

Energy consumption of electric vehicles in different climate and driving conditions

Antti Lajunen^{1,2}, Kari Tammi²

¹ *McMaster University, McMaster Automotive Resource Centre (MARC), Hamilton, ON, Canada*

² *Aalto University, School of Engineering, 00076, Aalto, Finland, antti.lajunen@aalto.fi*

Summary

This research investigates the energy consumption of electric vehicles. The energy consumption is analysed based on simulation results in different climate and driving conditions. A complete vehicle simulation model was developed with a detail cabin and powertrain thermal management systems. The simulation model was validated against measured energy consumption presented in the literature. Simulations were carried out in several different driving cycles including a real-world highway cycle. According to the simulation results, a significant amount of energy is lost in tyres in all conditions. In extreme cold and hot conditions, the cabin thermal management consumes the major portion of the energy. Depending on the driving cycle, the energy consumption varied from 110 to 200 Wh/km at 20 °C of ambient temperature. In cold conditions, the energy consumption was highest in low speed cycles being even more than 500 Wh/km at -30 °C. The highest driving range was 190 km and it could reduce more than 70% in cold and 40% in hot conditions.

Keywords: electric vehicle; energy consumption; simulation; thermal management; driving cycle; range

1 Introduction

Electric vehicles (EV) can be considered as energy efficient vehicles and relevant options to replace conventional vehicles [1]. Every year more EV models are available in the market and their sales are steadily increasing. Recently, the major automotive companies have released new EV models, or at least, they have announced significant technology investments on vehicle electrification. Even though EVs are energy efficient, their energy consumption can significantly increase in different climate and driving conditions [2]. Electric vehicles are well suitable for stop and go, inner city type driving. In more demanding highway cycles, the energy consumption can be much higher than in city driving [3]. The extreme climate conditions are the major challenge for EVs. In hot ambient temperatures, the cabin and battery require a substantial amount of cooling power to ensure passenger comfort and keep the battery within the recommended operating temperature limits [3]. In cold conditions, the cabin has to be heated by using battery energy because not enough waste heat is available [4]. The geographical and temporal differences in climate can also cause significant reductions on the driving range of electric vehicles [5], [6].

An ideal operating temperature for lithium-ion batteries is between 25-40 °C to ensure good performance and avoid aging [7]. In cold conditions, already in mild ambient temperatures, the lithium-ion battery performance is degraded resulting in limited output power and faster aging [8]. Cabin heating is probably the most problematic challenge for EVs in cold conditions. Experimental studies have showed that the range of electric vehicles can drastically decrease in cold driving conditions [4], [6], [7], [9]. Because there are no

natural heat sources (such as engine) in electric vehicles that could be used for cabin heating, a separate heater (usually an electric heater) is needed to ensure passenger thermal comfort [10]. Heat pumps are an efficient solution for mild ambient conditions [11], [12]. Sometimes even fuel burning heaters have been proposed and used for cabin heating [4], [13]. Already in freezing ambient temperatures, the charging power may be limited due to the increased internal resistance of the battery [9], [14]. Different measures have been presented in the literature to increase the range of EVs in cold and hot climate conditions [15], [16]. Especially thermal preconditioning of the cabin and powertrain has been found to be quite effective solutions [5], [14], [17]. Recently, also thermal storages have been investigated to improve thermal management and energy efficiency of electric vehicles [18], [19].

This paper investigates the energy consumption of EVs in detail manner. A complete vehicle model with an electric powertrain, HVAC (Heating, Ventilation and Air Conditioning) system with cabin thermal management was developed in the Autonomie software. The electric vehicle model was configured and validated corresponding to a midsize passenger car. The model validation was carried out by using the measured energy consumption data presented in the literature [20]. Simulations were carried out in the standard test cycles from North America, Japan and European Union as well as other commonly known driving cycles. One real-world driving cycle was generated based on measured cycle data from Finland. The vehicle energy losses were thoroughly analysed based on the simulation results and the impact of thermal energy losses in different ambient conditions were evaluated. Detail breakdowns of the vehicle energy losses are also presented.

2 Vehicle modelling and simulation

2.1 Electric vehicle model

Simulation models were developed in the AMESim and Autonomie software. AMESim provides several predefined vehicle and system level models for vehicle thermal management simulations [21], [22], [23]. Figure 1 presents the powertrain layout for the simulated electric vehicle in the Autonomie. Thermal systems were modelled inside the component plant models. The original thermal models were modified to correspond to the developed electric vehicle structure. Most of the modifications were made for the cabin heat transfer calculations. The predefined parameters were used for the battery and electric motor thermal systems. The tyre rolling resistance parameters, which are speed and temperature dependent, were adjusted to correspond to the modeled vehicle.

