Fuel Consumption for Conventional and Electrically Driven AC Compressors

C. Marais[a], H. Holdack-Janssen[a, b] and T. van Niekerk[b]

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The emergence of hybrid vehicle technology also sparked the development of different electrical systems that were made viable by the higher onboard voltage systems employed in hybrid vehicles. One of these developments is the electrical air conditioning compressor for use in automobile applications. The question arises whether it would be feasible and sensible to employ an electrical air conditioning system in conventional combustion engine vehicles from an overall fuel consumption and vehicle emissions point of view.

This study attempts to answer this question by making use of simulation tools to represent an average combustion engine vehicle. The simulation is constructed in such a way that it is possible to simulate the vehicle without an air conditioning system and then provides the opportunity to add both a conventional as well as an electrical air conditioning system to it in order to facilitate a comparison between the systems. The ultimate goal of the study is to provide an analysis to evaluate the performance of electrical air conditioning systems in conventional combustion engine vehicles.

Additional keywords: Automotive, hybrid, air conditioning, modelling

1. Introduction

Important and severe climatic changes are brought about by the emission of so-called greenhouse gases from human activities. According to the US government's National Oceanic and Atmospheric Administration, the increase of CO_2 emissions from 2004 to 2005 was determined at 2.6 ppm. An increase of over 2 ppm per year has been occurring for three of the past four years while previously the number has not increased by more than 1 ppm since recording started in the 1950s[1].

The amount of CO_2 emissions will have to be reduced by between 70 % and 80 % just to stabilize the atmospheric concentrations. All automobile manufacturers and their suppliers are collectively working on the development of measures to reduce overall fuel consumption and emissions of not only their vehicles and products, but also reducing the general overall impact of their processes on the environment[2]. Reducing overall fuel consumption provides significant gains in various aspects of environmental conservation. Not only do vehicles with lower consumption significant gains in various aspects of environmental conservation. Not only do vehicles with lower consumption require less fossil fuel, but they also have a significantly lower emission rate. Furthermore the use of electrically driven compressors potentially lowers the leakage rate of AC systems by housing the drive and compressor in a single unit, eliminating the inefficient shaft seals in current compressors[3].

a University of Applied Sciences Braunschweig/ Wolfenbüttel, Institute of Vehicle Engineering, Wolfsburg, Germany.
b Nelson Mandela Metropolitan University, Department of Mechanical Engineering, Port Elizabeth, South Africa.
E-mail: Theo.vanNiekerk@nmmu.ac.za

2. Experimental Setup

2.1 Air conditioning system

The air conditioning system that is used for the experimental setup is from the Polo 9N series. The reason for this choice was to match the air conditioning system to the actual vehicle that is to be simulated.

It was also possible to obtain results from practical engine measurements for the actual 1.4 L diesel engine used in the test vehicle. The combination of the engine results, the physical properties and dimensions of the vehicle and the air conditioning test bench results, allow for a realistic representation of the real-life influences of the air conditioning system on the fuel consumption of the vehicle.

The test setup is constructed to be an exact representation of the system as it is built into the vehicle. This means that the relative heights between the various components are representative of the actual positions that the components have when built into the vehicle.

The components are all the exact parts that are used in the real life system, including the connecting pipes and the HVAC box containing the evaporator and expansion valve. Figure 1 shows a schematic representation of the sensor locations on the test setup.

