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eCULT – a concept study of a lightweight, affordable 48V urban vehicle

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Summary

The purist and award winning vehicle demonstrator CULT (Cars Ultra Light Technologies) of Magna Steyr, originally equipped with an innovative 3-Cylinder 600 ccm CNG engine with direct CNG injection, has been rebuilt into the 48V eCULT electric vehicle at UAS/FH-Joanneum. This concept study - performed by students and lecturers - shall prove whether an extremely lightweight 4-seater electric vehicle equipped with two relatively small 48V e-motors is feasible in city driving and shall evaluate it’s environmental impact.

In the pure electrified version a powertrain with two 15 kW asynchronous 48V e-motors from series production including two reduction transmissions for each front wheel has been chosen.

The paper confirms that both projects – the original CULT and the new eCULT version - deliver satisfying city driving performance. In normal city speeds the eCULT provides more active and smooth driving performance, above 70 km/h the more powerful CNG version is superior.

In terms of energy consumption and CO_2, the eCULT concept provides about 30% better results, although in manufacturing especially the battery requires higher energies, which has been concluded in a parallel LCA (Life Cycle Analysis).

Keywords: BEV (Battery Electric Vehicle); Demonstration; light vehicle, LCA (Life Cycle Analysis)

1 CULT Vehicle Introduction

Figure 1**:** CULT vehicle

The original CULT (Cars Ultra-Light Technology) project was backed by a consortium of seven industrial and scientific partners under the leadership of Magna Steyr, a company of the Magna International group. The other project partners were: FACC (know-how in the aeronautic sector), 4a manufacturing (known for the highly innovative sandwich material 'CIMERA'), the Technical University of Vienna (responsible for all powertrain tasks, especially the implementation of CNG direct injection and the hybrid functionalities), the Austrian casting institute ÖGI (all casting tasks) as well as the Polymer Competence Center Leoben PCCL (determination of the material data) and the University of Leoben for the production processes of fiber composites.

The targets for the four-seater car CULT were a net weight of 600 kg and CO_2 emissions lower than 50 g CO_2/km in the NEDC driving cycle [1]. These visionary ideas should also be turned from a concept into a real prototype (see Fig. 1).

The CULT vehicle is a prototype demonstration vehicle featuring lightweight technologies and has been positioned among competitor vehicles such as Toyota IQ or Smart. The vehicle concept is based on a multi-material chassis.

The main objective of the vehicle concept was to demonstrate CO_2 emissions lower than 49 g/km, but with the added constraint that the cost of the CULT vehicle should not exceed costs of similar benchmark vehicles by more than EUR 3,000.-. Thus, the vehicle remains affordable for the end customer, especially if the 'total cost of ownership' is considered. [1]

1.1. Weight Reduction Approach

Fundamentally, the main variables identified to accomplish a significant CO_2 reduction were 'aerodynamics', 'rolling resistance', 'efficiency increase', 'lightweight design' and the 'powertrain' (CNG direct injection).

In the CULT project, each of these variables were addressed in an adequate work package. However, in this chapter the focus will be on the topic of 'lightweight design', because achieving the ambitious weight goal is a prerequisite for attaining all the other goals.

In order to reduce the vehicle weight significantly (the objective is to reduce the original weight of 900 kg by 300 kg) while making sure that the vehicle is still affordable, a holistic approach is necessary.

This approach – shown in Fig. 2 – is based on three pillars, namely 'functional integration', 'material substitution' and 'downsizing/exploitation of secondary effects'.

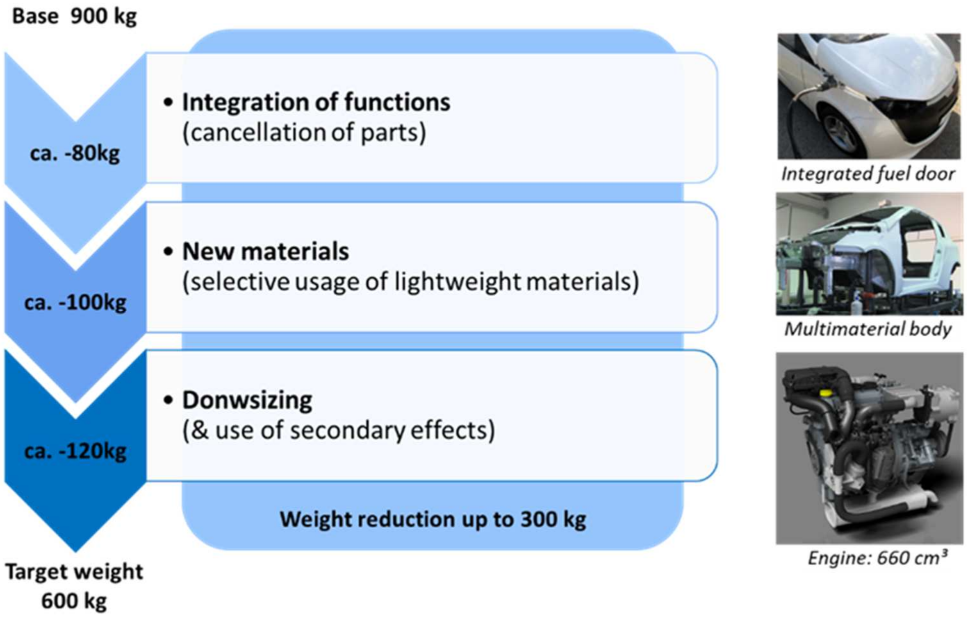

Figure 2: Holistic approach to weight reduction in the CULT project

Functional integration means that every part has to fulfill as many functions as possible in order to reduce the number of parts. One example is the possible elimination of conventional interior trim components by designing the inner structural parts in such a way that they already have a surface ready for lamination.

