Lecture Notes in Mobility

Jörg Wellnitz
Aleksandar Subic
Ramona Trufin *Editors*

Sustainable Automotive Technologies 2013

Proceedings of the 5th International Conference ICSAT 2013

Springer

Lecture Notes in Mobility

Series Editor

Gereon Meyer

For further volumes:
http://www.springer.com/series/11573

Jörg Wellnitz · Aleksandar Subic
Ramona Trufin
Editors

Sustainable Automotive Technologies 2013

Proceedings of the 5th International Conference ICSAT 2013

Springer

Editors
Jörg Wellnitz
Ramona Trufin
Faculty of Mechanical Engineering
Technische Hochschule Ingolstadt
Ingolstadt University of Applied Sciences
Ingolstadt
Germany

Aleksandar Subic
RMIT University School of Aerospace Mechanical and Manufacturing Engineering, (KOMMA)
RMIT University
Melbourne, VIC
Australia

ISSN 2196-5544 ISSN 2196-5552 (electronic)
ISBN 978-3-319-01883-6 ISBN 978-3-319-01884-3 (eBook)
DOI 10.1007/978-3-319-01884-3
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013946894

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Mobility is an essential part of our lives. The ability to move freely is central to meeting our social and economic needs. For this reason, we have embraced the car over the past century, perhaps more than any other technology or consumer product. Today there are around 900 million vehicles on the world's roads with another 60,000,000 new vehicles produced each year worldwide. The scale of the automotive industry is significant and far-reaching. For example, it is estimated that around two-thirds of the world's oil output goes to transportation, whereas road vehicles alone consume around 40 % of the world's rubber and 25 % of the world's glass, with the consumption of raw materials and other resources growing further due to the rapid development of the automotive sector in China, India, Thailand, and Mexico. Transportation accounts for around 25 % of greenhouse emissions worldwide, whereas 90 % of transport-related emissions come from road vehicles, predominantly cars. Clearly, current levels of consumption and emission are unsustainable. This in turn suggests that mobility as we know it, based on the traditional vehicle technology and existing production and consumer practices, is unsustainable.

The challenge of developing new sustainable approaches to mobility confronts industries and our societies in general. The concept of sustainable mobility is multidimensional and the challenge of achieving it is quite complex. Based on current knowledge it is becoming painfully clear that there is no "silver bullet" or single technology available at present to address this challenge. To succeed we will most likely have to pursue a range of different technologies and approaches with short-term and long-term gains. This book aims to draw special attention to the research and practice focused on new technologies and approaches to meet renewable energies and urbanization.

The Ingolstadt ICSAT Conference widely addresses issues of mobility in general, redefines the future with respect to the vehicle, and its link to the city with respect to all challenges of urbanization. Within this, new fuel concepts play a major role despite all the activities in electro-mobility, the Ingolstadt conference focuses on all aspects of renewable energy sources.

We gratefully acknowledge the authors and the referees who have made this publication possible with their research work and written contributions. We would also like to thank the IFG Ingolstadt, Audi AG Ingolstadt, RMIT University, and Technische Hochschule Ingolstadt for their generous contribution. We hope that a

book on the multidisciplinary subject of sustainable mobility, as diverse in topics and approaches as this one, will be of interest to automotive technology researchers, policymakers, practitioners, and enthusiasts, whatever their background or persuasion.

Our special thanks also go to Birgit Paolini and Eva Wilhelm doing a great job for ICSAT 2013.

Jörg Wellnitz
Aleksandar Subic
Ramona Trufin

Contents

Part I
Fuel Transportation and Storage

Energy Flux Simulation on a Vehicle Test Bed for Validating the Efficiency of Different Driving and Assistance Systems

S. Geneder, F. Pfister, C. Wilhelm, A. Arnold, P. Scherrmann and H.-P. Dohmen

Abstract Legislation claims a sustainable handling of existing resources. For this reason all newly registered vehicles must emit less then maximum 130 g/km CO_2 on average by 2015. Car manufactures are therefore forced to use new approaches in the fields of propulsion technology and assistance systems. For the development of such efficient vehicles new methods are needed which exceed the determination of the consumption at the chassis dyno or the road test. It is necessary that the results concerning the real consumption as well as the distribution of the energy losses are available at an early stage of the development cycle. Furthermore, the safeguarding of the functionality of new highly networked powertrain systems is an important aspect. Here, the energy flux analysis at the vehicle test bed comes into place. As integrated validation environment it will be referred to as Function and Energy Flux Simulator (FES). With FES, real driving situations are emulated by means of a vehicle dynamics simulation. With dynamometers the occurring wheel torques are impressed on the vehicle. At the FES, driving scenarios and the

S. Geneder (✉) · A. Arnold
Institute for Applied Research (IAF), Ingolstadt University of Applied Sciences, Esplanade 10 85049 Ingolstadt, Germany
e-mail: stefan.geneder@thi.de

A. Arnold
e-mail: armin.arnold@thi.de

F. Pfister
AVL List GmbH, Hans-List-Platz 1 8020 Graz, Austria
e-mail: felix.pfister@avl.com

C. Wilhelm · P. Scherrmann
AUDI AG, I/EG-34 85045 Ingolstadt, Germany
e-mail: christian.wilhelm@audi.de

P. Scherrmann
e-mail: patrick.scherrmann@audi.de

H.-P. Dohmen
AVL Deutschland GmbH, Berliner Ring 95 64625 Bensheim, Germany
e-mail: hans-peter.dohmen@avl.com

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_1,

environmental conditions are exactly reproducible so that the results are significant. In addition, a continuous superordinate process for validating the energy efficiency which reaches from the office simulation to the trial at the test bed as well as to the road drive with portable measurement systems was set up.

1 Motivation

Legislation claims a sustainable handling of existing resources. In order to reduce CO_2 emissions the EU has put in place a legislation that sets an average new car emission limit of 130 g/km by 2015 and 95 g/km by 2020. Car manufactures are therefore forced to use new approaches in the fields of propulsion technology and assistance systems. With the use of information from the navigation system it is possible to realize predictive advanced driver assisted systems (ADAS), like e.g. Green ACCs or autonomous driving on the motorway. Due to the megatrends energy efficiency and vehicle safety such forward-looking assistance systems will find their way into series production.

In the following parts of this paper, selected examples will be illuminated briefly. In the current Audi A6 various navigation-based ADAS are realized in a conventional vehicle with an internal combustion engine, for e.g. a speed limit display (Lipinski 2011), navigation supported ACC (Vukotich et al. 2011) and an intelligent shift strategy (Woloschin et al. 2011). In the case of the latter the transmission control unit (TCU) of an automatic transmission gets its information regarding the expected velocity from the vehicle navigation system, so that inefficient shifting before turns or sections with constant velocities can be avoided.

Especially due to the demand for enhanced energy efficiency, ADAS which influence the powertrain, are developed. Porsche works e.g. on an intelligent cruise control (Green ACC), which adapts the speed anticipatory to avoid unnecessary heavy deceleration and acceleration. The system uses information from the radar sensor, the camera as well as from digital maps for the autonomous longitudinal control of a car (Radke and Roth 2011). The system shall allow to reduce fuel consumption up to 10 % (Porsche 2012).