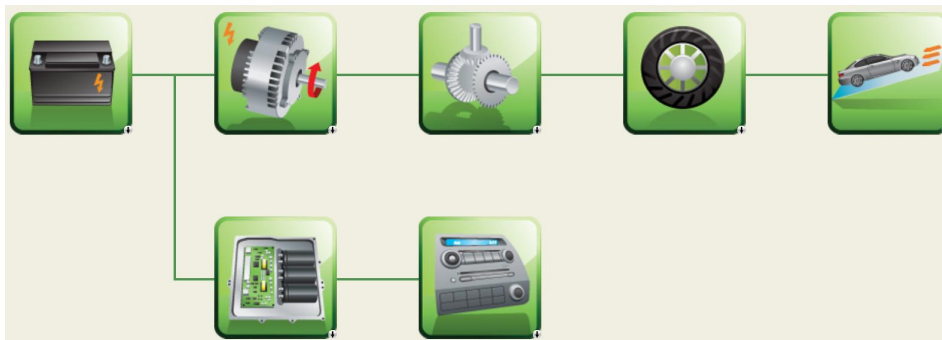


Figure 1: Powertrain layout. First row: Battery, Electric motor, Differential gear, Wheels, Chassis. Second row: Power converter, Auxiliary devices.

The Autonomie thermal system models include battery cooling/heating, electric motor and inverter cooling, and the cabin HVAC systems. An HVAC system and cabin heat transfer model were previously developed in the AMESim [23]. The Autonomie cabin and HVAC model was complemented with AMESim model which has more detail model for the ventilation system and cabin heat transfer. The battery and electric motor are liquid cooled with separated cooling circuits. The battery can also be cooled by the cabin air conditioning system. Figure 2 shows a block diagram presentation of the electric vehicle thermal systems. The high voltage battery powers the A/C compressor, battery heater, and cabin heater via a dc/dc converter. The cabin model calculates the heat transfer from the cabin elements based on heating and cooling power which limits the model use only for energy consumption and hot start purposes. The following elements were taken into account in the cabin thermal balance: solar radiation, roof, windows, bottom (including dashboard), sides,

powertrain (battery heat), seats, and occupants. For more detail thermal management simulations, heat transfer should be calculated through the air which is heated or cooled by the HVAC system and then blown into the cabin.