Substitution of materials means the targeted use of lightweight materials (carbon fiber compounds, magnesium, etc.).

Downsizing/exploitation of secondary effects expresses the idea that a vehicle that is significantly lighter will need smaller and lighter (and normally cheaper) components which satisfy the same functional requirements. For example, such a lightweight car needs smaller brakes for the same braking distance, or the powertrain delivers the same performance even if the displacement and the number of cylinders are reduced.

The cost reduction as a result of 'functional integration' and 'downsizing/exploitation of secondary effects' leads to a partial compensation of the additional cost resulting from the substitution of materials.

1.2. Weight result achieved

With this approach a total vehicle weight of 672.5 kg was achieved. Although the actual value falls short of the original target of 600 kg by 12 %, this is partly due to the fact that the adopted CNG powertrain involves additional weight by micro hybridization. But for the purpose of optimizing CO_2 emissions, the benefit of increased efficiency of the powertrain compensated the penalty of the slightly higher weight.

Compared to A-segment benchmark vehicles equipped with a CNG powertrain, the CULT weighs approximately 400 kg less. In particular, the body in white (147 kg) and the doors & closures (62 kg) are best in class.

The work on weight reduction led to the development of lightweight modules – of which the most important is the lightweight body as expected. In line with the motto "choosing the right material in the right place", a multi-material approach was chosen for the body. As shown in Fig. 4, cast aluminum nodes were combined with aluminum profiles, a firewall from the sandwich material 'CIMERA', a fiber compound underbody and glass fiber reinforced thermoplastics.

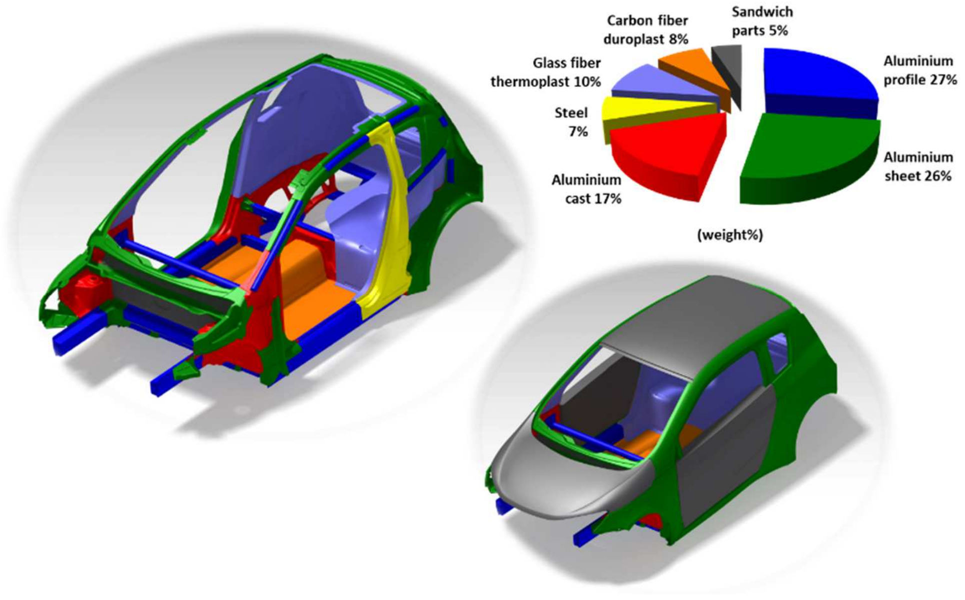

Figure 3: CULT body concept

The big challenge of such a multi-material concept is the joining technology of the different material pairings and the risk of corrosion caused by the difference in the electro-chemical potential. In particular, all material combinations involving carbon fiber show critical corrosion behavior. Within the scope of the CULT project, many tests were performed to identify the fatigue life and corrosion resistance of joining partners and joining elements. [1]

2 Powertrains

2.1 CNG Powertrain

The original CULT vehicle was equipped with a 3-cylinder 600 ccm CNG engine from the Japanese Kei-Car market with direct CNG injection, micro belt-starter-generator (BSG) hybridization (12 V belt integrated) and automated transmission. [3]

One of the main hybrid features in the CULT vehicle was the adaption of a BSG on the transmission side (BSG-Transmission, see Fig. 4) instead of the conventional layout including the BSG device in the belt-drive of the internal combustion engine (BSG-ICE). Due to de-clutching the ICE and the lack of the drag torque in the decelerating state, the amount of the recuperation energy could be increased. The ultra-light vehicle concept and a BSG maximum motoring power of 1.4 kW enable stationary speeds up to 35 km/h to be driven purely electrically. [2]