BMW presented a system to optimize the control strategy for hybrid electric vehicles which also uses information from the navigation system. Here, a static, speed-based charge strategy for the vehicle battery was combined with a predictive energy management, which focuses on two driving conditions. On the one hand a foresighted conditioning takes place. This means that the battery charge is lowered before sections with sloping to facilitate maximal recuperation. On the other hand a rise in the battery charge can be observed for sections with low velocity and a high quotient of start-stop to allow a large section of pure electric driving. Therefore, potential savings up to 4 % at downhill journeys and up to 8 % at tailbacks (Wilde et al. 2009) are possible.

For the application of such highly complex assistance systems a large amount of information concerning the state of the vehicle and the environment must be available. Among others, this makes a vehicle navigation system necessary which comprises digital maps with additional information like the 3D road topography, the category of the road and all traffic signs including speed limits. With this data plus historical and real time traffic data the navigation system can predict the most probable path for the vehicle and pass this information to the other control units.

Furthermore, such predictive systems need information on the vehicle's environment through diverse sensor systems, e.g. temporary speed limits through camera or information concerning the ahead driving vehicles via radar.

Beyond that, the knowledge of the state of the own vehicle (actual velocity, state of charge of the battery, fuel consumption) via intern sensors is necessary. The mentioned sensors are available in most modern vehicles already. By the fusion of sensor data such value-added functions can be realized only with additional software. This integration leads to two major challenges: The safeguarding of the functionality of the highly networked systems and the analysis of the influence on the entire system that means the fulfillment of the desired behavior. The single subsystems can be validated relatively easy with the help of a HiL or a mechatronic component test bed. The entire system can only be tested by the pure office simulation, with a networking HiL or in the real test drive. Due to some simplifications the office simulation has only a limited evidential value. With a networking HiL, mainly the interaction between the control units can be tested; however, not the performance of the whole system. The real test drive bears the problem that differences of two applications of the system, with impacts in the percentage range, cannot really be compared, as they are covered by different environmental states. So the question is how such systems can be validated as a whole. A precondition for a solid validation is a reproducible stimulation of the previously mentioned sensor systems to get a reliable statement regarding the complete behavior of the system.

2 Energy Flux Simulation

For the development of such new efficient vehicles new methods are needed. It is necessary that the results concerning the real consumption and the distribution of the energy losses can be made at an early stage of the development cycle. Here, the energy flux analysis at the vehicle test bed comes into place. Furthermore, the safeguarding of the functionality of new highly networked powertrain systems is an important aspect. For this reason, methods are developed by the car manufacturer AUDI, the simulation and test bed producer AVL and Ingolstadt University within the BluOcean project which allows such inspections at the integrated vehicle test bed, which is called Function and Energy Flux Simulator (FES).

With FES real driving situations are emulated by means of a vehicle dynamics simulation. With dynamometers the occurring wheel speeds are impressed on the vehicle. Necessary sensor information is also inducted into the vehicle by simulation. The vehicle drives like in the real world. At the FES, driving scenarios and the environmental conditions are exactly reproducible so that the results regarding the energy efficiency are significant.

Through an integrated approach (see Fig. 1) the advantages of the particular test environments can be associated. The pure office simulation offers results with a great flexibility at a very early stage. The real test drive delivers significant results as well as real behavior, which cannot be depicted in pure simulation even with a very high modeling effort. Here, also the perceptible vehicle performance, that means the drivability, can be validated and so the fine tuning of the system parameters can be made. However, due to environmental influences reproducibility is missing in this case. Besides, due to problems concerning the availability of the hardware, tests are only feasible at a very late stage of the development process.

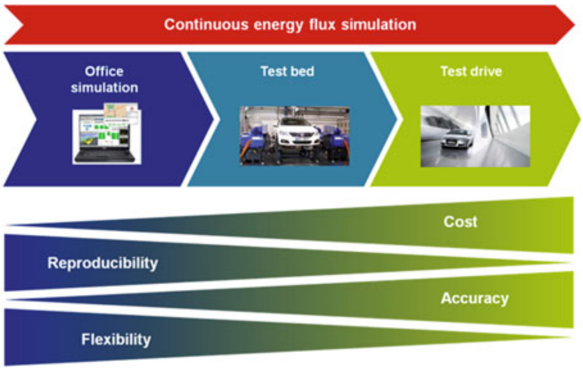


Fig. 1 Approach for the continuous energy flux simulation from office over test bed simulation to the real drive according to (Voigt et al. 2012): Properties of the single test environments

The vehicle test bed can be a bridge between pure simulation and the real test drive, as it owns the properties of both environments to a certain degree. By the assignment of the test bed simulation various functions can be validated before the test drive with a very high reproducibility, which leads to a high evidential value. With this front-loading it is possible to save development time.

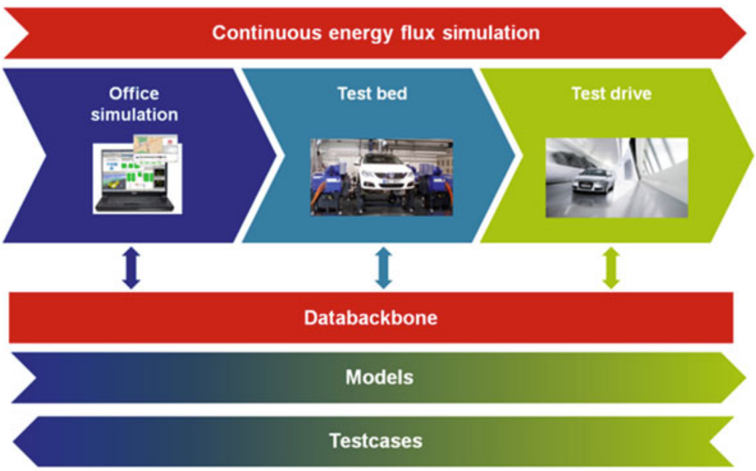


Fig. 2 Approach for the continuous energy flux simulation according to (Voigt et al. 2012): Data flow

Based on the mentioned advantages of each environment it is not advisable to resign one of them. Moreover, they all have their place in the development process. Thus, the goal is to link the single validation steps with each other. To ensure consistency a superordinate process (see Fig. 2) for validating the energy efficiency which reaches from the office simulation to the trial at the test bed as well as to the road drive with portable measurement systems was set up. Thus, the models from the office simulation find their way to the test bed or in the case of observer models for validating intern quantities also to the real test drive. By contrast, the test cases are defined by the test drive and therefore must be mapped in all other environments as well. It can be seen that for an efficient validation a continuous data backbone for the handling of the test cases, the models and the results is necessary.

2.1 Virtual Test Drive

As mentioned before, the real test drive is the final validation basis. Therefore, it is of central importance as a virtual test drive for office and test bed simulations (see Fig. 3). This so-called Real-Life-Testing is e.g. realized in the simulation tool AVL InMotion/IPG CarMaker (cf. Schick et al. 2012). A virtual driver moves with a virtual vehicle through a virtual world, in which the road including all marks and traffic signs as well as the environment with traffic and objects are mapped. The vehicle mockup contains also virtual sensors (radar, ultrasonic sensor, camera, etc.) for the detection of environment objects.