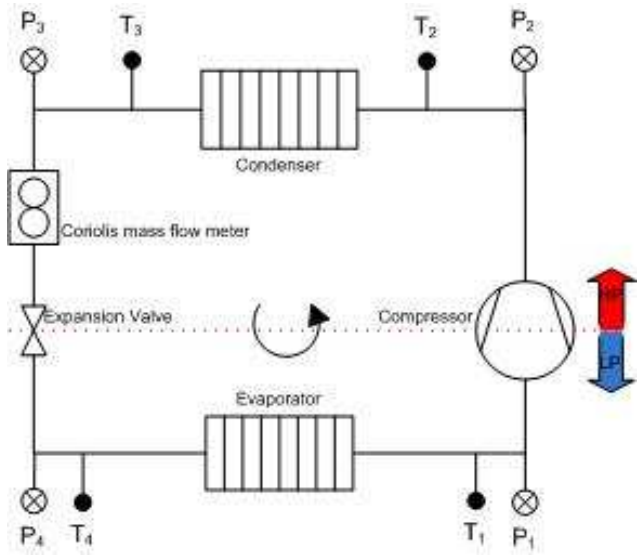

Figure 1: Major components of automotive air conditioning

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Measurements on the system are made by means of various thermocouples, pressure sensors and the mass flow rate is monitored with a Coriolis mass flow rate meter. It was necessary to modify the original connecting pipes of the system slightly to make it possible to connect the various sensors in the appropriate locations. These modifications were kept to a minimum and care was taken to minimize their influence on the overall system performance and behaviour. However it is still possible that their influences may be significant and correction factors may be required in the simulation environment to compensate for these irregularities.

2.2 Compressor drive system

It was necessary to redesign the available system to enable it to drive different types of compressors and to eliminate measurement problems. The system now consists of an asynchronous electrical motor and an adjustable retaining plate that serves the dual purpose of mounting the compressor and tensioning the drive belt between the electrical motor and the compressor. The torque and rotational speed sensors were mounted on the end of the driveshaft. By mounting each compressor to be used on an adapter plate that connects to the retaining plate of the drive system, it is possible to mount any compressor onto the system and then adjust the tension on the drive belt to suit each compressor individually by correctly positioning the retaining plate. The rotational speed of the electrical motor can be controlled by a software protocol and frequency converter to allow for speeds of up to 9000 rpm.

2.3 Measurement system

Measurements, data acquisition and processing are all done by means of SCXI hardware measurement systems from National Instruments. The NI SCXI measurement hardware is then combined with measurement software from the National Instruments LABView software range. This allows the processing of the measured data while the measurement is running and enables it to be exported directly to spreadsheet software such as Microsoft Excel.

2.4 Comparison to simulation

Figures 2 to 4 show the comparison between the measured and simulated values for the compressor power, evaporator load and COP values at an air mass flow rate of 195 kg/h.

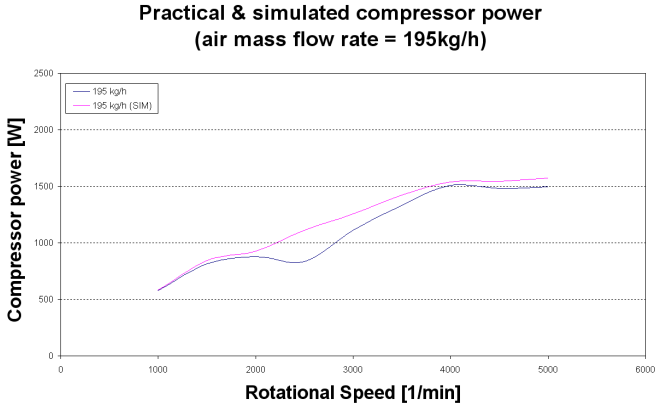

Figure 2: Practical and simulated compressor power

By adjusting the dimensioning of the simulation environment according to the actual test system and adjusting various appropriate parameters of the simulation setup, it was possible to achieve a relatively good representation of the actual system. The average differences between the simulation and test results for the evaporator load, compressor power and coefficient of performance (COP) lie between 8 % and 10 %.