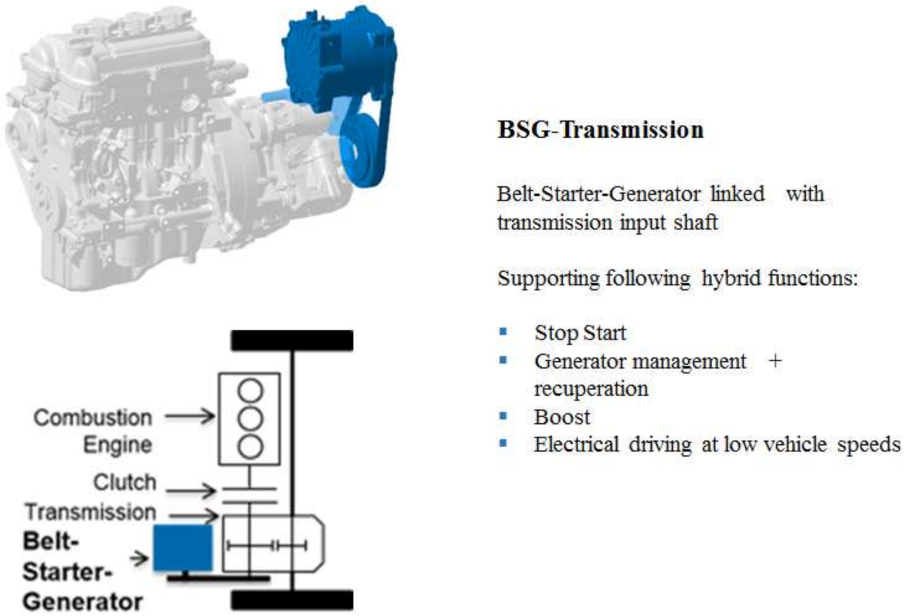

Figure 4: CULT CNG powertrain concept with mild hybridization

The benefit of the micro-hybrid approach, including intelligent generator management and recuperation, dominated in spite of the minor additional weight. Up to 2.8 kW maximum power in the generating state could also be used for recovering brake energy. Therefore, it is possible to partly compensate the consumption of the different electrical devices.

2.2 New electric powertrain

At the UAS Joanneum students performed paper studies considering several electric powertrains. It was concluded that the variant shown in Fig. 5 will be the best compromise between performance goals, affordability and availability of components.

In fact, the idea was to combine two Renault Twizy powertrains with the ultra-light chassis of the CULT.

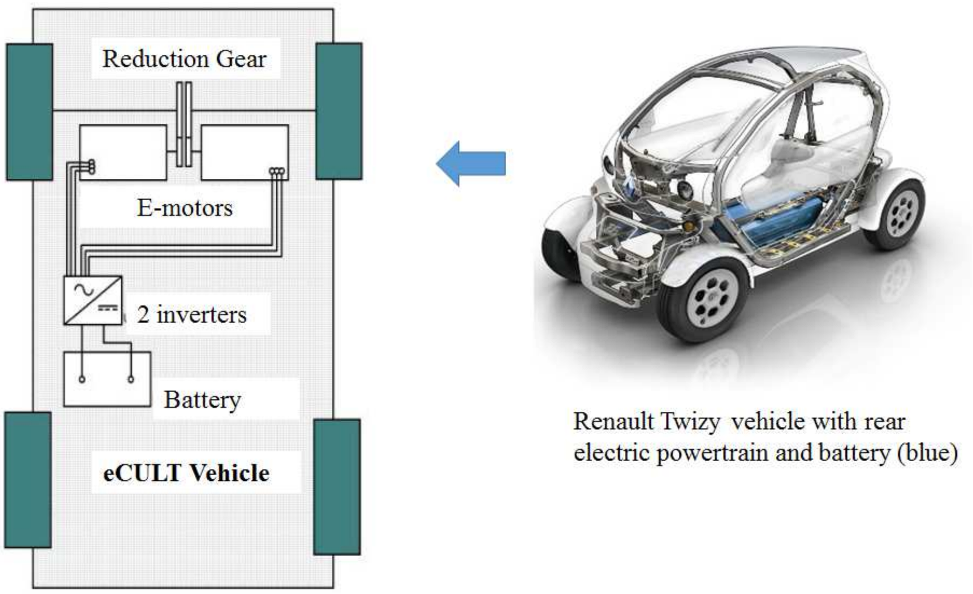

Figure 5: Principal layout of the eCULT powertrain concept

The original CNG powertrain and the CNG tank has been removed from the vehicle and an electric powertrain utilizing a double drivetrain has been adapted to the chassis.

As can been seen in Fig. 6 an entangled arrangement of the two drive units had to be chosen as the used transmission has a preferred rotation direction and so in this arrangement both transmissions can maintain this preferred direction. Otherwise modifications to the transmission would have been necessary.