Fig. 3 Virtual test drive in AVL InMotion/IPG CarMaker (*source* IPG Automotive)

Over various interfaces it is furthermore possible to import real roads including (Fig. 3)additional information, like e.g. the number of lanes or traffic signs. Therefore, during the virtual test run the (GPS-) Position of the own vehicle as well as other vehicles are available.

The integration of complex powertrain systems, predictive energy management and ADAS in the entire vehicle simulation is e.g. with AVL Cruise and Matlab/ Simulink possible. So a complete virtual emulation of the real test drive can be made. The virtual driver IPGDriver operates the virtual vehicle and drives the prescribed road completely autonomously in real time. Here the behavior and the driving strategy can be adapted.

Fig. 4 The X-in-the-loop-process in AVL InMotion/IPG CarMaker: model- (*MiL*), software- (*SiL*), hardware- (*HiL*), engine- (*EiL*), battery- (*BiL*), powertrain- (*PiL*), vehicle- (*ViL*) und driver-in-the-loop (*DiL*)

AVL InMotion, which is based on the vehicle dynamics software IPG CarMaker, allows a maneuver-based testing of various items (Units Under Test) on the test bed (see Fig. 4) through an extension called X-in-the-Loop-Interface (cf. Düser 2010). Thereby, a real driving situation can be tested on the test bed. Test scenarios could be performed in a reliable simulation environment at an early state in the development process, so that errors can be quickly detected and an expensive removal, e.g. errors which are detected in the final test drive shortly before SOP, can be avoided. In addition, such a largely parameterized vehicle can be made available to the application engineers so that they can concentrate on the fine tuning in the test drive.

2.2 *The Vehicle Test Bed (ViL) as Function and Energy Flux Simulator*

The possibilities of the maneuver-based trial at the test bed should be explained at the vehicle test bed (see Fig. 5). With its help, the validation of the function and the analysis of the energy flow of highly complex vehicle systems like new powertrain systems (hybrid and battery electric vehicles) and ADAS are possible.

The referred test rig is a conventional powertrain test bed, which also can be used to validate the entire vehicle (ViL, Vehicle-in-the-Loop). The test bed is connected with the AVL InMotion real time node. Real drives can be emulated with the vehicle simulation running on the real time computer. With dynamometers the occurring wheel speeds are impressed on the vehicle. The torque demand on the vehicle takes place according to the configuration over the EGAS and TCU interface or via a pedal actuator. The resulting wheel torque is induced in real time in the simulation.

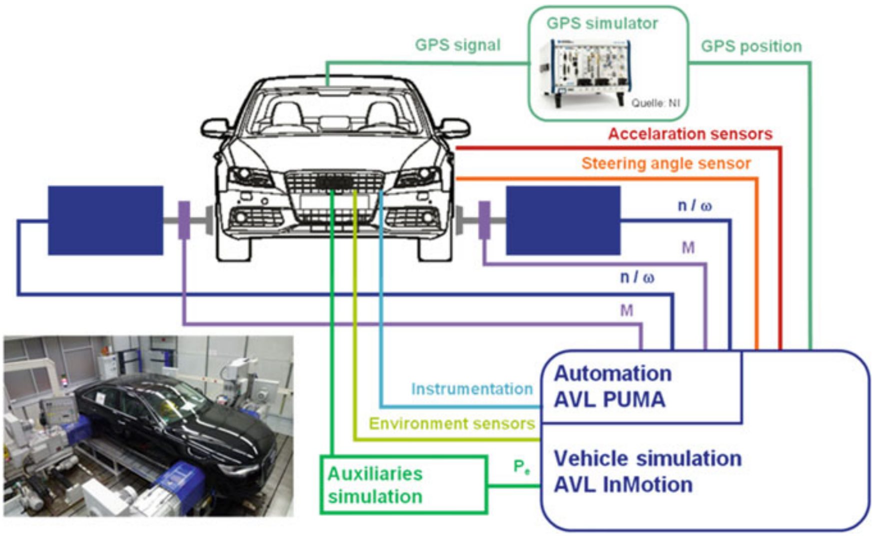


Fig. 5 Structure of the function and energy flux simulator

Necessary sensor information (e.g. from steering angle-, acceleration- und environment sensors) is also inducted into the vehicle by simulation. The vehicle drives like in the real world. With the vehicle simulation it is possible to drive real tracks at the FES that have been recorded with a GPS receiver or imported from a road map data base. By adding a GPS simulator, new forward-looking systems like Green ACCs or hybrid strategies can be validated. Furthermore, the effects of auxiliaries, which could not be validated directly at the test bed (e.g. electric power steering), on the overall energy consumption can be emulated over electronic loads, so-called EVamps. For the recording of signals or measurement values conventional test bed instrumentation or portable measurement technology can be used and integrated in the automation system. The FES has the great advantage, that driving scenarios and the environmental conditions are exactly reproducible so that the results are significant. Furthermore, complete test campaigns to secure the functionality can run independently.

2.3 Generation of the Virtual Road

The virtual road as copy of the real road can be generated from diverse sources (cf. Pfister and Schick 2011). A difference can be made between the import from a map and the import from a GPS trace. Over a module to Navteq ADAS RP it is possible to export very long roads with a high accuracy, which contains information regarding the road infrastructure. The export of a track from Google Earth is a simple and free alternative. Via various online services it is possible to add additional height information to the kml-Files imported from Google Earth. Out of this, a road importer generates tracks in a segment-based format which can be directly used from AVL InMotion/IPG CarMaker. Furthermore, characteristics of the road, e.g. width, friction coefficient or speed limit can be adjusted via the road importer as well. The import of tracking data is also done with the road importer; here, the accuracy depends on the used GPS system.

2.4 Navigation-in-the-Loop

As mentioned before, the GPS position of the own vehicle during the virtual test drive is available in the vehicle simulation. With a connection to Google Earth the virtual test drive can be tracked by the engineer during simulation. The GPS position in the MiL-/SiL-mode is available for the modules to be tested. In the case of the validation of real vehicle systems this can either be done with an ECU-specific interface or with the standardized ADASIS protocol. With the combination of the vehicle simulation AVL InMotion and the GPS simulation system developed by National Instruments a direct test of ADAS on every XiL test bed is possible; there is no open interface required (Fig. 6). The navigation unit receives the emulated GPS signals directly via an RF-interface. The advantage is here that there is no reason to manipulate the system, e.g. the use of special ECUs, and so no additional sources of errors are produced. Thus, an entire trail at the test bed can be made for the first time. A detailed description of the systems can be seen in (Geneder et al. 2012).

Fig. 6 Structure of the demonstrator consisting of the AVL InMotion real time PC, the NI GPS simulator and a mobile navigation system

The GPS position from the driving simulation AVL InMotion is sent via an appointed protocol in a cycle of 40 ms over the CAN bus to the NI GPS simulator.

