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Reducing the Fuel Consumption by Optimizing the Air Conditioning System

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ABSTRACT

Today, most cars are equipped with an air conditioning system. However, using this system increases fuel consumption and therefore leads to additional CO_2-emission.
Currently, the Chemnitz University of Technology investigates several promising modifications for reducing CO_2-emission. Some of these modifications were not considered in respective publications yet. The investigation results are presented in the paper and it will be shown that the CO_2-emission caused by the air conditioning system can be reduced significantly.

1. INTRODUCTION

In order to limit negative consequences of global warming, ever-tightening emission regulations are passed, which forces the automotive industry to develop vehicles that emit significantly fewer pollutants. This is an enormous challenge, because the driving comfort and safety must not be impaired. Air conditioning systems, which are standard components of today's cars, contribute essentially to the driving comfort. However, the usage of an air conditioning system increases fuel consumption considerably. To reduce this fuel over-consumption the automotive industry has applied a few modifications, e.g. externally controlled air conditioning compressors. This makes it possible to adjust the displacement to the refrigerating capacity demand and thus to decrease the required driving power, but in this case the compressor is driven with a poor efficiency.

Beside the mentioned displacement control, there are further promising optimization possibilities, that were not considered in scientific investigations up to now. In addition, mostly only midsummer conditions were considered in the publications concerning the optimization of vehicle air conditioning systems, but these are also used in cold seasons to avoid misted up windows. This is why, as will be shown in this paper, the improvements that can be achieved within an entire year have also to be considered for evaluating modifications.

Based on the described situation, geometry and process-based models for

- the compressor,
- the heat exchanger (condenser and evaporator),
- the expansion valve, and
- the passenger cell

were developed at the Chemnitz University of Technology (Baumgart and Tenberge, 2008). These models were combined to one complete model, which simulates the processes in the whole refrigeration cycle and the passenger cell for all driving cycles and environmental conditions. Using this model, several optimization approaches were investigated regarding fuel saving and the reduction of CO_2-emission. Some of these modifications were not considered in relevant publications yet. In the following, some investigation results will be introduced in detail.

2. ADDITIONAL FUEL CONSUMPTION OF AN AIR CONDITIONING SYSTEM

Initially, an air conditioning system equipped with an externally controlled seven-cylinder compressor with a maximum displacement of 155.2 cc was investigated. The transmission ratio of the belt drive between the combustion engine and the compressor is i_{Belt} = 0.741 (into higher speed). Furthermore, it is assumed that the compressor pulley does not include an electromagnetic clutch. Similar compressors are standard components in car types such as Audi A3 and Volkswagen Golf. The above-mentioned air conditioning system serves as a reference for the optimizations investigated in Chapter 3.

Table 1 illustrates the simulated fuel overconsumptions as well as additional CO_2-emissions caused by the air conditioning compressor. The calculations were based on the environmental conditions of two different days in the Test Reference Year for Germany (Christopher *et al.*, 2004), and an urban, an extra urban, and a highway driving cycle.

Table 1: Fuel overconsumption for different conditions

date (start 2.00 pm)	driving cycle	overconsumption [l/(100km)]	overconsumption [l/h]	add. CO_2-emission [g/km]
July 5th	urban	1.505	0.359	34.91
July 5th	extra urban	0.503	0.342	11.68
July 5th	highway	0.323	0.296	7.50
May 23rd	urban	0.525	0.125	12.17
May 23rd	extra urban	0.201	0.137	4.67
May 23rd	highway	0.128	0.117	2.98

Compared to the 5th July, the refrigerating capacity on the 23rd May is lower, because the climate is cooler then, which causes the compressor to operate at a lower relative displacement and driving power. This leads to reduced fuel overconsumptions and CO_2-emissions (Table 1). As expected, the highest distance-related overconsumption of 1.505 l/(100km) is reached in the urban driving cycle under summer conditions (July 5th), which goes along with an additional CO_2-emission of 34.91 g/km.

To determine the annual fuel overconsumption, the urban, the extra urban and the highway driving cycle were distributed over an entire year, which resulted in an overall driving distance of 15,901 km. The weather conditions for the simulation were also based on the Test Reference Year for Germany.