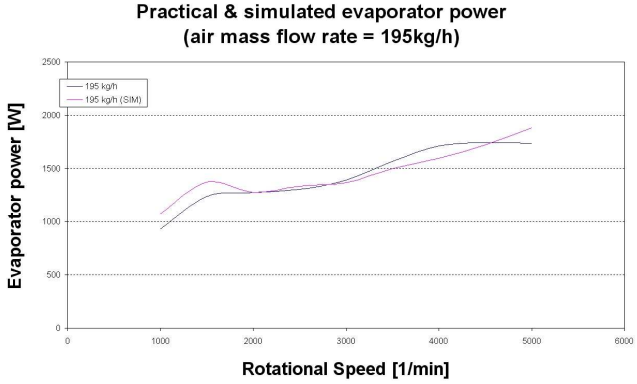

Figure 3: Practical and simulated evaporator power

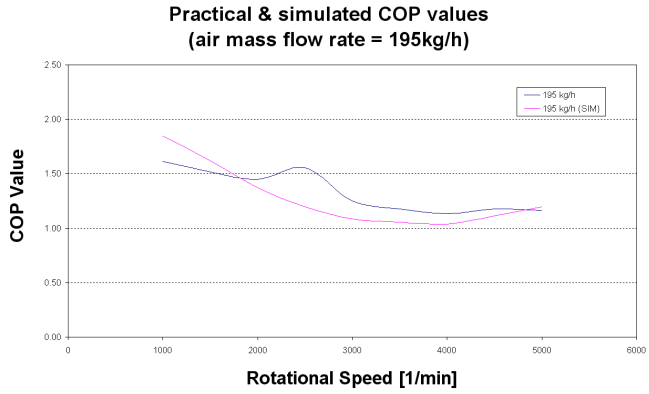

Figure 4: Practical and simulated COP

3. Simulation

The simulation of the air conditioning system and all the corresponding components (see figure 5) was greatly supported by the Institute of Thermodymics at the Technical University Braunschweig and TLK Thermo GmbH, a company that specializes in thermodynamic

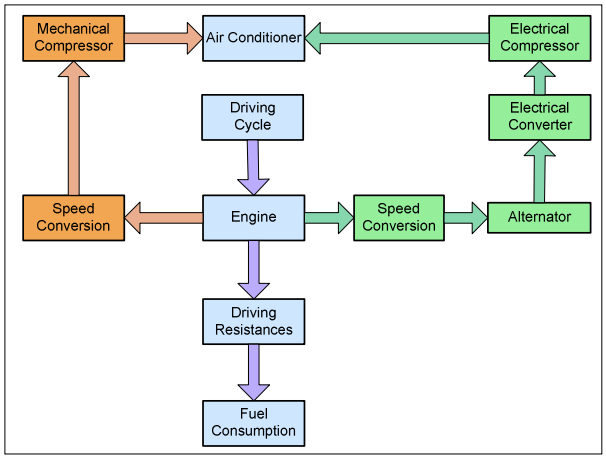

Figure 5: Simplified block diagram of the simulation

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simulation tools and applications. Figure 5 shows the composition of the simulation as a simplified block diagram with the simulation environment is divided into 3 basic sections.

The first is the vehicle driving system which includes the driving cycle, vehicle characteristics and engine characteristics. The second and third parts are both concerned with the air conditioning drive system and its influence on the vehicle's fuel consumption with reference to the first section. The air conditioning system (condenser, evaporator and expansion valve) is common to both the second and third sections with the difference being in the compressor system that is used.

The simulation is constructed using various components from the TIL Library from TLK Thermo combined with some freely programmable parts of the general purpose Modelica libraries.

3.1 Driving cycle

The driving cycle that was used is the New European Driving Cycle (NEDC) and is a standard driving cycle that is used as a reference to make emission level analysis and also to determine the average fuel consumption for a vehicle on a dynamometer[4].