With the position and the time the GPS-Simulation-Toolkit determines based on Alamanac and Ephermis Files, which contains the necessary satellite information, e.g. satellite location, trajectory and state, the visible satellites (cf. NI 2009). The information can be downloaded at the Navigation Center of Excellence (Alamanac Files) as well as at the NASA Goddard Space Flight Center (Ephermis Dateien). For the visible satellites the GPS L1 Coarse Acquisition Signals (C/A-Signals) are calculated. Various criteria ensure the exact positioning. The different satellite signals are summarized and then generated with a NI RF vector signal generator and transferred over an RF-interface directly to the GPS receiver. The navigation system then can determine the position and pass this information along with additional map-based information (e.g. speed limit) via the vehicle bus to the ADAS-ECUs. Therefore, it is possible to validate ADAS at the entire vehicle HiL without adapting the ECUs.

2.5 Integration of the Measurement Instrumentation

In the real test drive ETAS INCA including suitable hardware for the acquisition of the signals and measurement values is used. For a simple integration of the vehicle the instrumented measurement devices of the test drive should be used for the test bench setup as well. Therefore INCA-MCE is used, which has a direct high performance interface to the test bed automation system AVL PUMA (see Fig. 7). The software is originated in the field of calibration. There it allows an automatic application at the engine's test rig. In this use case the ES910 module should act as a gateway between the conventional ETAS measurement modules. Therefore, the vehicle has to be equipped with measurement technology only once.

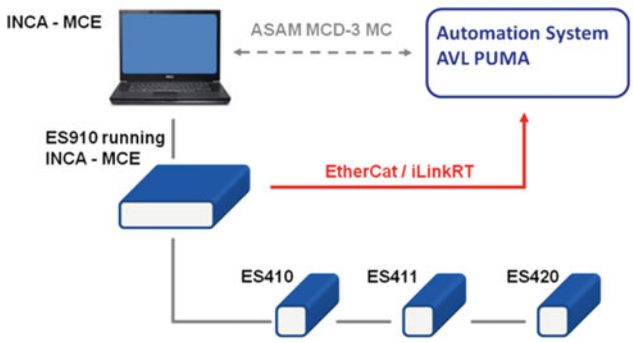


Fig. 7 Integration of the vehicle instrumentation in the automation system of the test bed

Moreover, this leads to portability between the FES and the test drive. After securing the function at the FES the fine tuning of the drivability in the test drive could take place at the pre-applied car. If any errors occur during the test drive, the car could put on the FES, where the situation can be recreated to make exact examinations. With this consistency the advantages of the FES and the real test drive in combination benefits of both can be used.

2.6 EVamp

For the purpose of emulating the influences of various consumers on the overall energy budget, which cannot be validated at the test bed easily, a electronic load, so-called EVamp, is used.

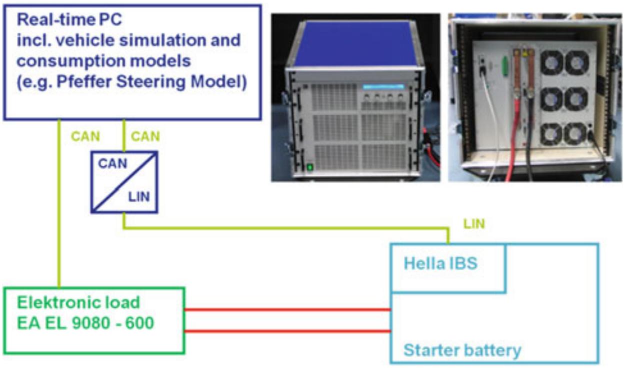


Fig. 8 Laboratory setup to integrate the electronic load into the real time system (cf. ETAS 2011)

Figure 8 shows the laboratory setup consisting of the real time system with AVL InMotion, on which a consumption model e.g. the Pfeffer Steering Model (IPG Automotive 2012) is running and which is accessing an electronic load via CAN bus. This load then consumes power from the 12 V energy network. In this setup, a 12 V-battery with an intelligent battery sensor was used as an artificial network. This sensor delivers information via a LIN interface regarding the power system or rather the battery state. It should be mentioned that consumers which are connected to the high voltage energy network (e.g. the electric air conditioning system) could be emulated with a battery simulator that is often available at a vehicle test bed.

3 Conclusion/Summary

In the present article, the structure of the function and energy flux simulator as integrated test environment has been presented and its placement in the vehicle development process has been shown. Furthermore, the subsystems of the FES have been explained. At the moment, the series integration of the GPS simulator and the EVamp at the vehicle test bed is done as preparation for an integrated test. Furthermore, the measurement configuration of a reference car for the test drive is carried out, so that first results should be available shortly.

References

Düser T (2010) X-in-the-Loop – ein durchgängiges Validierungsframework für die Fahrzeugentwicklung am Beispiel von Antriebsstrangfunktionen und Fahrerassistenzsystemen. Dissertation, Karlsruher Institut für Technologie

ETAS: INCA - MCE V1 - Measurement and Calibration Embedded. Stuttgart (2011)

Geneder S, Arnold A, Pfister F, Saller A, Tobler K (2012) Hardware-in-the-loop-test von GPS-basierten Assistenzfunktionen in der virtuellen Fahrzeugerprobung durch Echtzeitsimulation der Satellitensignale. In: Wissensforum VDI (ed) VDI–Berichte,VDI - Verlag, Düsseldorf, vol (2169) pp 799−810

IPG Automotive: CarMaker - Reference Manual Version 4.0 (2012)

Lipinski D, (2011) Tempolimitanzeige, Automobiltechnische Zeitschrift ATZ, vol 113 Der neue Audi A6, pp 188–189

NI: GPS Multiple—Satellites Signal Generation (2009)

Pfister F, Schick B (2011) Die Zukunft hat einen Sensor: Location Awareness meets Powertrain Controls. In: AVL Deutschland (ed) 4. Internationales Symposium für Entwicklungsmethodik, Wiesbaden, pp. 255–262

Porsche (2012) ACC InnoDrive. http://www.porsche.com/germany/aboutporsche/responsibility/environment/technology/accinnodrive/. Accessed 14 Sept 2012

Roth RT (2011) Energetische Modellierung von Schaltvorgängen mit Hilfe statistischer Versuchsplanung als Voraussetzung optimaler Betriebsstrategien. In: AVL Deutschland (ed) 4. Internationales Symposium für Entwicklungsmethodik, , Wiesbaden pp. 143–151

Schick B, Leonhard V, Lange S (2012) Vorausschauendes Energiemanagement im virtuellen Fahrversuch. Automobiltechnische Zeitschrift ATZ, 114(4):328–333

Voigt KU, Denger D, Conrad M (2012) Durchgängig, integriert und einfach−hybride Entwicklungsumgebung in der Antriebsstrangentwicklung. In: Wissensforum VDI (ed) VDI−Berichte,VDI−Verlag, Düsseldorf, vol 2169 pp 733–746

Vukotich A, Duba GP, Gollewski (2011) TFahrerassistenzsysteme - Vernetzung und Datenfusion, Automobiltechnische Zeitschrift ATZ, vol 113. Der neue Audi A6, pp 178–180

Wilde A, Herzog T, Herzog HG, Löwenau J, Durekovic S (2009) Adaptives Energiemanagement in Hybridfahrzeugen Situationsgerechte Ladestrategien unter Berücksichtigung von Verkehrs-, Geschwindigkeits- und Höheninformationen. In: Sirch O (ed) Elektrik, Elektronik in Hybrid- und Elektrofahrzeugen, expert verlag, Renningen - Malsheim, pp 26–37

Woloschin H, Weidemann D, Zäpfel S, Volkmar K (2011) Kraftübertragung, Automobiltechnische Zeitschrift. - ATZ, vol 113, Der neue Audi A6, pp 62–65

Assessment of the Viability of Vegetable Oil Based Fuels

I. F. Thomas, N. A. Porter and P. Lappas

Abstract This paper provides results of extensive trials using a 50/50 blend of unheated vegetable oil and diesel fuel in an unmodified vehicle on roads in Victoria, Australia. The work was inspired by the success of an on-road trial using 100 % waste vegetable oil in 2004 and positive indications in the literature. As well as being a sustainable alternative fuel, vegetable oil has the added safety advantage of having a much higher flash point than any other. Constant routes were used analogous in-part, to using prescribed drive cycles. Results were logged and bar-charts comparing fuel consumption for various fuel blends are presented. There was no clearly discernible difference (within the uncertainty of the measured data) in fuel consumption between the 50/50 blend and diesel fuel.