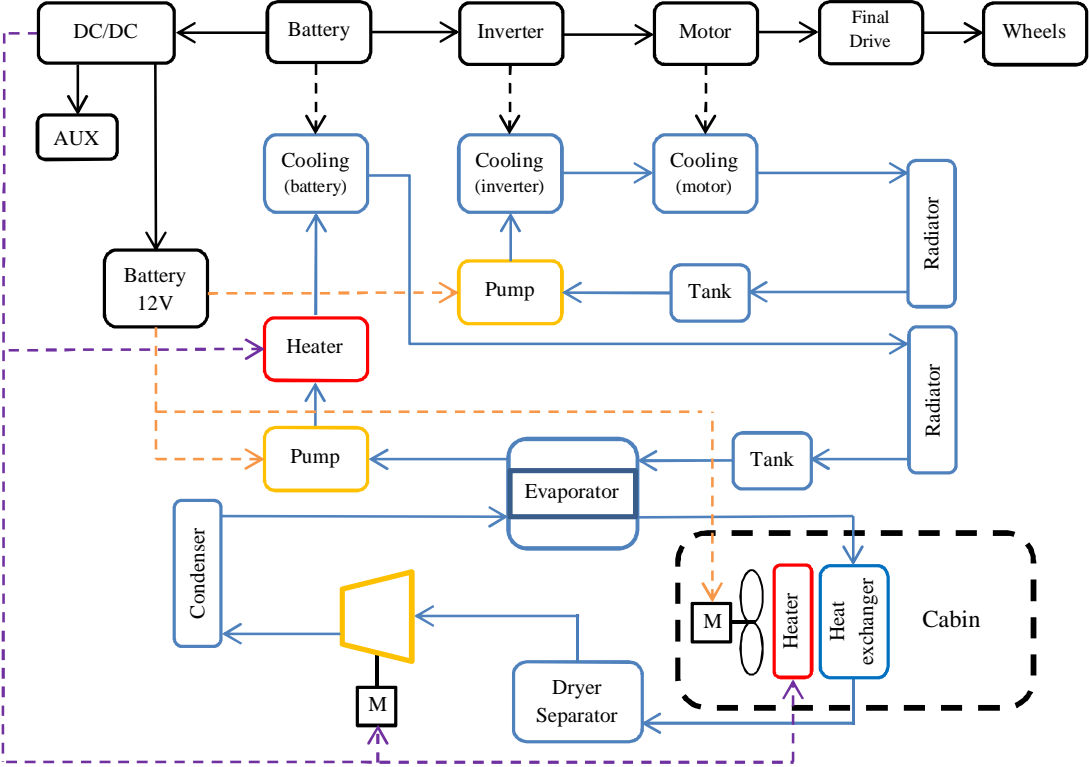


Figure 2: Block diagram of the simulation model including thermal systems.

2.2 Model parameters

The simulated electric vehicle model corresponds to a midsize passenger car. The key technical specifications are described in Table 1. The cabin heating system consist of an electric heater with maximum power of 6 kW and air conditioning system with compressor maximum power of 4 kW. The energy consumption of the other auxiliary devices was taken into account as constant power of 350 W.

Table 1: Vehicle general specifications

Simulated weight (kg)	1760
Vehicle frontal area (m ²)	2.06
Drag coefficient	0.30
Interior passenger volume (m ³)	2.55
Tyres	205/55R16
Battery nominal capacity (kWh)	23.9
Battery depth of discharge, DOD (%)	85
Battery nominal voltage (V)	318.2
Battery cell capacity (Ah)	75
Electric motor max power (kW)	107
Motor max torque (Nm)	253
Final drive ratio	1:7.82
Final drive efficiency	0.97
Power converter efficiency	0.95

Simulations were conducted in different ambient temperatures from -30 to 40 °C. The air relative humidity was 50% and air density was based on the ambient temperature. The cabin target temperature was 22.2 °C (72 F). Solar radiation was defined for ambient temperatures higher than 15 °C and it was linearly increasing being 600 W/m² at 20 °C, 800 W/m² at 30 °C and 1000 W/m² in 40 °C.

2.3 Driving cycles

Simulations were carried out in 13 different driving cycles to comprehensively investigate the vehicle and HVAC energy consumption in different driving conditions. Table 2 presents the descriptions of the simulated cycles. The chosen driving cycles can be divided into three categories based on the average driving speed as described in Figure 3A. The speed categories are marked in Table 2 and Figure 3A as follows: low speed = red, medium speed = green, and high speed = orange. UDDS, US06 and HWFET are US EPA official emission and fuel consumption test cycles. JC08 was introduced in 2005 by the Japanese emission regulation for the chassis dynamometer test cycle for light vehicles. NEDC is the current European test cycle to assess the emission levels of car engines and fuel economy in passenger cars. WLTC is the new proposed emission and fuel economy test cycle for worldwide use [24]. Artemis driving cycles (The Common Artemis Driving Cycles, CADC) are chassis dynamometer procedures developed within the European Artemis project [25]. Those cycles are based on statistical analysis of a large database of European real world driving patterns include three driving cycles: 1) Urban (AE), 2) Rural road or extra urban (AEU), and 3) Highway (AH). There are two variants of the highway cycle with maximum speed of 130 and 150 km/h. The LA92, often called the Unified driving schedule, was developed as an emission inventory improvement tool by the California Air Resources Board. Compared to the UDDS, the LA92 has a higher top speed, a higher average speed, less idle time, fewer stops per distance, and a higher maximum rate of acceleration. The Porvoo cycle is a real-world driving cycle which was measured between cities of Helsinki and Porvoo in Finland [23]. The cycle includes two parts of city driving and one part of high speed driving in a motorway. The US EPA NYCC simulates low speed urban driving with frequent stops. The ECE cycle has been designed to represent typical driving conditions of busy European cities and it forms the city driving part of the NEDC.

Table 2: Description of driving cycles.