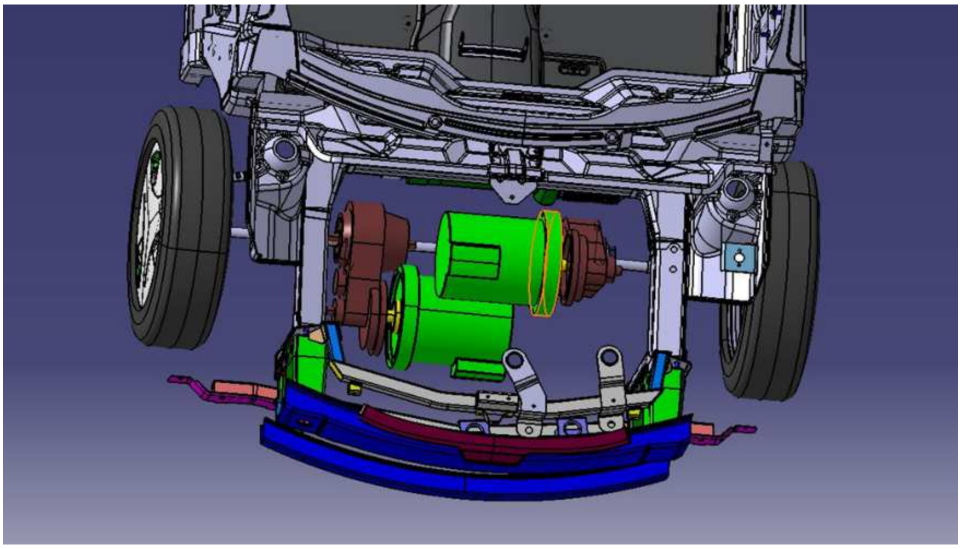

Figure 6: Drive units arranged in the front of the eCULT vehicle

The photo in Fig. 7 shows the installation of the two drive units using an auxiliary frame and this frame utilizes the same mounting positions as the CNG engine.

Figure 7: Photo of the eCULT's front with subframe and milled cooling devices for the inverters

A further major component is the high voltage lithium nickel manganese cobalt oxide (NMC) traction battery. The battery consists of 84 cells, where 6 cells are in parallel and 14 of those packages are in series. Each cell has a nominal voltage of 3.7 V and a capacity of 60.5 Ah. This results in an overall nominal voltage of 48 V and 18,8 kWh energy. The battery is managed by a customized battery management system, which balances the individual packages of 6 cells in the battery. With this setting it is possible to draw 600 A continuously out of the battery. The two inverters are limited to 300 A each, not to exceed this limit and guarantee a long lifetime of the battery. With the limited charging current, it is able to charge the battery without active cooling system what reduces the weight and also the complexity of the system.

The battery location in the vehicle can be seen in Fig. 8. The battery box used the space available under the rear seats and under the trunk. Initially, the plan was to use the space in the tunnel to accommodate the battery cells (round types), but after choosing 84 LG pouch cells the space of the tunnel was used for the battery management system (BMS), the power distribution, fuses, the DC/DC inverter for the 12V board battery and the on-board charger.

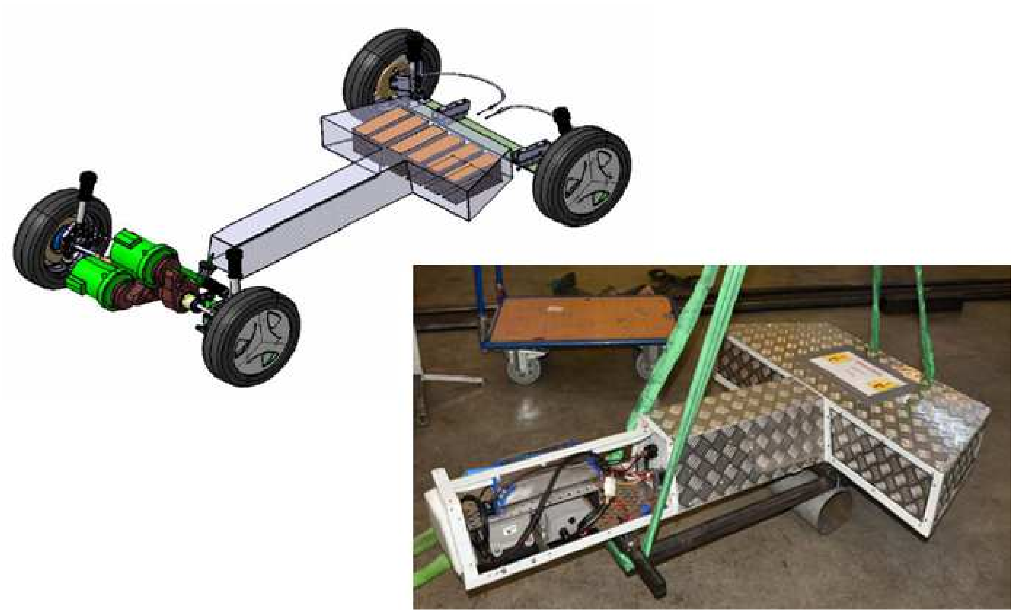

Figure 8: CAD design of the battery installation and photo the battery box

3 Specification Comparison

The specifications for both powertrains are given in Table 1. Comparing the power, the CNG powertrain is stronger by 17 kW, which also promises better performance at higher speeds and loads.

The ICE engine offers 47 kW whereas the two electric motors can only provide 30 kW, although at low speeds the electric powertrain provides an approximately 40 Nm better torque. This leads to better acceleration capability as can be seen in Table 2.

Due to the demanded affordability, the electric powertrain has been kept simple and cheap and does not have any active cooling devices, all systems are only cooled by convection or by the headwind. So it was not possible to choose high end components like PSM motors, liquid cooled high performance inverters, etc. These decisions need to be reconsidered when envisaging the production of a higher number of such vehicles or even a series production.