Table 2 provides the results of the simulation for an entire year. For the exemplary marginal conditions, this simulation is based on, the annual fuel overconsumption caused by the compressor is 25.54 l. This is the same as a distance-related overconsumption of 0.161 l/(100km), or rather an additional CO_2-emission of 3.74 g/km.

Table 2: Fuel overconsumption and additional CO_2-emission for an entire year

fuel overconsumption [l]	fuel overconsumption [l/(100km)]	add. CO_2-emission [g/km]
25.54	0.161	3.74

3. REDUCING THE FUEL CONSUMPTION AND THE CO_2-EMISSION

3.1 Increasing the maximum air temperature at the evaporator outlet

To avoid the build up of odors, the air conditioning system is usually operated in a way which keeps the air temperature at the evaporator outlet from exceeding a maximum value of e.g. 10 °C. This value can be increased by applying appropriate coatings, which makes it possible to run the compressor at a lower relative displacement and therefore at reduced driving power.

Figure 1 shows the operating behavior of the standard air conditioning system described in chapter 2 (black curve). The maximum air temperature at the evaporator outlet is 10 °C in this case. This behavior is compared to the results of a maximum air temperature raised by 4 °C (grey curve). The chosen environmental conditions equal those of the 5th July in the Test Reference Year. As a driving cycle, the extra urban cycle has been selected.

environmental conditions	July 5th Test Reference Year of Germany, region 13
starting time [CET]	2.00 pm (14:00 CET)
driving cycle	extra urban

