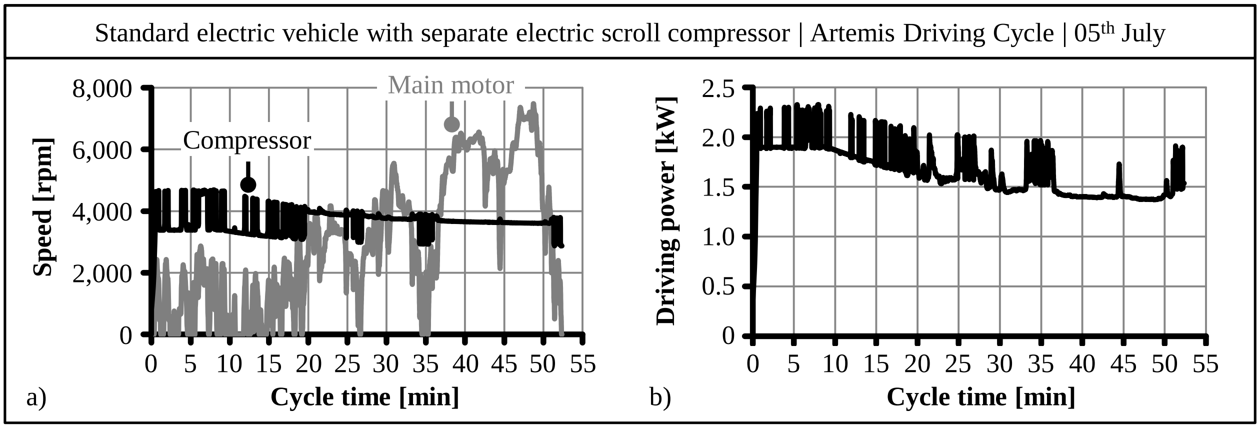

Figure 6: Results for a standard electric car with a separate scroll compressor

The required driving power for the scroll compressor is shown in Figure 6b. At the beginning of the cycle the power is quite high at about 2.3 kW. During the cycle the cooling demand and the driving power are decreasing because the air in the passenger compartment reaches the set temperature. In addition, Figure 6b presents the influence of the vehicle speed on the compressor power, especially between 36 min and 50 min. During this period, the speed of the car is very high (cf. Fig. 5b). This leads to an improved air flow at the condenser, which reduces the pressure ratio in the air conditioning system and consequently the driving power of the compressor.

Figure 7 presents the simulation results for the electric vehicle equipped with the new ESD-powertrain concept and an externally controlled axial piston compressor. The diagram in Figure 7a shows, likewise Figure 6a, the speeds of the main motor (EM1, dark gray curve) and the compressor (black curve), but it is now extended by the speed of the compressor motor (EM2, light gray curve). This speed differs from the compressor speed whenever the compressor is driven by the main motor.

The driving power profile (Figure 7b) of the compressor is qualitatively similar to the reference vehicle. At the beginning of the cycle the driving power is comparatively high and it decreases during the cycle, when the set temperature of the cabin is reached.

Figure 7d illustrates the relative displacement of the compressor. The displacement is regulated whenever the compressor is driven by the main motor (EM1). If the compressor is driven by the compressor motor (EM2), however, the compressor operates nearly at its maximum displacement and thus with its best efficiency.

Below, the operating principle of the ESD-concept, the compressor and the two electric motors will be detailed with the help of an exemplary time of the driving cycle. At the time 1,042 s the vehicle speed is 46.8 km/h and the acceleration is 0.14 m/s² (cf. Figure 7c).

The main motor (EM1) operates at 2,321 rpm and a torque of 24.3 Nm to drive the car. The efficiency of the motor is 86 %, which corresponds to a power loss of 770.7 W (cf. Figure 7e).

The compressor motor (EM2) operates at 1,447 rpm and a torque of 10.6 Nm for the drive of the air conditioning compressor. This leads to a power loss of 88.2 W (cf. Figure 7f).

At this time it is worthwhile regarding the energy efficiency to stop the compressor motor (EM2) and to shift the ESD-transmission, so that the compressor is driven by the main motor (EM1). Thus the efficiency of the main motor (EM1) increases to nearly 90 % (Figure 7e). The sum of power losses decreases from 858.9 W to 801.4 W. This corresponds to a reduction of 57.5 W and 6.7 % respectively at this time.