1 A Brief Literature Appraisal

A review of literature covering the period from 1982–2012 revealed 119 papers describing the use of vegetable oil as a transport fuel. A wide range of oil types have been researched with most concentrating on non-food sourced oils such as Jatropha (Bhupendra et al. 2010) Camelina (Bernardo et al. 2003), Hazelnut (Murat 2007),

I. F. Thomas (✉)
Principal, I. F. Thomas & Associates,
123 Nelson place, Williamstown 3016, Australia
e-mail: ifta@ifta.com.au

N. A. Porter
Discipline Head, Environmental Science, School of Applied Sciences, RMIT University,
Swanston Street, Melbourne 3000, Australia
e-mail: nichola.porter@rmit.edu.au

P. Lappas
Lecturer, Renewable Energy, School of Aerospace, Mechanical and Manufacturing
Engineering, RMIT University, Plenty Road Bundoora East, Melbourne 3083, Australia
e-mail: petros.lappas@rmit.edu.au

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_2,

Karanja (Deshmukh 2009), Cottonseed (Fontaras et al. 2007), Mustard seed (Niemi 2003), Rice Bran (Agarwal 2010), Neem (Shiva 2005) and Silk Cotton Tree oils (Orwa et al. 2009). Some workers have studied multiple oil types (Abolle et al. 2009). Waste vegetable oil has also been studied in laboratory test engines (Dorado 2002; Pugazhvadivu 2005). Most report that the reasons for not using Straight Vegetable Oil are related to its high viscosity and injector and engine fouling. These can be offset by preheating and use of saturated oils (Babu and Devaradjane 2003). Several in particular Tippayawong (2003), indicate that SVO may be used only in the short term and that longer term usage needs further investigation. Tippayawong also states *'Vegetable oils and their products appear to be obvious choices as future fuels and are of exceptional importance'*. Nabi (2003) cites Elbert and Kaiser, '*Considering overall energy, health, environmental, and economic aspects, vegetable oils could be the fuel of the future'*. Many claim that vegetable oils are viable in substantially unaltered engines provided that the oil concentration is not greater than 30 % unless the fuel is preheated (Haldar 2009). Others are staunch advocates of the improved lubrication impacts (lubricity) of vegetable oil in improving the life of injector pumps, pistons, piston rings, cylinder bores and combustion chambers (Roegiers and Zhmud 2009). Some claim an increase in PAHs (Polycyclic Aromatic Hydrocarbons)(Lance and Andersson 2004; Krahl 2009) and others claim a reduction (Abbass 1990). The absence of sulphur in vegetable oil is known to reduce sulphur oxide emissions but claims regarding other emissions relative to diesel fuel vary. Table 1 shows some examples and includes noise impacts.

2 The On-road Trial

Two instances have been found where on-road trials have been conducted by others (Fontaras et al. 2007; Lance and Andersson 2004). The first involved a Euro 2 Volkswagen Golf 1.9L Tdi over a distance of 20,000 km and a Euro 3 Renault Laguna 1.9L dCi common-rail vehicle driven for 14,000 km. Both vehicles fueled with a 10 % cottonseed oil/diesel blend, met EU Emissions Directive 2003/30/EC. The second involved two secondhand Euro 2 compliant vehicles, a 1.9L DI vehicle with 52,000 km odometer reading at commencement and a 1.5L IDI vehicle with a reading of 21,000 km. Each was fitted with a fuel preheating kit and driven on 100 % Canola (Rapeseed) oil which complied with the German Rapeseed Fuel Standard, for multiple 200 mile runs. Both of these groups of workers conducted extensive engine performance and exhaust emission testing. They urged others to perform further tests in view of the potential importance of SVO and of blends with diesel as future fuels.

The present work used a second-hand (odometer reading 252.000 km), mechanically injected, pre-Euro 2, 1996 model Mitsubishi Triton utility vehicle, equipped with a 2.5L In-Direct Injection (IDI) turbocharged diesel engine. This model as sold in the UK was required to comply with the Euro 3 standard. Current diesel engines in Australia are Direct Injection (DI) common-rail, complying with

Table 1 Emission and Noise Impacts for Various Oil Types

Reference	CO	CO_2	HC	PM	NO_X	Smoke	Noise	Oil type etc.
Bhupendra et al. (2010)	Up	Up	Up	–	Down	–	–	Jatropha
Deshmukh (2009)	Up	–	–	–	Same	–	–	Karanja
Pugazhvadivu (2005)	Down	–	–	–	–	Down	–	WVO
Babu and Devaradjane (2003)	Down	–	Down	–	–	Down	Down	Rapeseed
Lance and Andersson (2004)	Up	–	Up	Up	Down	–	–	Canola
Abbass (1990)	Up	–	Up	Up	–	–	–	Sunflower
Mormino (2009)	–	–	–	–	Down	–	–	Rapeseed etc.
Vojtisek-Lom (2007)	Up	–	Up	Up	Down	–	–	Canola (in traffic)
Vojtisek-Lom (2007)	Down	–	Down	Down	Down	–	–	Canola (country)
Yoshimoto (2001)	–	–	–	–	–	Down	–	Rapeseed
Nettles-Anderson and Olsen (2009)	–	–	–	–	Down	–	–	Saturated VOs
Cheng and Lee (2008)	–	–	–	–	Down	–	Down	Cottonseed etc.
Kumar and Khare (2004)	–	–	–	–	–	Down	Down	Linseed etc.
Devan and Mahalakshmi (2009)	Up	Down	Up	–	Down	Up	–	Poon
Gangwar and Agarwal (2008)	Down	Same	Down	–	Up	Down	–	Jatropha