Table 1: Comparison between powertrain components of the eCULT and CNG CULT

	ICE Powertrain		**Electrical Powertrain**	
Engine	3-cylinder CNG ice engine		Asynchronous eMotor	
	Displacement	658 cm³	Inverter	48 V / 400 A
	Mixture formation	Direct injection		
	Power max.	47 kw (@ 5000 rpm)	Power max.	2 x 15 kW
	Torque max.	103 Nm (@ 2500 rpm)	Torque max.	2 x 70 Nm
Transmission	Automated transmission		Reduction gear	Comex
	Gears	6	Ratio	7,13
	Dry slump lubrication		Blocked differential	
	Electrical oil pump		No oil pump	
Energy Storage	CNG Type 4 Carbon fiber high pressure vessel	50 l, 8 kg CH4 at 200 bar	60 Ah LG Li-Ion 84 Cells 14s6p	18 kWh
			Available net capacity	16 kWh
Electrical Components	Belt-Starter-Generator	12 V		
	Power max. generating	2,8 kW	DC/DC converter	13,8 V / 50 Amax
	Power max motoring	1,4 kW	On-board charger	48 V / 25 A
	Voltage electrical system	12 V	Voltage level	12 V / 48 V
	On-board battery	12 V / 38 Ah	On-board battery	12 V / 38 Ah

4 Testing preparation

4.1 Coast down test

In order to accurately determine the energy consumption of the vehicle at the chassis test bench and in simulation, the rolling resistances had to be determined. Therefore, a coast down test had to be performed.

In a coast down test, the vehicle is accelerated to a higher speed (in this case 100 km/h) and then coasted to standstill. During this procedure, the speed of the vehicle needs to be measured. This data is then used to determine the deceleration of the vehicle, i.e. providing the rolling resistances.

The test itself was performed on a runway at the Zeltweg Military Airport. Vehicle speed and time were measured via a VBox using GPS data. The test yielded results from four runs in each direction, from which the rolling resistances were calculated.

In order to simulate the vehicle's rolling resistance at different speeds on a chassis dynamometer, it needs to be modelled as follows:

$$F(v) = F_0 + F_1 v + F_2 v^2. \tag{1}$$

F_0 represents a constant part due to rolling friction, F_1 a linearly increasing viscous resistance, and F_2 represents the vehicle's air resistance, which has a squared dependency on velocity.

In the first step the vehicle velocity was numerically differentiated in order to determine the deceleration over time. In order to eliminate the influence of the minimal runway's inclination,

$$a_{inc} = g \sin \alpha \tag{2}$$

was subtracted. It was possible to calculate the angle of inclination α for every measurement step from the available GPS data.

In the second step, the acceleration was multiplied by the sum of the vehicle's mass and a mass representing the inertia of its rotating parts, in order to calculate the force acting on the car at different speeds during coasting.

The last step consisted of approximating a polynomial equation via the least squares method:

$$F(v) = 113{,}14 + 0{,}8761v + 0{,}0279v^2. \tag{3}$$

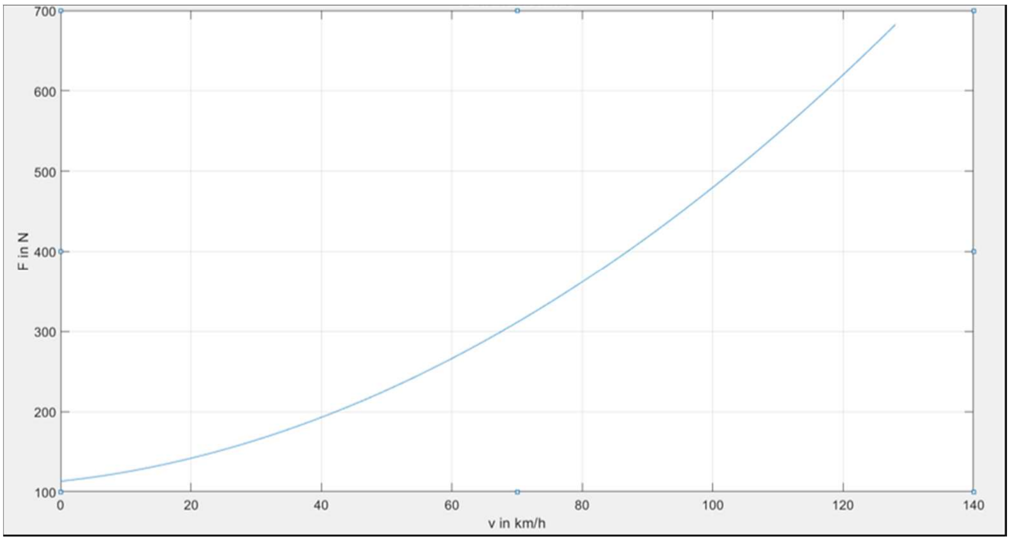

Figure 9: Model of the vehicle's rolling resistances

4.2 Chassis dynamometer tests

Two testing cycles were performed on the chassis test bench: NEDC and the new WLTC. The use of these predetermined cycles provides a basis on which it is possible to compare the dynamometer results to the simulation. Constant velocity tests in ten km/h steps up to 100 km/h were also performed in order to examine the stationary energy flows in the vehicle.

The obtained measurement data was evaluated by a MATLAB file, which delivered power and energy consumption.

4.3 Simulation

In order to understand the results of energy flows and energy consumption in any phase and as a base for further optimisation steps, a simulation model was set up in MatLab Simulink. The power was determined via the simulation before the battery and after the electric motor. In simulation the driving cycle (NEDC, WLTC) can be selected too. The parameters obtained from the coast down test were used in the simulation to determine the torque applied to the motor shaft. The efficiency of the motor was also considered in the simulation.