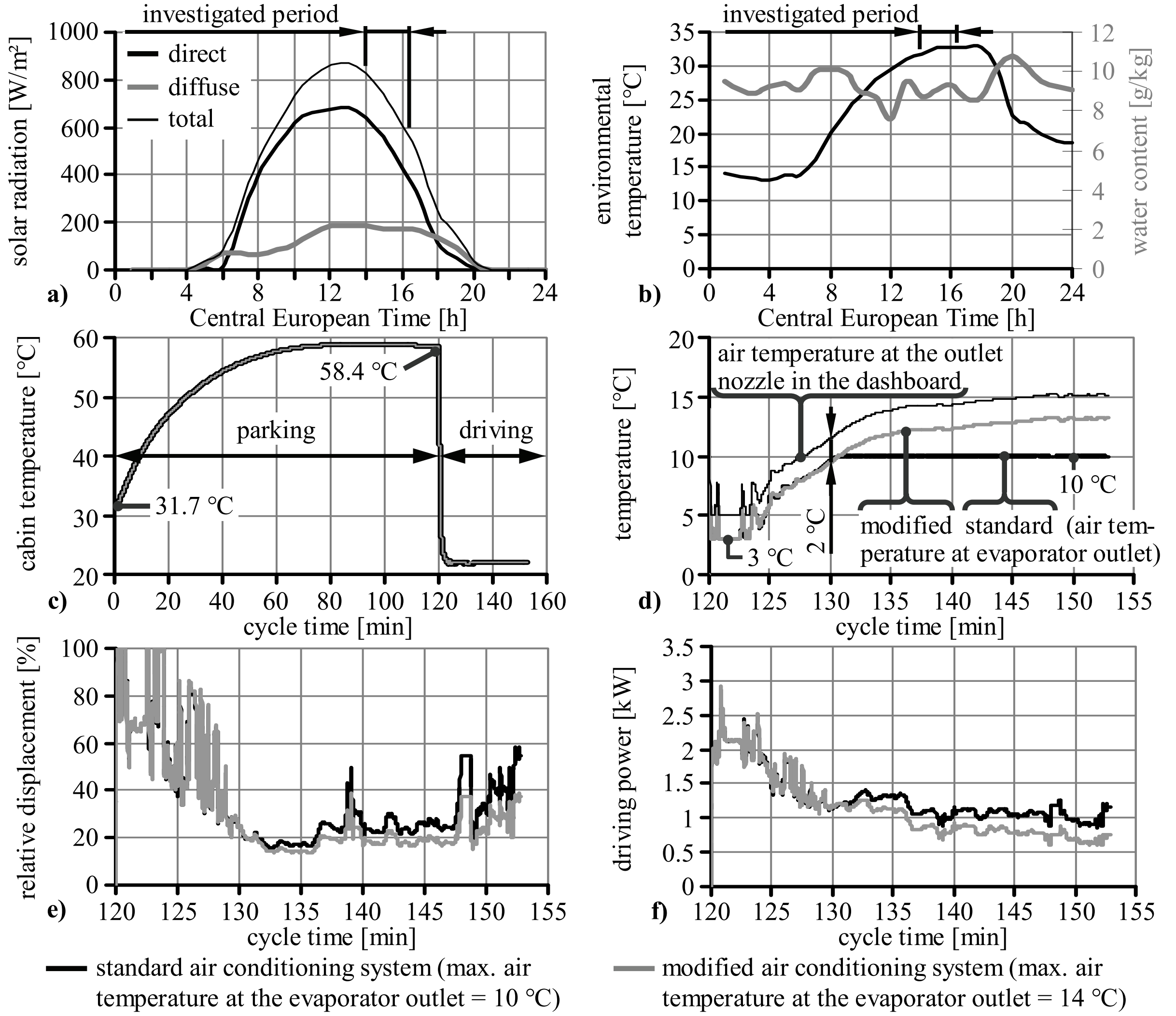


Figure 1: Operating behavior of the air conditioning at an increased maximum air temperature at the evaporator outlet

Because the temperatures of the components and the air in the passenger cell are unknown at the beginning of the simulation, all temperatures are equated with the environmental temperature initially. It is assumed, that the car was parked for two hours before driving with the air conditioning running. During that time, the components and the cabin air reach the respective starting temperatures. In the above shown example, the cabin temperature rose from 31.7 °C to 58.4 °C while parking (Figure 1c).

Figure 1d shows that during the cool down period the air temperature at the evaporator outlet is 3 °C, which is defined as the minimum value here. On the way from the evaporator to the outlet nozzle in the dashboard, the cooled air is warming up. To consider this circumstance approximately in the calculations, a temperature rise of 2 °C was assumed for all operating conditions under which the passenger cell needs to be cooled.

Until a cycle time of 130.5 min, both, the standard and the modified air conditioning system, show identical behaviors (Figure 1d, e, f). The standard system reaches the maximum air temperature (10 °C) at the evaporator outlet after 130.5 min (Figure 1d). From this point in time on, the relative compressor displacement can be decreased by increasing the maximum air temperature to 14 °C. Thus, the driving power can be reduced in a great part of the driving cycle (Figure 1d, e, f).

The fuel savings and the CO_2-reductions achieved through this modification can be seen in Figure 2. It appears that the increased maximum air temperature at the evaporator outlet allows CO_2-reductions up to 1.95 g/km (Figure 2b) compared to the standard system (cf. Table 1).

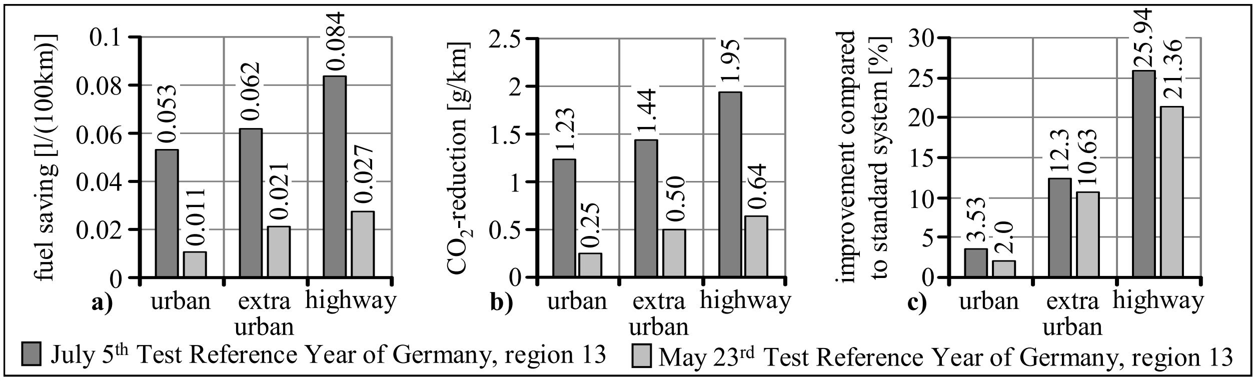


Figure 2: Improvements by increasing the maximum air temperature at the evaporator outlet

Nevertheless, the actual saving per year is small (Table 3), because the increase of the maximum air temperature at the evaporator outlet only has an effect when the cabin needs to be cooled. Otherwise, the air conditioning system is only activated to dehumidify the cabin air to avoid misted up windows. In this case, the air conditioning system works at the minimum air temperature of 3 °C at the evaporator outlet and therefore the increased maximum air temperature is effectless.