Euro 4. Euro 5 will apply to all Australian vehicles from November 2013 and Euro 6 in 2017. The test vehicle was powered using 100 % waste cooking oil for a 1000 km pre-trial period in 2004. The vehicle ran well until a 5 mm wire mesh filter inside the fuel injector pump became partially blocked with paint particles from the drums that the waste oil was stored in and would not travel above 80 km/hr. The fuel injector pump was repaired, injectors refurbished and the vehicle operated on conventional diesel fuel for a year. Trials were recommenced in November 2005 using a 10 % blend of vegetable oil with conventional diesel fuel. Following successful operation, the oil concentration was progressively increased to 50 %. The reported thirty trials consisted of seven diesel fuel control runs, four 50/50 blend runs and a total of nineteen runs comprising 50/50 blend with an additive. Additives used were isopropanol, ethanol, ethyl acetate and a range of industrial perfumes. Trials were conducted over 21 months from April 2008 to January 2010, covering a total distance of 42,269 km. They were not without fault. The fuel filter blocked regularly leading to loss of power and excessive exhaust smoke. The cause was fuel containing a dispersion of finely divided solid fats and high melting point oils. Problems reported by others such as fuel acidity, injector fouling and fuel polymerisation were not experienced. On completion, the engine was found to have suffered extremely low cylinder head and cylinder bore wear and no acidity

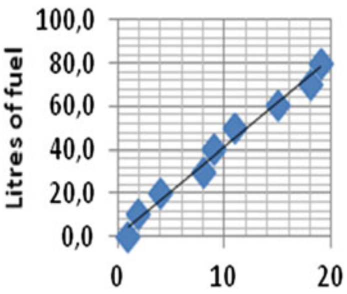
was evident in the lubricating oil (pH 7.0). Fuel consumption was measured for all trials, country runs and city runs. Average speed was also measured for country runs. Measuring other variables such as vehicle condition, wind, temperature, power, torque and traffic conditions required more resources than were available. This was offset by using two principal routes with relatively constant journey times:—*Williamstown-Kilsyth-Brooklyn-Williamstown, 116 km city runs, twice per week in off-peak traffic; Williamstown-Bahgallah-Williamstown, 750 km country runs, approx 8 times per year.* Other variables such as vehicle performance (apparent power) and smoke emission, were noted in the trial log. [1]More recent trials as the odometer reading approached 300,000 km, assessed vehicle performance by logging the gear required and speed achieved when climbing two 'test hills'.

2.1 Fuel

Standard diesel fuel in Australia complies with Fuel Standard (Automotive Diesel) Determination 2001. This permits up to 10 mg/kg sulphur and requires a minimum Cetane Index of 46, a viscosity range of 2.0–4.5 cSt at 40 °C, a minimum flash-point of 61.5 °C and maximum PAHs of 11 % mass/mass. Australia also has a biodiesel fuel standard but unlike Europe (Fontaras et al. 2007) does not yet have a vegetable oil fuel standard. 50/50 vegetable oil/diesel fuel was the basis for all formal trials performed. The purpose of using additives was to assess whether they would improve performance. Principal examples used were a range of industrial grade perfumes, formulated as additives for disinfectant, detergent and bleach formulations. Perfumes consisted of complex proprietary mixtures of both natural and synthesised fragrances. Examples are eucalyptus oil, terpineol, 2-phenoxy ethanol, 2-octanol- 2, 6 dimethyl acetate, benzyl benzoate, and 6-acetyl-1,1,2,4,4,7-hexamethyltetraline. The blending technique was to mix 10L each of diesel fuel and decanted waste vegetable oil in a calibrated container. For trials involving an additive, 2L was added to the 20L blend. Additive blends were therefore 45.5 % WVO, 45.5 % diesel fuel and 9 % additive. The mixed fuel was filtered using Nital 9 monofilament filter cloth. The fuel gauge was calibrated by draining the tank and noting gauge readings following addition of a series of 10L increments. The calibration graph is presented at Fig. 1. Fuel consumption was measured either by filling the fuel tank with a measured amount and running until empty or more commonly, by adjusting for the fuel gauge reading at the start and finish of a run and adding any fuel additions made during the trial. Some trials with additives were grouped together for the purpose of analysing results.

[1] Full trial log available

Fig. 1 Gauge reading (1–19 = empty to full)



2.2 Results

The suppliers of WVO purchased cooking oils comprising Canola (six sources), Sunflower (two), a Canola/Sunflower blend (one) and Cottonseed (one source). Their calorific values are Canola 34–36 MJ/L, Sunflower 37 MJ/L and Cottonseed 42 MJ/L[2] (Wakil and Ahmed 2012; Tamilvendhan and Ilangovan 2011; Sustainable Energy Ireland 2004). Slightly lower values for vegetable oils compared with diesel fuel (37–42 MJ/L), might lead to higher fuel usage than diesel fuel for the same energy consumption. Here-following, trial duration and fuel consumption are presented for each type of fuel used.

2.2.1 All Trials

Figure 2 and its key above, show that of the 30 trials performed, the most tested fuel was the 50/50 blend. Figure 3 shows that the lowest fuel consumption was achieved using 50/50 blend with Citrus perfume (8.6L/100 km). Second lowest was the 50/50 blend with lemon perfume (9.4L/100 km) and one of the straight diesel fuel runs was fifth best (10.1L/100 km).

Diesel	*Conventional diesel fuel alone*
50/50	*50 % waste vegetable oil and 50 % conventional diesel*
IPA	*50/50 blend with isopropyl alcohol*
WKR	*50/50 blend with white king regular perfume*
Brn Euc	*50/50 blend with brown eucalyptus perfume*
Citrus	*50/50 blend with citrus perfume*
Lemon	*50/50 blend with lemon perfume*
Lem/Euc	*50/50 blend with lemon or eucalyptus perfume*
Euc	*50/50 blend with eucalyptus perfume*
D + Euc	*50/50 blend with eucalyptus perfume or straight diesel*
Et/EtAc	*50/50 blend with ethanol and ethyl acetate*

[2] Details of WVO types and suppliers available on request

Fig. 2 Trial distance (km) for all trials versus fuel type

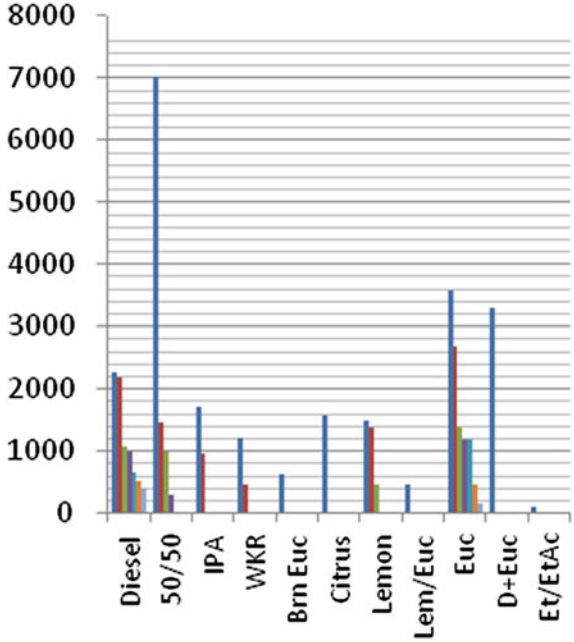
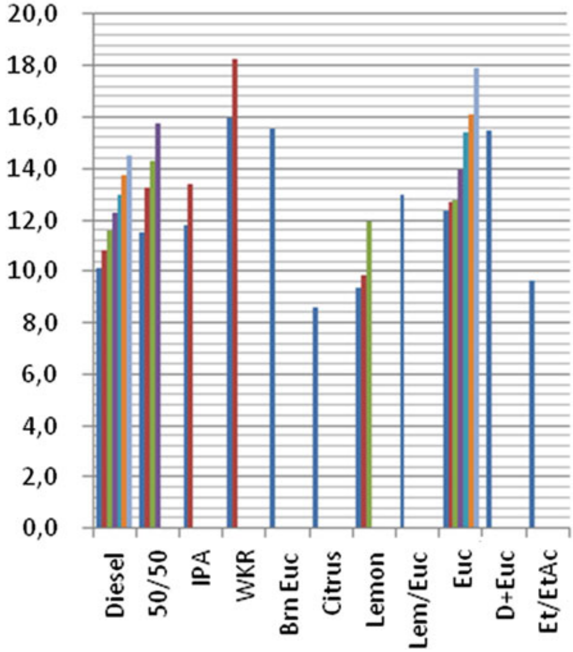