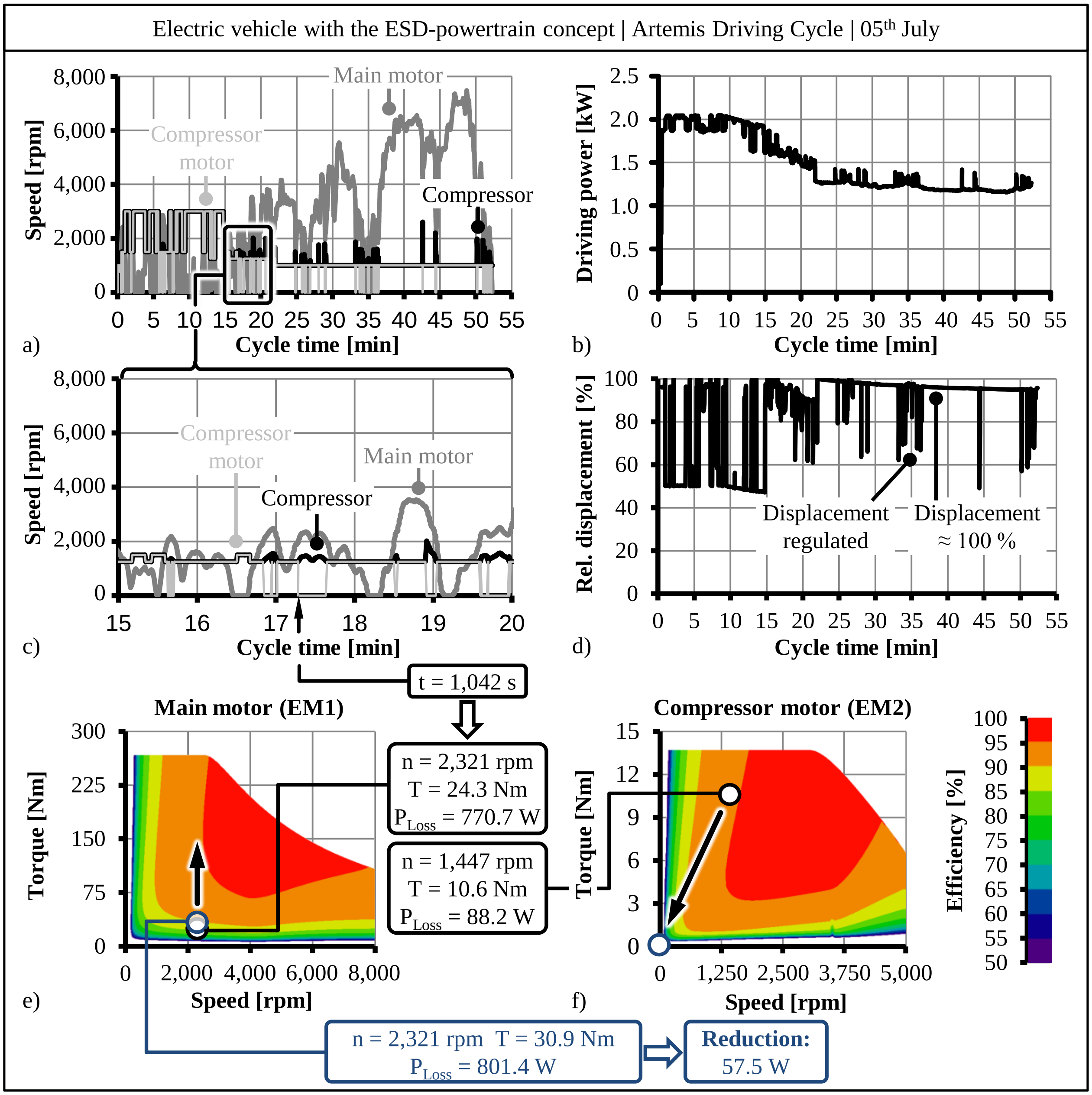

Figure 7: Results for an electric car with the ESD-powertrain (coupled compressor)

Figure 8 presents the achievable cruising range of the electric vehicle with the ESD-powertrain in comparison with a standard electric vehicle. To achieve comparable simulation results, the functionality of the ESD-concept was - as already mentioned - reduced: The compressor motor (EM2) was only used for the drive of the A/C-compressor. The main motor (EM1) was used for the drive of the vehicle and for the drive of the compressor. The most efficient configuration was chosen at any time during the simulation.

The cruising range of the standard electric vehicle with a separate electric scroll compressor is 195.5 km in the NEDC considering the weather conditions of the 22nd May of the Test Reference Year. Using the ESD-concept with an externally controlled axial piston compressor the achievable cruising range can be increased by 8.2 % to an overall distance of 211.5 km.

On the warmer weather conditions of the 05th July the cruising range is less than on the 22nd May due to the higher cooling demand. The standard vehicle reaches only 145.6 km. However, the ESD-concept enables an increase of 1.7 % to 148.0 km.

As already mentioned above, the average driving power of the Artemis driving cycle is significant higher compared with the NEDC. Consequently, the main motor operates at a better efficiency most of the time. This is why the cruising range increase by the ESD-concept is mostly less than in the NEDC. The achievable increase is 2.6 % on the 22nd May and 1.9 % on the 05th July respectively.