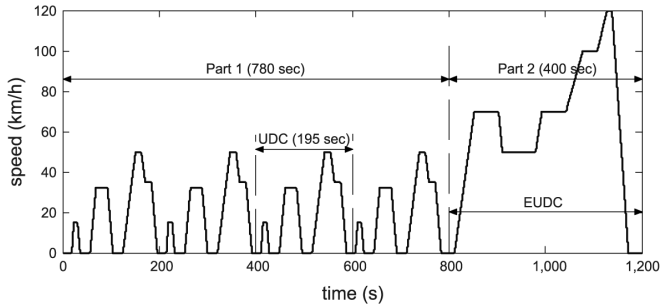

Figure 6: New European driving cycle

3.2 Engine characteristics

The required data for the 1.4 L Diesel engine was measured on an engine test stand that is equipped with all necessary sensors and measurement systems. A complete set of parameters was recorded including various pressures, temperatures, ratios, consumption and exhaust emission values. The relevant parameters are filtered out and then used as look-up tables to provide the necessary input values under specific conditions for the simulation.

3.3 Consumption calculations

Determining the engine's fuel consumption can be achieved by considering a complete set of required parameters. All the relevant driving resistances and their compositions[5] are necessary to determine the force required to accelerate or decelerate the vehicle at the determined time instances as prescribed in the NEDC. The rolling resistance and aerodynamic resistance (drag) was determined experimentally on an available test track. The NEDC is a cycle that was developed for tests on a dynamometer and it is therefore assumed that the climbing resistance that may occur in real-life driving conditions may be disregarded in this case.

3.4 Compressors

Both the mechanical and electrical compressors were assumed to be "standard" compressors and incorporated into the simulation as adapted versions of existing models from either the TIL library from TLK Thermo or the AC Library from Modelon.

3.5 Alternator

A load curve of the alternator was produced by allowing it to charge two completely discharged 12 V batteries and the delivered current from the alternator was measured using LEM current measurement modules. Additionally the torque and rotational speed were also measured from which the delivered power as well as efficiency can be calculated. Once the batteries are charged, different loads can be added to the system to present a partial load situation as may occur during normal driving conditions in a vehicle, thereby producing a partial load curve for the alternator.

4. Model Testing and Verification

4.1 Vehicle consumption

The first simulated system is the vehicle with no air conditioning system incorporated. The NEDC cycle is used as the benchmark and the physical dimensions and characteristics of the vehicle is matched to that of the Polo 9N that is to be used as reference. Different environmental conditions were not considered in the simulation of the vehicle without the air conditioner. The resultant vehicle consumption will be used as a reference to compare the increases in fuel consumption caused by the electrical and conventional systems respectively. The results of the simulation of the vehicle's fuel consumption over the duration of the NEDC can be seen in figure 7 with a total average consumption of 5.22 L/100 km.

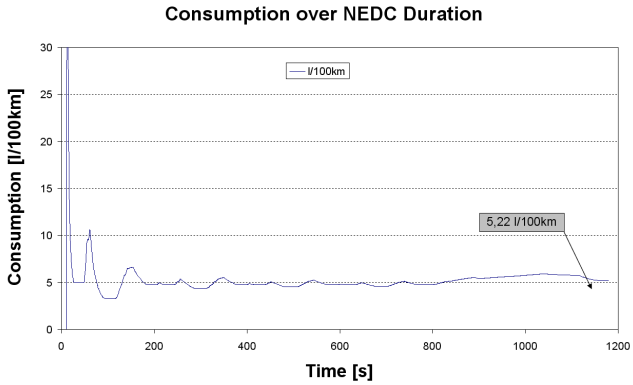

Figure 7: Consumption in L/100 km over NEDC duration

Figure 8 shows a results graph of the acceleration and the vehicle consumption over the duration of the NEDC. As can be seen in figure 8, the simulation is idealized so that the fuel consumption immediately becomes zero when the acceleration becomes negative. Theoretically this is also the case under real driving conditions in diesel vehicles since the injection valves are closed and no fuel is injected into the engine whenever the driver completely releases the accelerator. The simulation does not consider the fact that the driver may not have released the accelerator completely

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or that the driver's release reaction was delayed during deceleration phases.