Fig. 3 L/100 km versus fuel type for all trials



2.2.2 Country Runs

The range of average speeds achieved for outbound and return runs is similar (outbound 66.6–92.0 km/hr; return 64.6–90.6 km/hr). Broadly speaking, outbound runs were against the prevailing westerly wind and the vehicle was more heavily laden whereas return runs were with the wind and the vehicle was more lightly loaded. The route had few built-up areas, constant very limited traffic, substantially no road works and very few traffic lights. Average fuel consumption for outbound runs was 17.3L/100 km and return, 15.3L/100 km indicating that to achieve similar journey times, more fuel was consumed outbound. There was no diesel control outbound and so comparisons have been made with the 86/14 diesel/WVO blend. Figures 4 and 5 show fuel consumption versus fuel type. The best outbound fuel was 50/50 blend with lemon perfume (12.2L/100 km). Second best was 50/50 blend with citrus perfume (14.1L/100 km) and third best was 50/50 blend with IPA (16.0L/100 km). Worst performing was one of the blends with eucalyptus perfume (20.4L/100 km), followed closely by the 86/14 diesel surrogate, one of the 50/50 blends and a WKR blend (18.7L/100 km). Return runs showed 50/50 with lemon perfume to fare best (12.0L/100 km). Second was citrus blend (12.3L/100 km). Third and fourth were a 50/50 blend and a lemon blend (13.3 and 13.4L/100 km). Diesel was fifth at 13.9L/100 km.

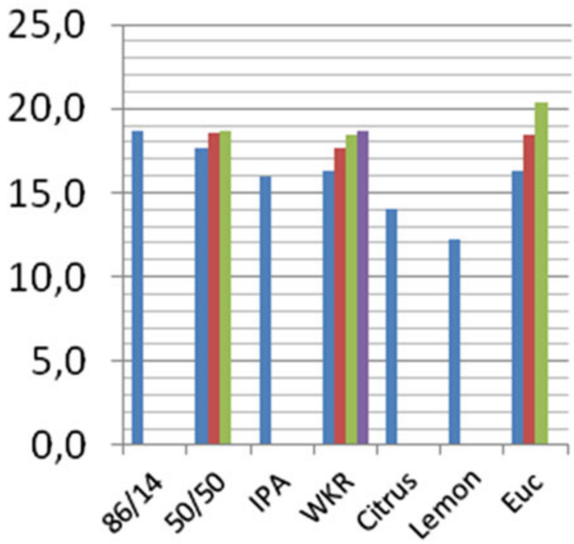


Fig. 4 L/100 km versus fuel type for outbound country runs

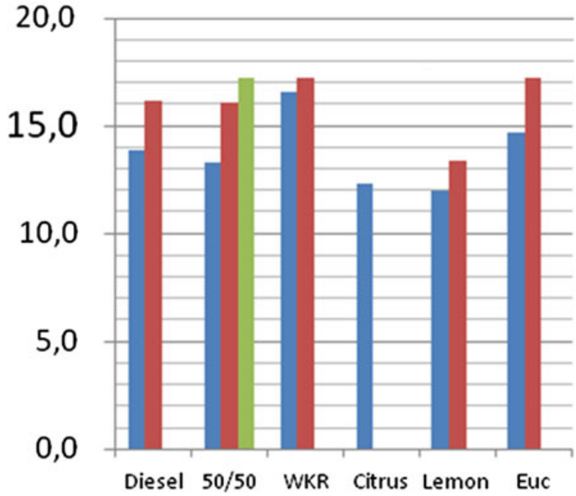


Fig. 5 L/100 km versus fuel type for return country runs

2.2.3 Statistical Analysis

For sets of more than four results for the experimental fuels (except for D + 86/14 vs. lemon for combined country runs), two-sample *t* test findings at 95 % confidence level are reported in Table 2. Results are presented in six blocks, (a) all trials, (b) outbound country runs, (c) return country runs, (d) all country runs, (e) all outbound versus all return country runs and (f) all city runs. There was insufficient data for two of the return country runs. For all trials, 50/50 blends containing eucalyptus perfume performed significantly worse than diesel fuel. Conversely, 50/50 blends containing citrus or lemon perfumes performed significantly better than diesel fuel. An equally important finding, is that there was no significant difference between diesel fuel and the most tested experimental 50/50 diesel/WVO blend. Country runs saw no significant differences apart from between all outbound runs and all return runs where the impact of the different prevailing conditions is borne out. Notwithstanding this, one of the best performing experimental fuels, 50/50 blend with lemon perfume when assessed for all country runs, was close to presenting a significant difference (t-stat [2.5] not > t-critical [2.8] and P two-tail [0.06] not < alpha [0.05]). This run showed significant difference at the lower, 90 % confidence level. City runs showed no significant differences between fuel types.

Table 2 T-Test Outcomes

1st variable	2nd variable	L/100 km		No of samples		Significant ? [b]
		1st mean [a]	2nd mean [a]	1st	2nd	
All trials						
Diesel	All other	12.3 ± 1.5	13.4 ± 1.1	7	23	No
Diesel	Citrus/Lemon	12.3 ± 1.5	9.9 ± 2.3	7	4	Yes
Diesel	Cit/Lem/LemEuc	12.3 ± 1.5	10.5 ± 2.3	7	5	No
Diesel	IPA/C/L/Et-EtAc	12.3 ± 1.5	10.6 ± 1.6	7	7	No
Diesel	W/L-Eu/Eu/D-Eu	12.3 ± 1.5	14.9 ± 1.4	7	11	Yes
Diesel	50/50	12.3 ± 1.5	13.7 ± 2.8	7	4	No
Diesel	Euc	12.3 ± 1.5	14.5 ± 1.9	7	7	Yes
Outbound country runs						
86/14[c]	WKR	18.7	17.8 ± 1.7	1	4	No
86/14[c]	All other	18.7	17.2 ± 1.3	1	13	No
86/14[c]	All additives	18.7	16.8 ± 1.7	1	10	No
Return country runs						
Diesel	All other	15.0 ± 14.5	15.3 ± 1.8	2	10	No
Diesel	All additives	15.0 ± 14.5	15.1 ± 2.4	2	7	No
All country runs						
D + 86/14	50/50	16.2 ± 5.9	17.2 ± 2.2	3	6	No
D + 86/14	Lemon	16.2 ± 5.9	12.6 ± 1.9	3	3	No (Yes 90 %)
D + 86/14	WKR	16.2 ± 5.9	17.7 ± 1.1	3	6	No
D + 86/14	Euc	16.2 ± 5.9	17.5 ± 2.7	3	5	No
D + 86/14	All other	16.2 ± 5.9	16.4 ± 1.1	3	23	No
D + 86/14	All additives	16.2 ± 5.9	16.1 ± 1.3	3	17	No
All outbound vs All return runs						
Outbound	Return	17.3 ± 1.2	15.3 ± 1.5	14	12	Yes
City runs						
Diesel	50/50	12.2 ± 1.4	13.2 ± 2.7	7	5	No
Diesel	Euc/B Euc/D + Eu	12.2 ± 1.4	13.3 ± 2.2	7	5	No
Diesel	All other	12.2 ± 1.4	13.0 ± 1.1	7	18	No
Diesel	All additives	12.2 ± 1.4	12.9 ± 1.4	7	13	No