Table 3: Saving per year at increased maximum air temperature at the evaporator outlet

saving compared to the standard air conditioning system (Table 2)		
fuel saving [l/(100km)]	CO_2-reduction [g/km]	relative improvement [%]
0.005	0.121	3.26

3.2 Application of a smaller compressor with lower maximum displacement

Another promising possibility for reducing fuel consumption and CO_2-emission is the application of a smaller compressor with fewer cylinders and lower maximum displacement. To generate the same refrigerating capacity as with a big standard compressor, the small compressor has to operate at a higher relative displacement, which improves the compressor efficiency. Furthermore, friction losses are reduced because of the lower number of pistons.

However, the use of a smaller compressor also has disadvantages, as will be described in the following.

environmental conditions	July 5th Test Reference Year of Germany, region 13
starting time [CET]	2.00 pm
driving cycle	vehicle speed: 5 km/h engine speed: 900 rpm

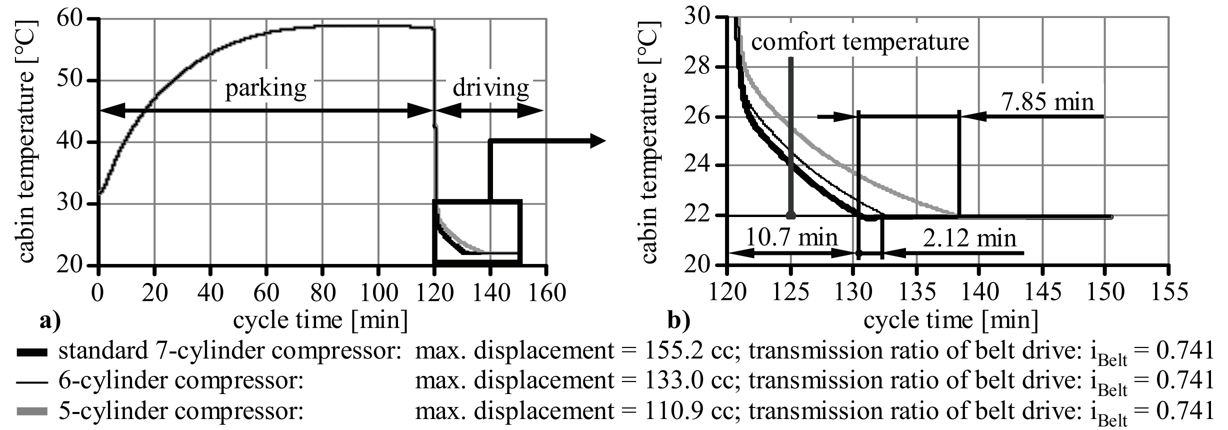


Figure 3: Increasing of the cool down period by using a smaller compressor

In Figure 3, the cool down curves are illustrated for compressors with a different number of pistons for an exemplary extreme condition, whereas the piston and valve geometry remained unchanged.

The simulation was based on weather dates of the 5th July in the Test Reference Year for Germany (cf. Figure 1a, b). After parking for two hours, the car moves for 30 min at a speed of 5 km/h and an engine speed of 900 rpm. With the seven-cylinder compressor (Figure 3b; bold black curve) the comfort temperature of 21.9 °C is reached after 10.7 min. The application of a compressor with only six cylinders (thin black curve) increases the cool down period by 2.12 min. Using five cylinders instead of seven even prolongs the cool down period by 7.85 min (grey curve). That is why, using of a compressor with fewer cylinders alone does not make sense, but through the modification described in the following, the advantages of a smaller compressor can be made use of. At the same time, the cool down period does not change compared to the respective period of the standard air conditioning system (10.7 min).

To achieve the same cool down period as with the standard compressor (10.7 min), the small compressor has to be run at higher speed during this period. After reaching the comfort temperature, it is possible to reduce the compressor speed and therefore the driving power given that the required refrigerating capacity can be generated. This can be accomplished easily by applying a two-speed planetary gearbox, that is integrated into the compressor pulley (Figure 4). These two gears can be shifted by an electromagnetic brake. When this brake is activated, the transmission ratio of the gearbox is e.g. $i_2 = 0.5$ into higher speed. If the brake is deactivated, the transmission ratio of the gearbox is $i_1 = 1.0$. In this case, the gearbox runs without any friction losses and the compressor is only driven by the transmission ratio of the belt drive.