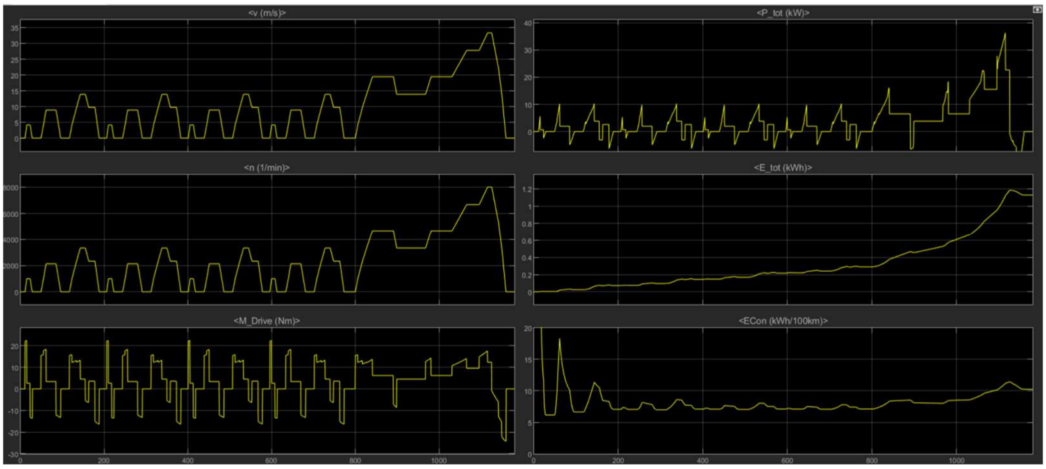

Figure 10: NEDC Simulation output

5 Energy Consumption & Driving Performance

For the determination of the driving range of the eCULT and the assessment of the accumulated energy consumption in the use phase in the following life cycle assessment, only NEDC measurements from the chassis dyno have been taken, representing an urban energy consumption. As in the very beginning of the original CULT Project the decision has been made that the vehicle will not be certified and registered for public roads, tests can be only performed at test tracks or at the chassis dyno. Some of the vehicle's features like cameras instead of mirrors are too advanced and not compatible with current legislation.

Table 2: Energy consumption and driving performance comparison between eCULT and CNG CULT

	ICE Powertrain		**Electric Powertrain**
Max. Speed	km/h	130	112
Accelerations	0 - 30 km/h	4 s *with corrected, reasonable shifting durations	3,1 s
	0 - 50 km/h	8 s*	6,2 s
	0 - 70 km/h	11 s*	11,8 s
	0 - 80 km/h	12 s*	14,09 s
Elasticity	30 - 50	4 s*	3,4 s
	30 -70	6 s*	8,1 s
	30 - 80	8 s*	11,9 s
Range (City / NEDC)	8 kg CNG		16 kWh net capacity
		> 300 km (8 kg CNG	~ 150 km
Empirical evaluation		long torque interrupts during shifting (1st Gen. AMT!)	very smooth acceleration
Energy consumption	2,8 kg CNG	both in real drive -	11 kWh

Due to the higher power the CNG CULT has a more attractive maximum speed compared to the eCULT. As expected the eCULT is more agile in the lower speed ranges resulting in better accelerations and elasticity values, whereas the ice powertrain is gaining better figures at higher speeds.

Both concepts proof that they are feasible for city driving, the eCULT provides a better drivability at normal urban speeds, the 47 kW of the CNG engine – of course – provides a wider application range especially considering highways in the outskirts of cities. For that application the power the electric powertrain need to be increased. Nevertheless the eCULT got the higher driver acceptance, also due to the smoother accelerations without torque interrupts.

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6 Life Cycle Analysis Comparison

In parallel and based upon the former analysis of the conventional CNG CULT, a life cycle assessment (LCA) of the electric CULT was performed. The goal of this comparative assessment was to analyze different propulsion systems including impacts related to country-specific energy mixes.

6.1 LCA Setup

The general framework and the boundaries for the LCA according to ISO 14040 are as follows:

- three major chapters: **Production Phase** (including processing of materials and manufacture of parts and subcomponents); **Use Phase** (covering the actual consumption of the product under assessment including upstream emission from fuel production and additional product flows) and **End of life Phase** (parts, materials and subcomponents being recycled, recovered and/or disposed, here in this analysis excluded as safe data for battery recycling are not available yet).
- The inventory analysis is based on the data base Ecoinvent 3.4, the former analysis was based on Ecoinvent 2.2 (EI), therefore correction factors have been applied; data have been also imported from the latest IPCC assessment report (AR5, 2013); reference processes and materials were modelled in the latest SimaPro v8.5 LCA-software; the CML baseline impact assessment method was applied in version 3.05 using the carbon footprint (GHG100a) as main indicator for environmental performance shown in this paper [4], see Fig.12.
- Total amount of driving emissions are influenced by four components:
  - Upstream emissions from electricity and fuel production, CO_2 and H_2S removal (CNG)
  - Midstream emissions from feedstock transportation and transformation losses
  - Downstream emissions from fuel dispensing, gas and transport, charging losses
  - Combustion of fuel (in case of CNG CULT, zero off-gas emissions for eCULT)
- The LiIon-battery pack was assumed to use 200 kg CO_2-eq/kWh; data are based on a study by M. Romare and L. Dahllöf of the IVL Swedish Environmental Research Institute [5].
- Market-specific datasets of Austria, Germany and Italy reflect respective country mixes, including electricity production, transport, and transformation losses.
- For actual greenhouse gas data for diesel, petrol, kerosene and natural gas lead by Exergia S.A [6] was consulted.