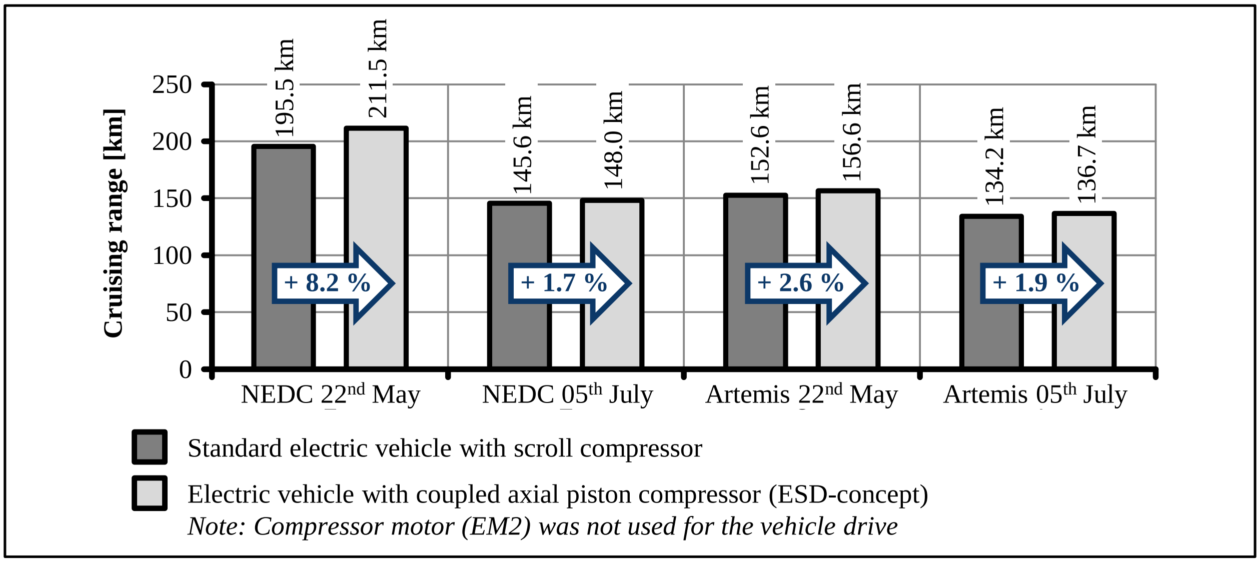

Figure 8: Achievable cruising range

The most significant increase of the cruising range occurs at a medial driving power (e.g. NEDC) and medial temperatures because the main motor (EM1) and also the compressor motor (EM2) are operating at a low efficiency then. By means of the ESD-concept one motor can be stopped and the other one can work at a better efficiency due to the higher load.

The investigations have demonstrated that already the double use of the main motor for the drive of the vehicle and the compressor leads to a remarkable cruising range increase.

A further increase can be achieved by using the compressor motor (EM2) for the drive of the vehicle at certain driving situations (cf. Figure 3). However, this opportunity was not used yet in order to get comparable simulation results.

6. CONCLUSIONS AND OUTLOOK

This contribution introduced the structure and functioning of a new powertrain concept, called “Efficient Synergy Drive” (ESD), first, which makes it possible to use the compressor motor for the climatization and also for the vehicle drive. Additionally, the main motor can be used for the drive of the car and the drive of the compressor, too. The ESD-concept allows an active synchronized two-speed transmission without traction interruption. Thereby, the climatization of the passenger compartment is guaranteed at any driving situation as well as during standstill.

Afterwards, the applied simulation models for the air conditioning system, the passenger compartment and the powertrain have been mentioned. In particular, the geometry and process based simulation model for scroll compressors was described.

These simulation models were used to investigate the achievable cruising range increase by the ESD-concept in comparison with a conventional electric powertrain for an exemplary electric vehicle. The simulations have clearly demonstrated that already the use of the main motor for the drive of the air conditioning compressor leads to a remarkable cruising range increase. A further increase can be achieved by using the compressor motor for the drive of the vehicle at certain driving situations.

Future works will investigate the achievable cruising range by using the full potential of the ESD-concept. Additionally, other driving cycles and weather conditions will be evaluated.

REFERENCES

Baumgart, R., 2010: *Reduzierung des Kraftstoffverbrauches durch Optimierung von Pkw-Klimaanlagen,* Dissertation Technische Universität Chemnitz, Verlag Wissenschaftliche Scripten, Germany, 207 p.

Christoffer, J.; Deutschländer, T.; Webs, M., 2004: *Deutscher Wetterdienst: Testreferenzjahre von Deutschland für mittlere und extreme Witterungsverhältnisse*. Selbstverlag des DWD, Offenbach, Germany, 99 p.

Danzer, C.; Tenberge P.; von Unwerth, T., 2012: Efficiency studies on a new powertrain concept with an integrated simulation approach for electric vehicles, *6th International CTI Symposium and Exhibition: Innovative Automotive Transmissions and Hybrid & Electric Drives*, Rochester Michigan, USA