	Time (s)	Distance (km)	Max speed (km/h)	Average speed (km/h)	Average driving speed (km/h)	Stops per km	Standing time (%)
NYCC	598	1.9	44.3	11.3	17.5	9.54	34%
AU	920	4.5	57.7	17.5	24.4	4.70	26%
ECE	195	1.0	50.0	18.7	27.7	2.95	27%
JC08	1204	8.2	81.6	24.4	34.7	1.35	27%
UDDS	1369	12.0	91.2	31.5	38.9	1.42	17%
NEDC	1180	11.0	120.0	33.6	44.7	1.18	24%
LA92	1435	15.8	108.1	39.6	47.3	1.01	14%
WLTC	1800	23.1	131.3	46.3	53.2	0.35	12%
AEU	980	16.4	111.5	60.3	61.8	0.18	2%
Porvoo	2961	59.3	127.7	72.1	75.1	0.13	4%
HWFET	764	16.5	96.4	77.7	78.2	0.06	0%
US06	600	12.9	129.2	77.2	83.4	0.39	7%
AH	1068	28.7	131.8	96.8	98.3	0.07	1%

2.4 Model verification

The energy consumption of the developed vehicle model was verified with the data measured by the INL (Idaho National Laboratory) from the 2013 Ford Focus Electric vehicle [20]. The simulation model was configured according to the measured vehicle specification data. This data was acquired from the INL

measurement results and EPA fuel economy testing data [26]. The INL test included measurements in three different driving cycles (UDDS, HWFET, and US06), and in three different ambient temperatures: 20 F (-6.7 °C), 72 F (22.2 °C), 95 F (35 °C). A comparison of the energy consumption between the simulated and measured results is presented in Figure 3B for UDDS and US06 cycles. The model energy consumption corresponds very well to the measured results in the US06 cycle. The model consumption is slightly lower in colder ambient temperatures in the UDDS cycle. This consumption difference is most probably caused by the cabin model inaccuracies.

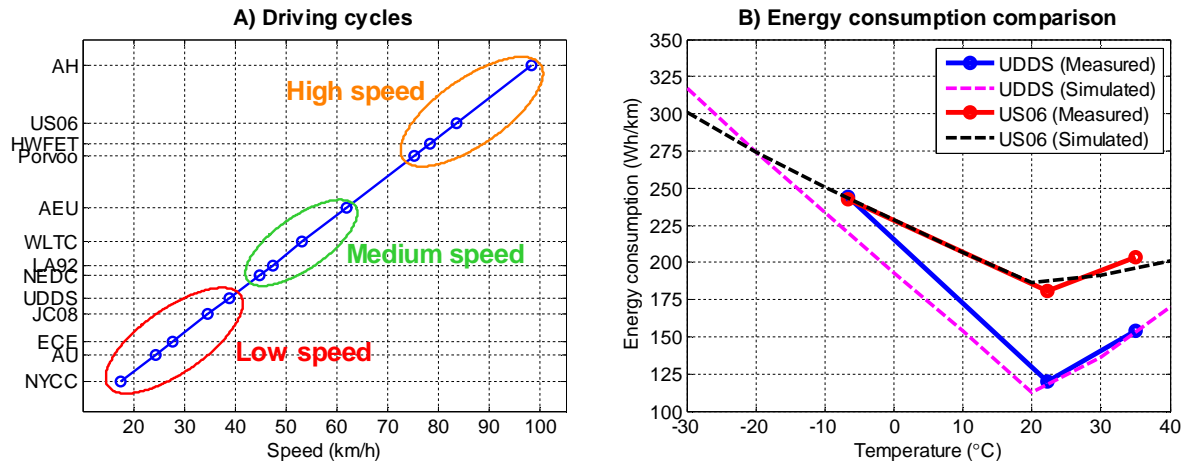


Figure 3: A) Driving cycle categories, B) Verification of the simulation model energy consumption.

3 Simulation results

3.1 Energy consumption and driving range

Simulation results were analysed to investigate the different aspects of the vehicle energy consumption in different ambient temperatures. Figure 4 shows the energy consumption (Wh/km) in all simulated cycles and three ambient temperatures. The cycles were arranged in the figures based on the consumption at the reference conditions corresponding to 20 °C of ambient temperature. The bar colours denote the cycle categories. The consumption varies between driving cycles from 110 to 200 Wh/km in the reference conditions. In cold conditions (-20 °C), the energy consumption increases significantly and it is between 215 and 540 Wh/km. In warm conditions (40 °C), the use of air conditioning increases the consumption being between 145–315 Wh/km.