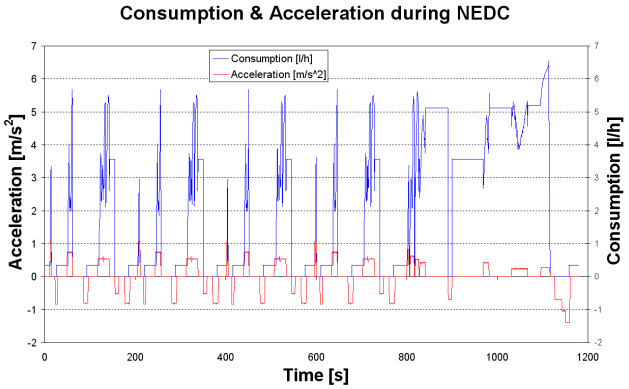

Figure 8: Fuel consumption and acceleration over NEDC duration

These results will be the basis for the comparison of the two air conditioning systems and when the results of the two air conditioning systems are compared, this value is simply an offset and will ultimately not influence the result of the overall comparison.

4.2 Mechanical compressor system

This represents the conventional air conditioning systems that are currently used in the majority of passenger vehicles. Making use of the same vehicle model as previously discussed, it is possible to connect the conventional air conditioning system to it and determine the expected overall fuel consumption for the vehicle. NEDC cycles were simulated for the vehicle as before with the air conditioning system connected to the engine as an external load. Simulations were run for ambient temperatures ranging from 20 °C to 40 °C in 5 °C steps. These results can be seen in figure 9 which shows the development of the vehicle's overall fuel consumption in L/100km over the duration of the NEDC.

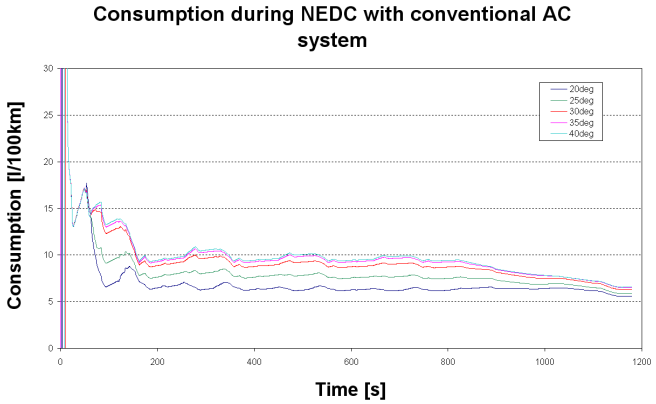

Figure 9: Consumption with conventional AC system over NEDC duration

With an ambient temperature of 20 °C, the value for the average overall fuel consumption is at 5.6 L/100 km. This implies an increase of 0.4 L/100 km in the overall consumption when employing the air conditioning system. Increasing the ambient temperature to 40 °C, the expected average fuel consumption of the vehicle therefore increases to 6.6 L/100 km for the duration of the NEDC. Combining the results from all five simulated environmental conditions, the average increase in the overall fuel consumption is 0,96 L/100 km for the duration of the NEDC. According to a European studies the increase in a vehicle's fuel consumption due to the use of an air conditioner is between 0.6 and 1.1 L/100 km[6, 7].

4.3 Electrical compressor system

The alternator forms the interface between the electrical air conditioning system and the combustion engine and it is assumed that it can deliver the entire required current to the electrical motor at all times. The charging capacity and energy storage efficiency of the battery is thereby removed from the simulation and the system is greatly simplified. The available alternator however could not deliver the required current spikes of up to 570 A and the values for the torque required at this current load were therefore extrapolated from the actual measured values from the alternator test. It is therefore important to note that these simulation results can only provide an estimate regarding the influence of the electrical air conditioning system on the overall fuel consumption and are not to be considered as final and irrefutable.