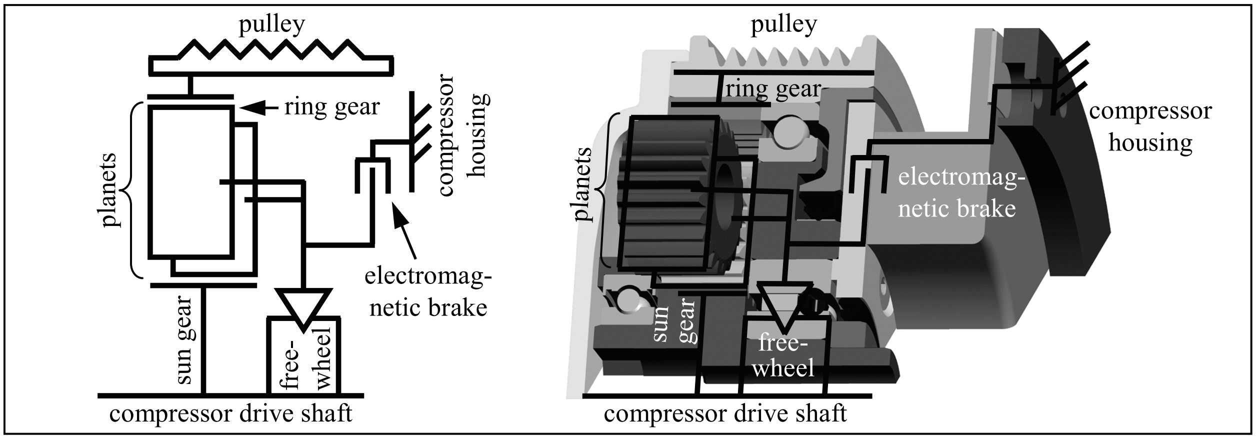


Figure 4: Two-speed gearbox (Baumgart *et al.*, 2006)

With a gear ratio of $i_2 = 0.5$, the transmission ratio of the belt drive can be increased from $i_{Belt} = 0.741$ to $i_{Belt} = 1.0$ by using a five-cylinder compressor. This configuration makes it possible to achieve the "standard" cool down period of 10.7 min under the above-mentioned extreme conditions (Figure 3). If the transmission ratio of the belt drive is reduced, the cool down period can even be shortened compared to the standard system.

Figure 5 shows the simulation results for a five-cylinder compressor with a two-speed gearbox (grey curve). As can be seen in Figure 5b, the comfort temperature can be reached without any delay in comparison with the standard system (black curve). To generate the required refrigerating capacity, the gearbox often works at the gear ratio of $i_2 = 0.5$ during the cool down period (Figure 5f). Here, the compressor speed is higher than in the standard system (Figure 5e). After reaching the comfort temperature, the gearbox shifts into the gear ratio $i_1 = 1.0$ and the five-cylinder compressor is driven at lower speed because of the higher transmission ratio of the belt drive (Figure 5e). Since the small compressor runs at a higher relative displacement (Figure 5c) the compressor efficiencies improve, which reflects in a considerable reduction of the required driving power (Figure 5d).

environmental conditions	July 5th Test Reference Year of Germany, region 13
starting time [CET]	2.00 pm
driving cycle	extra urban