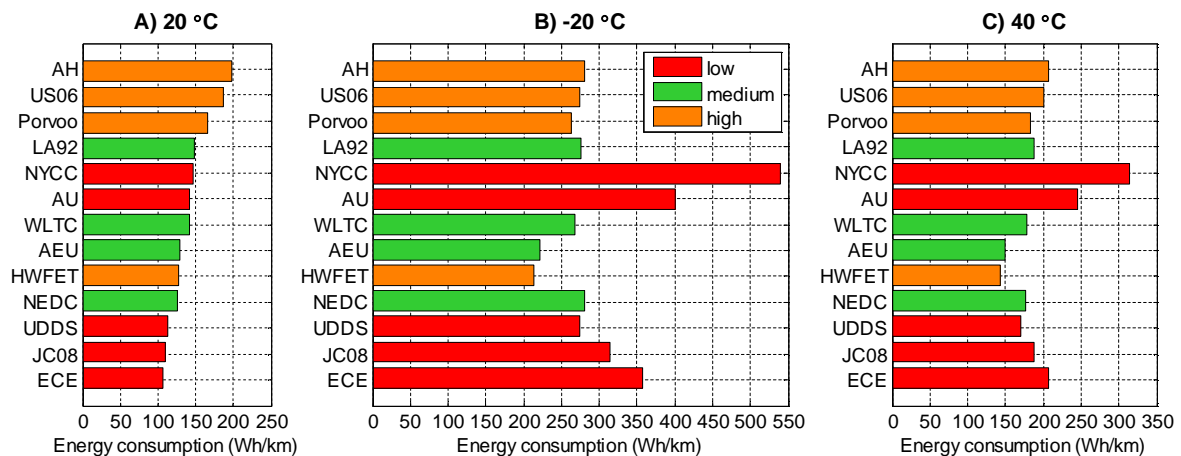


Figure 4: Cycle energy consumption in three different ambient temperatures.

Figure 5 shows the driving cycle influence on the energy consumption in different ambient temperatures. In low speed cycles and cold conditions, the energy consumption is very high as well as the consumption variation between cycles. The energy consumption variation within cycle categories is presented by the area coloured in light blue. Among the low speed cycles, the energy consumption is one of the lowest in the EPA test cycle UDDS. In the medium speed cycles, there is much less consumption variation due to the increased average speed which mitigates the influence of HVAC energy losses in cold and hot conditions. This can also be noticed in the high speed cycle results. However, the high average speed increases energy consumption in all ambient conditions. The new worldwide test cycle (WLTC) is in the higher end among the medium speed cycles as well as the US06 among the high speed cycles.

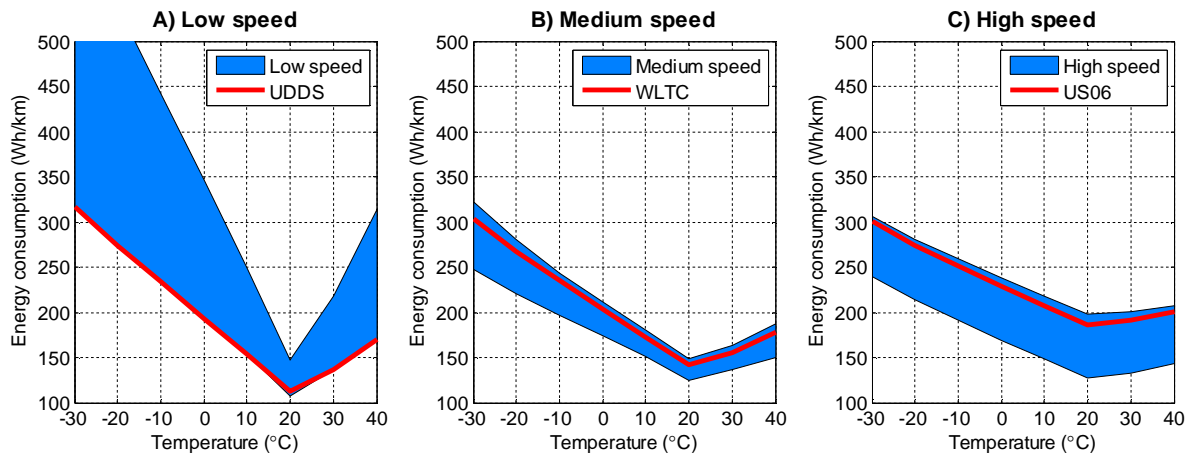


Figure 5: Energy consumption variation in cycle categories and different ambient temperatures.