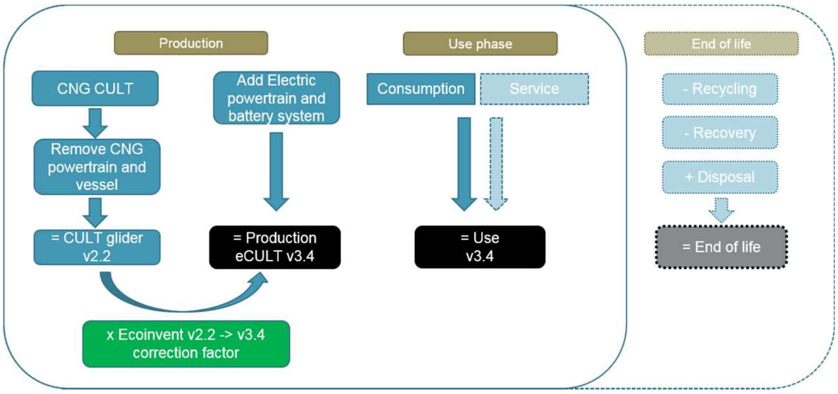

Figure 12: LCA framework and procedure

The former CNG CULT LCA assumed off-gas emissions of ~ 60g CO_2 per kilometer based on simulation and measurement results acc. NEDC. This scenario remains unchanged in this new setting. Additionally, this setting includes now upstream, midstream and downstream emissions for both the CNG CULT and the eCULT. This enables a comparability between the two technologies, as the eCULT inherently does not produce any emissions from combustion, but the use of electricity is accompanied with upstream emissions. The boundary conditions for the assessment of the use phase are as shown in Table 3:

Table 3: LCA system comparison of compared CNG CULT vs. eCULT

	CNG CULT	eCULT
Functional Unit	1,4 person passenger transport	1,4 person passenger transport
Mileage	150.000 km	150.000 km
Curb weight	680 kg	780 kg (due to battery weight)
Operational profile acc. NEDC	2,16 kg CNG/100 km (2,8 Kg CNG in real drive)	8,5 kWh/100 km (11 kWh/100 km in real drive)
Markets	AT/DE/IT	AT/DE/IT

6.2. Results

Depending on the source and location of the primary energy used for further utilization as fuel (CNG) or electricity, different indirect emissions have to be considered. Additionally, different energy efficiencies of the two different vehicle concepts lead to different complete vehicle results. Ongoing discussions in the search for an ideal vehicle concept for a sustainable mobility of the future have to consider the combination of vehicle's efficiency and energy sourcing efficiency.

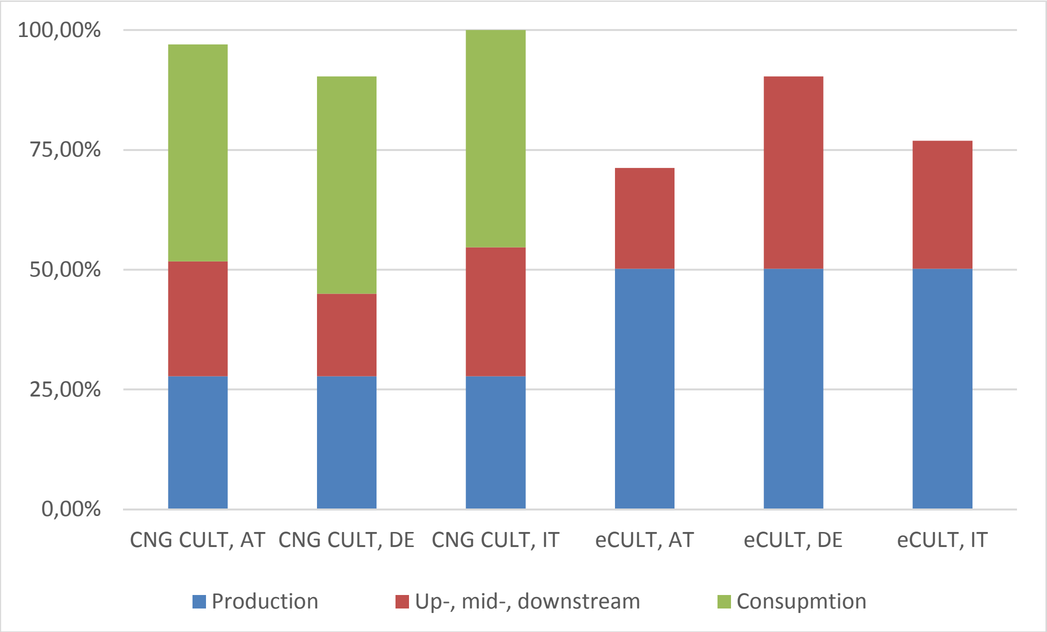

Figure 12: LCA Results for GHG emissions of CNG CULT vs. eCULT

The results of this study shown in Fig. 13. display that greenhouse gas emissions for both CNG CULT and eCULT are quite the same in Germany regarding environmental impact, category climate change. This result can be explained because of lower up-, mid- & downstream GHG emissions for Northern European natural gas sources provided to Germany. In addition to that, GHG emissions from electricity market mix for consumers in Germany are relatively high due to Germany's amount of coal power plants.

In Italy and Austria different energy resources are used and consumed compared to the German market. Up-, mid- & downstream GHG emissions from electricity and natural gas consumption caused by driving vehicles in these markets show a different picture: the electrically driven eCULT powered with market specific electricity consumer mixes available in Italy and Austria is favorable to the natural gas fueled vehicle CNG CULT.