Figure 10 shows the development of the overall vehicle fuel consumption during the NEDC for the same five environmental conditions as considered previously with the conventional air conditioning system The overall consumption ranges from 5.6 L/100 km at an ambient temperature of 20 °C to 7.4 L/100 km at 40 °C. This implies an increase of between 0.4 L/100 km at 20 °C and 2.2 L/100 km at 40 °C compared to the average overall consumption of the vehicle without the use of an air conditioning system. At this point it is to be noted that the calculated torque requirement for the alternator to deliver the current required by the electrical compressor is the result of extrapolated values from a practical test and therefore may be overestimated.

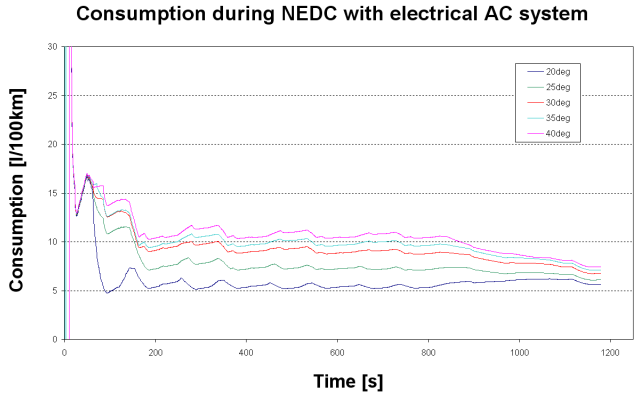

Figure 10: Consumption with electrical AC system over NEDC duration

Furthermore the control system for the electrical compressor was not included into the considerations for this project and was therefore extremely inefficient. Some of the required alternator current values are displayed in figure 11 as they occur during the NEDC simulation.

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According to the extreme oscillations in the required current, the required torque also oscillates between extreme points. The use of a more efficient control system for the electrical air conditioning system could eliminate these extreme oscillations and thereby provide significant improvements in the overall efficiency of the system and considerably decrease the influence on the average fuel consumption. The final result of the simulations for the electrical air conditioning system over the NEDC

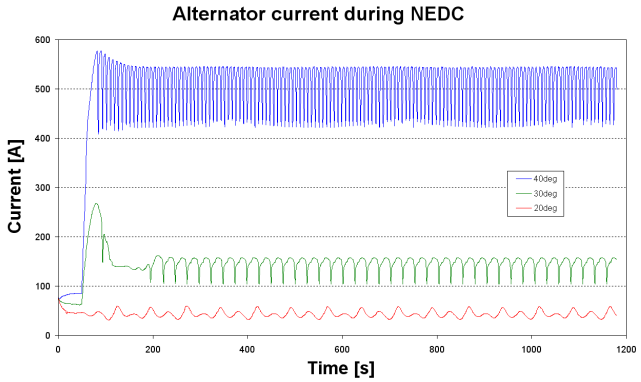

Figure 11: Current requirement of the electrical AC system over NEDC duration

show an average increase in the overall fuel consumption of 1.39 L/100 km. This is a considerably higher average increase than the 0.96 L/100km that is expected from the conventional system and indicates significant improvement possibilities when taking the battery into consideration, using a more suited alternator and more effective control system.

4.4 System comparison

The comparison between the two systems is only possible to a limited extent because the electrical air conditioning system was not specifically designed for the use in a vehicle with a conventional 12 V onboard voltage system. An alternator that is designed to power such a system obviously cannot deliver the necessary current to power the electrical compressor. As mentioned before, it is expected that the required power from the engine to drive the alternator to deliver sufficient current to the electrical compressor is greatly overestimated. This puts the electrical air conditioning system at a slight disadvantage in its comparison to the very much tried and tested conventional system.

Despite the disadvantages that the electrical system has in comparison, its potential is not to be disregarded. Figure 12 shows a direct comparison between the average consumption for each system across the whole ambient temperature range during the NEDC.