Vehicle energy consumption has direct influence on driving range. Estimated driving ranges in different cycle categories are presented in Figure 6. The maximum range is reached in the reference conditions and low speed cycles but the range decreases significantly in cold and hot ambient temperatures. This is due to the higher impact of HVAC energy losses when driving lower speeds. For low speed cycles, the range decrease is higher than 60% in cold and higher than 40% in hot conditions. In the medium and high speed cycles, the range decrease is much less being 30-50% in cold conditions and up to 15% in hot conditions. Practically, higher driving speeds mitigate the influence of heating and cooling power which is weakly dependent on the vehicle speed.

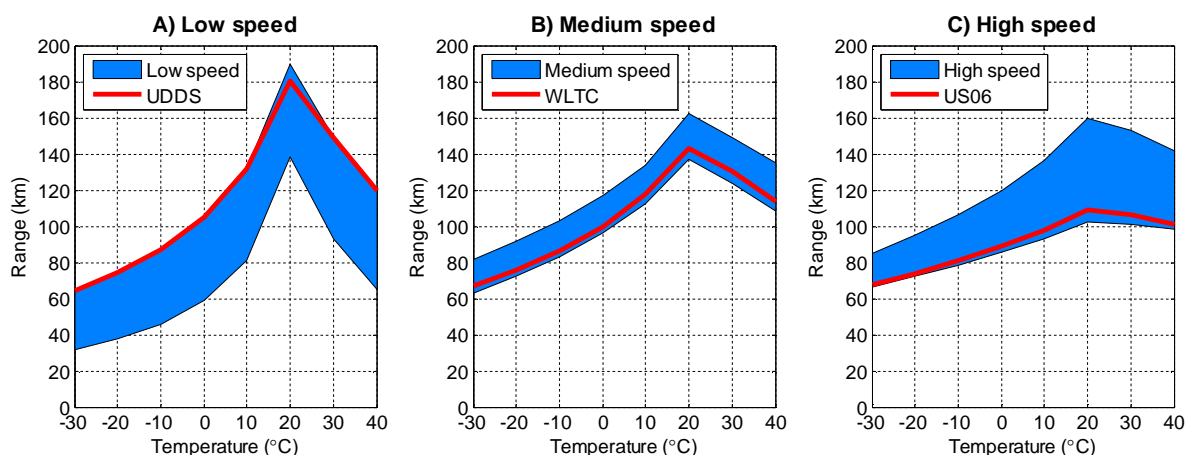


Figure 6: Variation of estimated driving ranges in different cycle categories.

3.2 Distribution of losses

Energy losses were calculated for different components of the vehicle. Figure 7 presents the relative loss shares of component at three different ambient temperatures. Auxiliaries include the 12V auxiliary devices

and HVAC system. It can be clearly observed that the auxiliaries consume an important part of the energy in cold and hot ambient conditions. In the high speed cycles (HWFET, Porvoo, US06 and AH), the aerodynamic losses are dominant in all conditions. The relative shares of the drivetrain (motor and final drive) and tyre losses are higher in the reference conditions (20 °C). However, tyre losses remain quite significant also in cold and hot conditions. In some cycles e.g. Artemis extra urban (AEU), Artemis urban (AU), and LA92, the braking losses are quite high due to the powertrain power or torque limitations to regenerate all the braking power. In comparison to other components, battery losses are generally rather small even though they are higher in colder conditions.

Figure 8 shows the component specific losses in WLTC and three different ambient temperatures. The auxiliary energy consumption can be more than 13 times higher (from 9 Wh/km to 124 Wh/km) in cold conditions but the relative loss share is only six times higher. This is because also other component losses are increased in cold conditions. Aerodynamic and tyre losses presents 68% of the losses at 20 °C and still 43% of the losses in -30 °C. Especially tyre losses increase in cold quite remarkably from 45 Wh/km to 74 Wh/km. It is also noteworthy that braking losses are lower in cold and hot conditions because part of the regenerated power can be directly used for cooling or heating of the cabin.