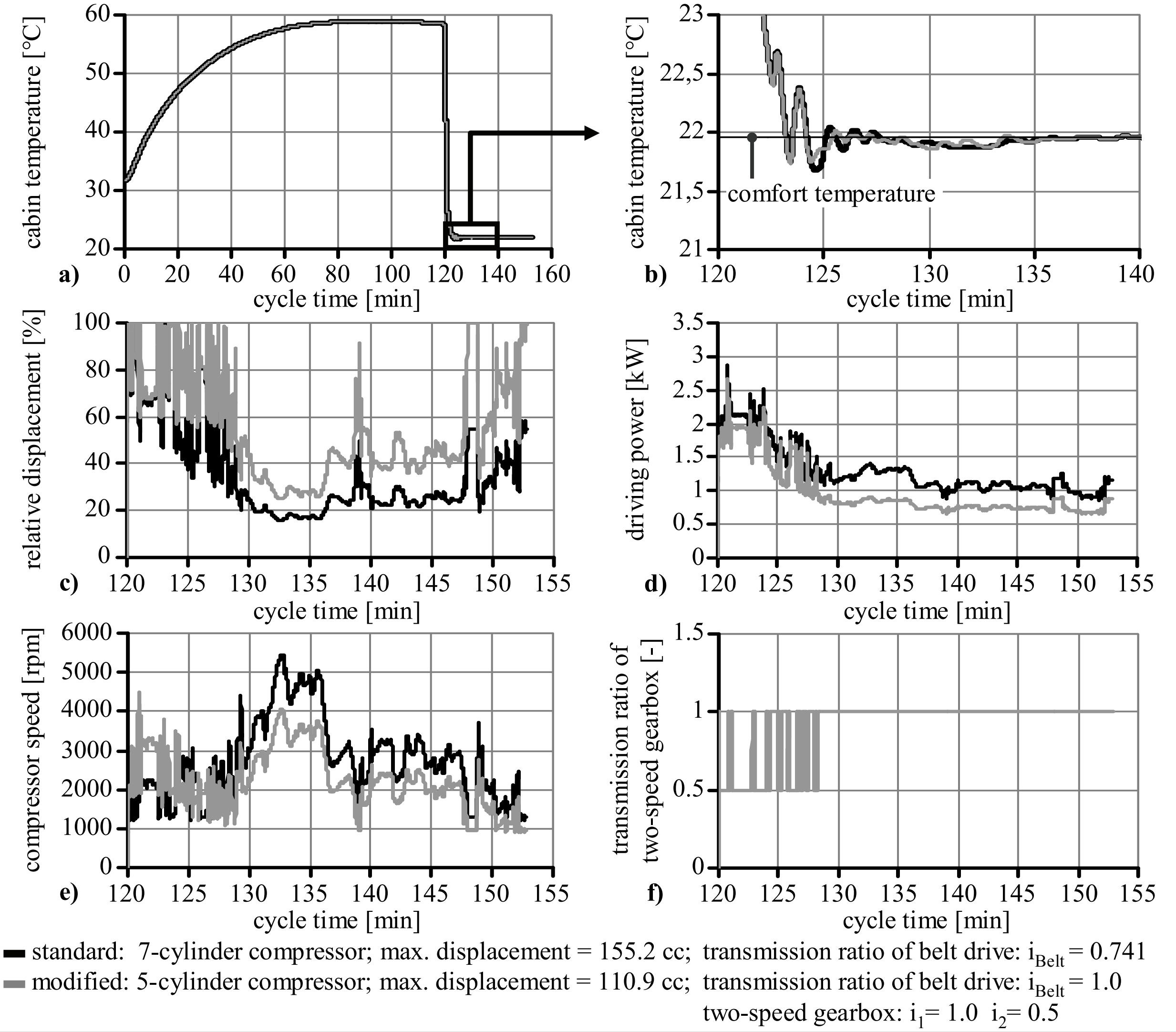


Figure 5: Operating behavior of the five-cylinder compressor with a two-speed gearbox

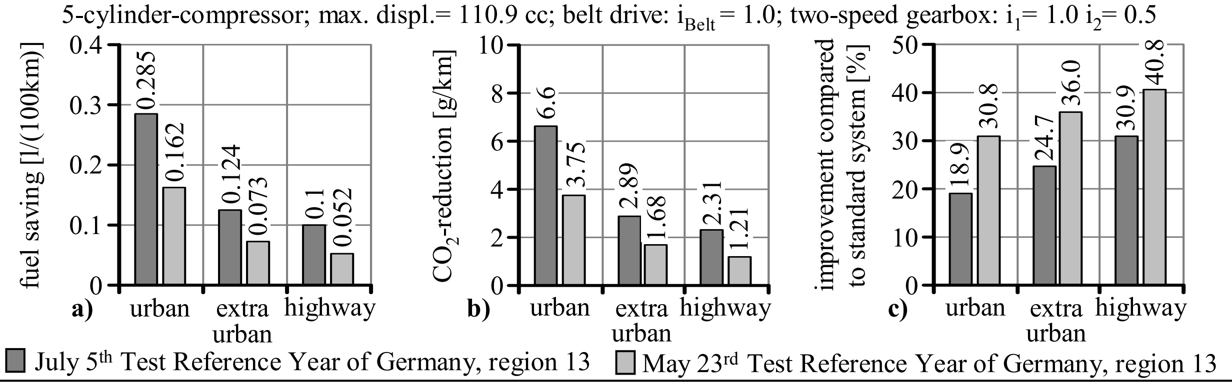


Figure 6: Improvements by using a five-cylinder compressor with a two-speed gearbox