This is explained by longer transport distances and higher losses during natural gas transportation and distribution on Austrian market on the one hand. On the other hand there are higher environmental impacts of liquefied natural gas production, e.g. imported in European's south. Rising amounts of natural gas based on shale gas extraction, so called fracking gas, are imported to Europe and amongst others fed into the Italian natural gas distribution network.

Overall results of the conducted LCA show that electric vehicles have a big potential to decrease GHG emissions. The trend to increase the share of renewable energies is expected, not only in the investigated and shown three European markets Austria, Italy and Germany. The environmental footprint of CNG vehicles could also show decreasing GHG emissions, if technically feasible synthetic gas production would be promoted. But in fact, trends show an increase of shale gas imports to Europe.

Considering this trend towards renewable electricity production, today's comparison between fossil powered CNG CULT and electric powered eCULT could show a larger difference in LCA results focusing GHG emissions in the future.

7 Conclusions

- The project proved that – although limited by human and financial resources – it was possible to realize an attractive electric vehicle with off-the-shelf components, when students, lecturers and industry (financial sponsoring) work together.
- The original CULT with the CNG engine has achieved approximately 60 g CO_2/km in the European test cycle. The results achieved with this configuration comprising a vehicle weight 680 kg have

proved that it is possible to achieve lower CO_2 emissions compared to an electrically driven vehicle considering the European electricity generation mix (~80 g CO_2/km).

- The electric powertrain of the eCULT consists of two 48 V drive units, one for each front wheel, providing 15 kW/70 Nm each. The 18 kWh battery has been located in the area over the rear axle and under the rear seats. The tunnel in which the CNG tank had originally been located is used for the BMS, the onboard charger, the DC/DC converter and the on board 12 V battery.
- Both vehicle concepts have proven to be sufficient for city driving without major disclaimers regarding acceleration and drivability. The drivability of the original CNG CULT was a bit disturbed by long shifting processes in the hydraulic AMT of the first generation AMTs. Naturally the drivability of the eCULT without shifting caused torque interrupts convinces from the very beginning. The range of the eCULT – of course – is roughly half than the range of its CNG precursor. That means a doubled frequency of recharging for a potential customer compared to refueling the CNG variant.
- Surprisingly small differences were calculated for the environmental impact of the two variants under the chosen boundaries excluding the recycling of the carbon fiber CNG tank and the recycling of the battery, especially in Germany. As expected, and also shown in other studies, the production of the powertrain components for the electric variant causes higher CO_2-eq emissions primarily due to the production of the battery. Considering the electricity production in different areas less emissions are calculated for the eCULT in Austria and Italy, as in these countries the use of coal for electricity production is not so high compared to Germany. In addition to that, the CNG resources used in the German market show lower CO_2-eq emission compared to Italian and Austrian market. This is due to shorter distances of transport and the share of liquefied natural gas based on imported shale gas.
- Finally it can be concluded that both powertrains for the ultralight vehicle CULT are well suited for city driving and represent a step in the right direction towards sustainable mobility. Their carbon footprints are almost similar. Of course, if the demand for carbon free mobility is inevitable, the eCULT would be the better choice provided that the electricity production has changed to renewable sources.

Acknowledgments

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	DI Dr. Martin Gossar finished his diploma studies in Electrical Engineering at the University of Technology in Graz in 2008. Afterwards he was employed at the University of Technology finishing his doctoral thesis in 2012 focusing on the enhancement of the current available data rates in passive proximity coupling devices. He started as RF System Engineer at NXP Semiconductors Austria where he was focusing on RF receivers for the automotive market. After several prototypes and in this area he stated his work as Senior Lecturer at the University of Applied Sciences in Graz. Now he is responsible for the electrical education in the automotive department and working on the implementation of electric powertrains in existing concepts.
	Dipl.-Ing (FH) Thomas Lechner works as a lecturer at the Institute of Automotive Engineering at the FH Joanneum. He studied Computer Engineering and is mainly responsible for the practical part of electro-technical and mechatronic education during the bachelor program. In addition to his work as a lecturer, he is preoccupied as measurement technician at the testing laboratory for vehicles.
	DI Dietmar Hofer studied process engineering and industrial environmental protection at Montan-Universität Leoben. After a short but intensive time in project engineering in the field of biobased alternative energy he changed to MAGNA STEYR Fahrzeugtechnik AG & Co KG in Graz. During his last 15 years he has been in several positions, as team leader, R&D project manager complete vehicle, environmental manager and LCA expert in MAGNA's Engineering Center Austria. Currently he is mainly occupied as a senior engineer for complete vehicle, lecturer at University of Graz, Institute of System Sciences, Innovation and Sustainability Research and guest lecturer for automotive eco-design at University of Applied Science/FH-Joanneum in Graz and at Montanuniversität Leoben / University of Leoben.
	With a background in Mechanical Engineering, Henning Sommer finished his master studies in Environmental System Sciences at the Graz University of Technology in 2017. Simultaneously to his studies, he gathered a broad range of international experience in the automotive product development at the Magna Steyr Engineering Center in Graz. His master thesis "Primary data-based life cycle assessment of automotive hybrid materials" in co-operation with Magna's Advanced Development and the Institute of System Sciences, Innovation and Sustainability deepened his focus on environmental performance assessments. He is currently occupied with product development in the complete vehicle area at Magna Steyr Fahrzeugtechnik AG & Co KG, focussing on environmental compliance, life cycle analysis and sustainability assessments.