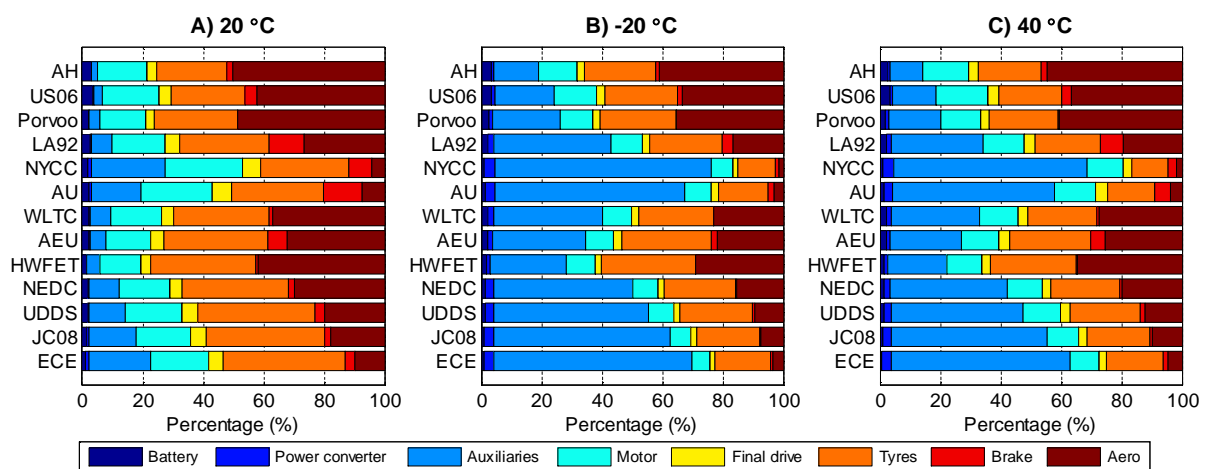


Figure 7: Distribution of vehicle losses.

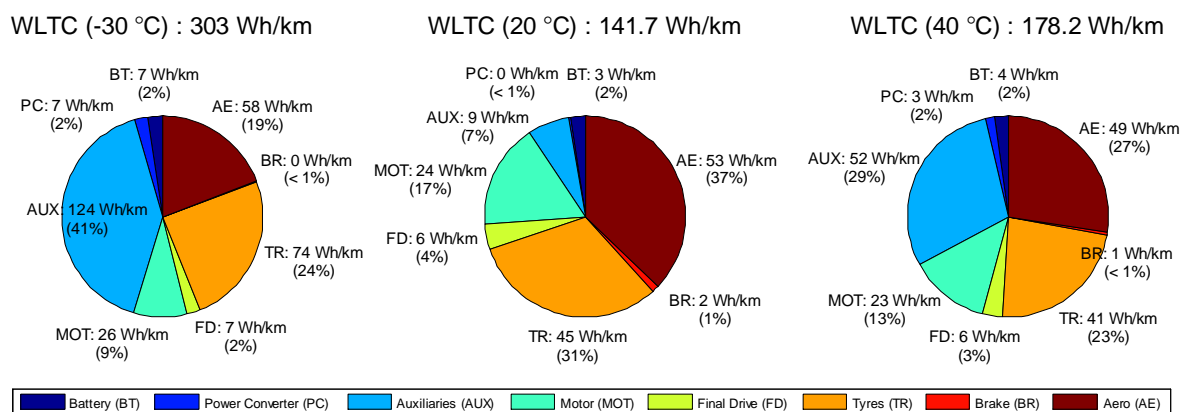


Figure 8: Component specific losses in WLTC and three different ambient temperatures.

Figure 9 shows the HVAC and tyre power losses in function of the ambient temperature. Because the cabin heating and cooling is only weakly dependent on other driving conditions than temperature, the HVAC power consumption has little variation between driving cycles. Tyre losses are quite complex to take into account without detail tyre measurements. In this case, the rolling resistance is dependent on the tyre temperature and vehicle speed. Figure 9B presents the tyre loss power variation in different driving cycle categories. In low speed cycles, tyre losses increase slightly in cold temperatures whereas losses are much higher in high speed cycles, and losses increase much more in cold temperatures.