The simulation results show a 0.4 L/100 km higher total average vehicle fuel consumption for the electrical system as compared to the conventional system. It is important to note that the electrical system requires an additional two energy conversions in comparison to the conventional compressor. The first conversion (mechanical to electrical energy) takes place in the alternator. The overall electrical energy demand in the vehicle is increased significantly with the use of an electrical compressor system. This means that the alternator requires more power to fulfil this increased energy demand when using an electrical system as compared to the conventional one. The second conversion (electrical to mechanical energy) takes place in the drive

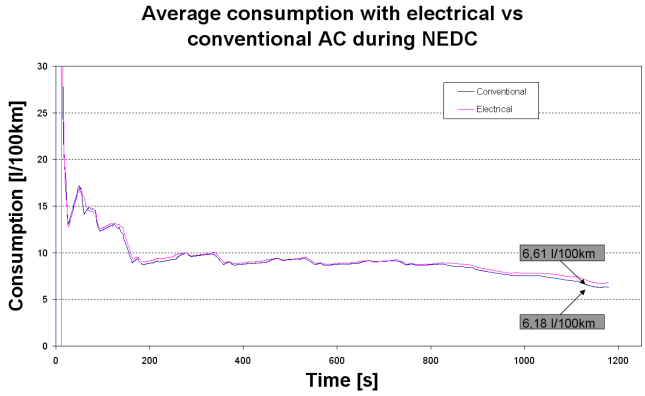

Figure 12: Average conventional and electrical AC consumption over NEDC duration

motor to power the compressor. The results show a calculated total average power requirement of the electrical system of 1932 W as compared to the 1635 W of the conventional system. This elevated power requirement of almost 300 W on the electrical compressor side is expected to be the result of the inefficiency of the control system used to represent it in the simulation. However, when excluding the results of the 40 °C simulation while considering the total average power requirement for the two systems, the 300 W difference is reversed. Then the average power requirement for the electrical system is 1070 W as compared to the 1350 W of the conventional system. It is therefore to be assumed that the inefficiency of the control system for the electrical compressor is the reason for its disadvantage in comparison to the conventional system.

An effective control system should be employed in order to allow for the compressor to be driven at its optimal operating point permanently. This will not only decrease the power requirement of the compressor in general, but also elevate the overall efficiency of the electrical system as a whole. It is therefore to be expected that considerable decreases in the overall power requirement of the electrical air conditioning system can still be achieved by making use of an effectively designed control system to optimize the overall system performance.

5. Summary

A simulation environment was developed to represent a Volkswagen Polo 9N and determine the expected fuel consumption of the vehicle under the driving conditions of the New European Driving Cycle. The simulation was extended to include an air conditioning system as a load on the engine for the duration of the driving cycle. This enables the calculation of the expected increase in the

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vehicle's overall fuel consumption due to the use of an air conditioning system.

An experimental setup was constructed to represent the exact conventional air conditioning system as was built into the actual Volkswagen Polo test vehicle. Measurements from the experimental setup could then be compared to the results of the simulation of the air conditioning system in order to ensure the simulation had an appropriate level of accuracy.

The simulation was then expanded by another level by adding the possibility to replace the mechanically driven compressor by an electrically driven one. By connecting the electrical compressor to the engine indirectly by means of the alternator, it was then also possible to determine the expected increase in the overall fuel consumption that will result from the use of an electrically driven air conditioning system.

6. Conclusion

A comparison can be made between the conventional air conditioning system and the electrical one with regard to their influences on the overall vehicle fuel consumption.

Even though the results of the simulation show that the electrical system has a 0.4 L/100 km higher overall fuel consumption compared to the conventional system, this is to be examined more closely. It is to be assumed that in combination with an effective control system, the electrical compressor system will show greater advantages over the conventional system. Furthermore the charging level and capacity of the battery was not considered in the simulation and the alternator was assumed to be able to deliver the entire required current. The characteristic curve for the alternator had to be extrapolated and it is therefore also to be assumed that the extrapolated torque values for the alternator may be somewhat overestimated. Using an appropriate alternator, combined with an efficient control system and including the battery into the simulation would further improve the performance of the electrical system when compared to the conventional one and possibly make it a viable option for both hybrid and conventional vehicles.

7. Acknowledgements

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