Combining a five-cylinder compressor with a two-speed gearbox allows a significant fuel saving of 0.285 l/(100km) in the urban driving cycle under summer conditions (5th July), which results in a CO_2-reduction of 6.6 g/km (Figure 6).

Compared to the standard system, the smaller compressor causes lower friction losses and the speed is lower when the gearbox runs at the gear ratio $i_1 = 1.0$. That is why, fuel consumption is also reduced when the air conditioning system is deactivated, e.g. in winter. This leads to considerably higher savings per year in comparison with other investigated modifications (Table 4). The combination of a five-cylinder compressor with a two-speed gearbox reduces CO_2-emission by 1.397 g/km per year, which is an improvement of 37.5 % compared to the standard compressor with seven cylinders. Moreover, it became evident that the two-speed gearbox runs at a gear ratio of $i_2 = 0.5$ in less than 1% of the overall driving time in an entire year, which is a huge advantage especially with regard to the wear and the dimensioning of the gearbox.

Table 4: Saving per year with a five-cylinder compressor with a two-speed gearbox

saving compared to the standard system (Table 2)			
fuel saving [l/(100km)]	CO_2-reduction [g/km]	improvement compared to the standard system [%]	time slice gear ratio $i_2 = 0.5$ active [%]
0.06	1.397	37.5	0.94

4. CONCLUSIONS

The investigations at the Chemnitz University of Technology have clearly shown that through several modifications the CO_2-emission caused by the air conditioning system can be reduced significantly and thus an important contribution to the environmental compatibility of future cars can be made. As a further realization can be stated that the saving potentials depend highly on the driving cycle and the environmental conditions. This leads to the insight that it is not sufficient to consider only summer conditions for evaluating modifications. Instead, the improvement potential per year has to be taken into account, too.