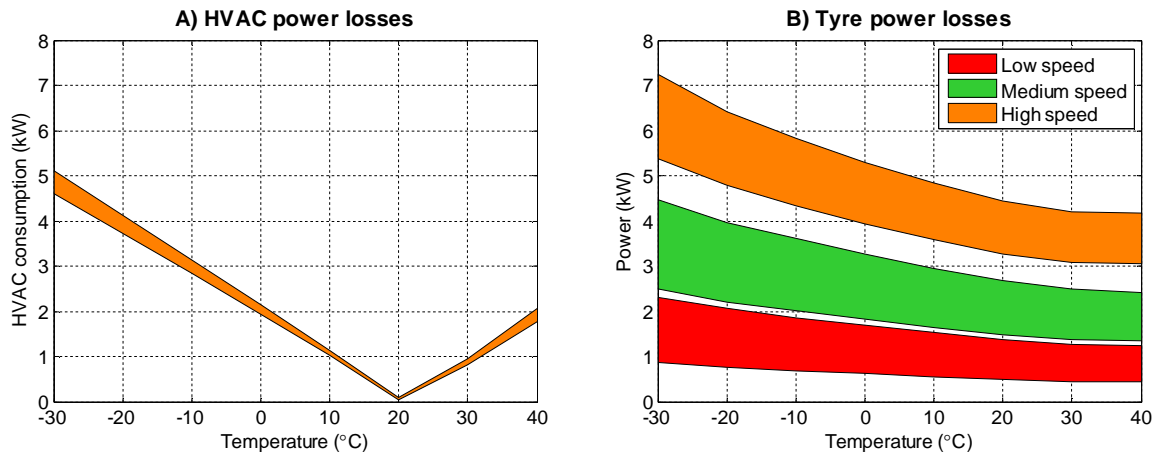


Figure 9: A) HVAC power losses, B) Tyre power losses.

4 Discussion and conclusions

The energy consumption of a midsize electric vehicle was investigated by simulations in different driving and ambient conditions. A simulation model with relevant thermal models was developed in the Autonomie software. The vehicle energy consumption in different conditions was verified with measurement data acquired from vehicle tests presented in the literature. Simulations were carried out on 13 different driving cycles and eight ambient temperatures. Overall, the simulation results showed that the energy consumption varies significantly depending on the driving cycle and ambient temperature. First, it was clearly shown by the three cycle categories (low, medium and high speed) that the energy consumption is generally higher in high speed driving cycles. Secondly, there was quite a lot of consumption variation between cycles within categories, especially in low speed cycles. Thirdly, cabin heating and cooling (HVAC consumption) increase massively in cold and hot ambient conditions, and increase significantly vehicle energy consumption in low speed cycles.

An analysis of the energy loss distribution was done to evaluate the influences of component losses on vehicle energy consumption. The relative loss shares illustrated the major impact of auxiliary devices (including HVAC) in hot and cold conditions as well as the important share of tyre losses in all conditions. The tyre losses can be up to 40% of the total losses, therefore relatively much higher than in conventional vehicles. Because power consumption of the auxiliary devices is only weakly dependent of vehicle speed, the relative losses of the auxiliary devices can be very different between driving cycles.

Because the driving range is directly dependent on the energy consumption, the range can be drastically shortened especially in cold ambient conditions. How to reduce the energy consumption at extreme temperatures? Assuming that the aerodynamic resistance remains at the same level, the focus turns on auxiliaries and tyre rolling resistance. Energy efficient tyres and careful road maintenance can contribute on the reduction of rolling resistance. The HVAC system remain a significant consumer at extreme temperatures. By using a heat pump system instead of a traditional air conditioning, cabin heating losses could be significantly reduced specifically in mild and mildly cold conditions. In cold ambient temperatures, better cabin insulation can reduce the heat losses from cabin to ambient air. Those type of measures unfortunately may increase the vehicle weight and then the total energy consumption.

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Authors



Antti Lajunen received the M.Sc. degree in Mechanical Engineering from Helsinki University of Technology, Espoo, Finland, in 2005 and Master of Advanced Studies degree in Industrial Engineering from Ecole Centrale Paris (ECP), Paris, France, in 2007. He received his D.Sc. in 2014 from Aalto University, Espoo, Finland. In his dissertation, he studied the impacts of powertrain electrification on energy efficiency and performance of heavy vehicles. He is currently working as visiting researcher at Aalto University. His main research interests are hybrid and electric vehicle modelling and simulation, techno-economical assessment of heavy hybrid and electric vehicles, and vehicle thermal management.



Kari Tammi works as Associate Professor for Design of Mechatronic Machines at Aalto University. Dr. Tammi received M.Sc., Lic.Sc. and D.Sc. degrees from the Helsinki University of Technology in 1999, 2003, 2007. His research interests are in mechatronics and how to improve the energy efficiency of machinery by the means of electrification and modern control technologies. The specific applications are in electrical power transmission and electrical vehicles. He teaches courses on Mechatronic Machine Design and Vehicle Mechatronics. Prior Aalto, he worked as Research Professor and Research Manager at VTT Ltd, Technical Research Centre of Finland. He was a visiting post-doctoral researcher at North Carolina State University in 2007-2008. Before joining VTT in year 2000, he worked with alignment and mechanical accuracy of particle detectors at CERN, Switzerland.