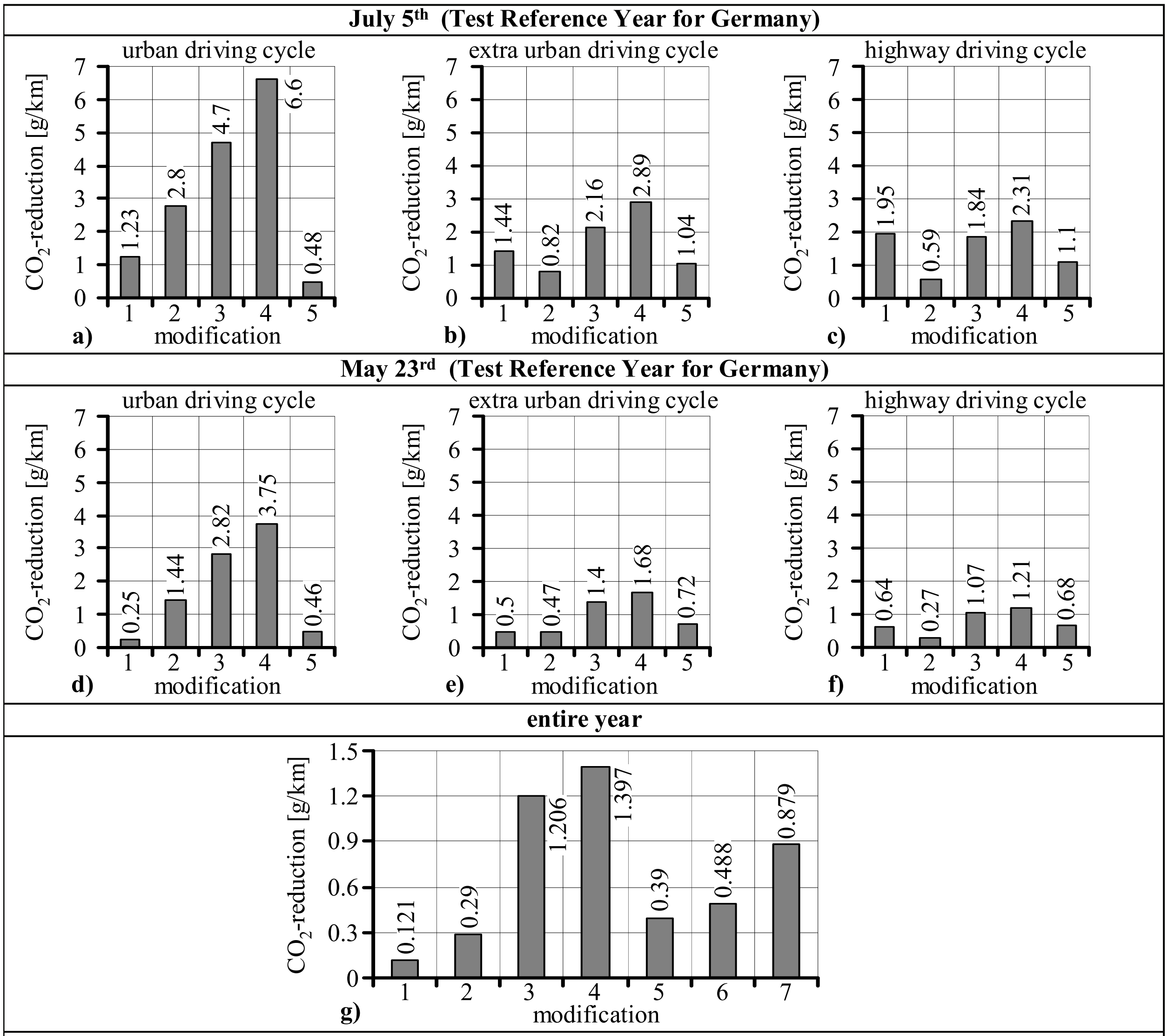
Considerable savings, at least under summer conditions, can be achieved by raising the air temperature at the evaporator outlet (Figure 7a-c, modification 1), whereas this modification has no effect when the air conditioning is not used. Thus, the CO_2-emission per year can be reduced by only 0.121 g/km (Figure 7g, modification 1).

Recently, the application of an electromagnetic clutch, that is integrated into the compressor pulley, is intensively discussed in the automotive industry. By using this clutch, the compressor can be stopped while the air conditioning system is deactivated, which avoids friction losses and therefore reduces CO_2-emission. However, when the air conditioning system is used, CO_2-emission increases because of additional current consumption for the electromagnetic clutch. Consequently, the CO_2-reduction per year is only 0.488 g/km (Figure 7g, modification 6). Therefore, the development of a new clutch which does not permanently require electric power would be a substantial progress (Figure 7g, modification 7).

With the five-cylinder compressor combined with the two-speed gearbox, the saving potential is somewhat lower as with the magnetic clutch if the air conditioning system is not activated. However, with this modification the highest CO_2-reductions can be achieved for a running air conditioning system in comparison to other solutions (Figure 7a-g, modification 4).

The next step of development would be to investigate other compressor types, such as the scroll compressor, which has many advantages, for instance its small size. However, adjusting the displacement of this compressor type is difficult, but instead of the displacement, the compressor speed can be controlled by an electric motor. That is why, this solution is very suitable especially for hybrid cars with a high-performance electrical system.

It would also be interesting to include the environmental conditions of other climate zones to the investigations. In this way the modifications could be adapted to the respective markets. It is also possible to modify the air conditioning system in a way that allows the minimization of the global CO_2-emission caused by a particular car type.



1 = increase of the maximum air temperature at the evaporator outlet
2 = blocking of the control mass flow in the compressor
3 = 6-cylinder compressor combined with a two-speed gearbox i_1=1.0 i_2=0.5 i_{Belt}=1.3
4 = 5-cylinder compressor combined with a two-speed gearbox i_1=1.0 i_2=0.5 i_{Belt}=1.0
5 = standard compressor with 7 cylinder combined with a two-speed gearbox i_1=1.0 i_2=3 i_{Belt}=0.741
6 = standard magnetic clutch (with permanent current consumption in active state)
7 = modified clutch (without permanent current consumption in active state)

Figure 7*:* CO_2-reductions for several modifications

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