[a] and [b] at 95 % confidence level
[c] Diesel fuel surrogate (86 % diesel, 14 % WVO)

3 Conclusions

- For all 30 trials inclusive of both city and country driving, (a) there is no significant difference between mean fuel consumption using 100 % diesel fuel and the 50/50 blend of WVO and diesel fuel, (b) 50/50 blends containing eucalyptus perfume performed significantly worse than diesel fuel alone and, (c) 50/50 blends containing citrus or lemon perfume performed significantly better than diesel fuel alone.
- Outbound country runs performed best using the 50/50 blend with low concentrations of lemon or citrus perfume and return runs performed best with the same perfume blends and the straight 50/50 blend. However, there is/are (a) no

significant differences between fuel types used in outbound runs or in fuel types used in return runs, (b) a significant difference in the mean overall fuel consumption outbound vs the mean overall fuel consumption in return runs consequent upon the different wind and vehicle loading conditions in the two groups and (c) a significant difference at the lower 90 % confidence level for the combined country runs between diesel fuel and the 50/50 blend containing lemon perfume.

- There is no significant difference between any of the fuel types for city runs.
- Fuel filter blockage was caused almost exclusively by suspended fats present in the waste vegetable oil used. These comprise higher melting point components of the vegetable oil blend used by the source fish-and-chip shop, hotel or restaurant, together with introduced fats from pre-cooked foodstuffs.
- Smoke emission is increased when the fuel filter is partially blocked, when the fuel injectors are worn and as the vehicle ages.

Acknowledgments Merck Pty Ltd Australia for providing solvents; DA Vale Diesel Injection Service Pty Ltd for providing information and equipment; I F Thomas and Associates for providing the perfumes; Mussels Fish and Chippery, Customs House Hotel, Yacht Club Hotel, Pelicans Landing Restaurant and Accent Cafe for providing waste vegetable oil and Symex Holdings Ltd for providing perfume Material Safety Data Sheets.

References

Abbass MK (1990) The composition of the organic fraction of particulate emissions of a diesel engine operated on vegetable oil. SAE 901563

Abolle A, Koakou L, Planche H (2009) The density and cloud point of diesel oil mixtures with the straight vegetable oils (SVO): palm, cabbage palm, cotton, groundnut, copra and sunflower. Biomass Bioenergy 33:7

Agarwal AK (2010) Comparative performance, emission, and combustion characteristics of rice-bran oil and its biodiesel in a transportation diesel engine. J Eng Gas Turbines Power 132(6):64503–64504

Babu AK, Devaradjane G (2003) Vegetable oils and their derivatives as fuels for CI engines: an overview. SAE 01-0767

Bernardo A et al (2003) Camelina oil as a fuel for diesel transport engines. Ind Crops Prod 17(3):7

Bhupendra SC et al (2010) Performance and emission study of preheated jatropha oil on medium capacity diesel engine. Energy 35:9

Cheng WL, Lee CF (2008) Comparison of performance and combustion characteristics of diesel fuel and vegetable oils in DI diesel engine. SAE 01-1639

Deshmukh BS (2009) Straight vegetable oil run diesel engine—a compromise solution. SAE 28-0033

Devan PK, Mahalakshmi NV (2009) Performance, emission and combustion characteristics of poon oil and its diesel blends in a DI diesel engine. Fuel 88:7

Dorado MP (2002) The effect of a waste vegetable oil blend with diesel fuel on engine performance. Trans of the ASAE 45(3):519–523

Fontaras G et al (2007) Experimental study on the potential application of cottonseed oil-diesel blends as fuels for automotive diesel engines. Trans IChemE, Part B, Process Saf Environ Prot 85(B5):8
Gangwar HK, Agarwal AK (2008) Emission and combustion characteristics of vegetable oil (Jatropha curcus) blends in an indirect ignition transportation engine. SAE 28-0034
Haldar SK (2009) Utilisation of unattended putranjiva roxburghii non-edible oil as fuel in diesel engine. Renew Energy 34:343–347
Krahl J (2009) Comparison of exhaust emissions and their mutagenicity from the combustion of biodiesel, vegetable oil, gas-to-liquid and petrodiesel fuels. Fuel 88:1064–1069
Kumar N, Khare U (2004) Use of macro-emulsion of vegetable oil in compression ignition engine. SAE 28-0040
Lance DL, Andersson JD (2004) Emissions performance of pure vegetable oil in two European light duty vehicles. SAE 01-1881
Mormino I (2009) Using vegetable oils and animal fats in diesel engines: chemical analyses and engine tests. SAE 01-0493
Murat C (2007) The use of hazelnut oil as a fuel in pre-chamber diesel engine. Appl Therm Eng, 27(1)
Nabi N (2003) Fundamental properties of different vegetable oils available in Bangladesh. SAE 01-3195
Nettles-Anderson SL, Olsen DB (2009) Survey of straight vegetable oil composition impact on combustion properties. SAE 01-0487
Niemi SA (2003) Exhaust emissions of an off-road diesel engine driven with a blend of diesel fuel and mustard seed oil. Am Soc Mech Eng, Intern Combust Engine Div 40:10
Orwa C et al (2009) Ceiba pentandra. Agrofor Database 4.0
Pugazhvadivu M (2005) Investigation on the performance and exhaust emissions of a diesel engine using preheated waste frying oil as fuel. Renewable Energy 30:13
Quality assurance for rape-seed oil as vehicle fuel (2004) Sustain energ, Ireland
Roegiers M, Zhmud B (2009) Tribological performance of ionised vegetable oils as lubricity and fatty oiliness additives in lubricants and fuels. Lubr Sci 21(5):169–182
Shiva V (2005) Stealing wisdom, stealing seeds: the neem tree of india becomes a symbol of greed for corporations. Int J Humanit Peace 21(1):77
Tamilvendhan D, Ilangovan V (2011) Performance, emission and combustion characteristics of a methyl ester sunflower oil eucalyptus oil in a single cylinder air cooled and direct injection diesel engine. Int J Eng Sci Technol 3(3):1977–1985
Tippayawong N (2003) Long term direct injection diesel engine operation on vegetable oil/diesel blends. SAE 01-1932
Vojtisek-Lom M (2007) Time-resolved emissions characteristics of modern passenger vehicle diesel engines powered by heated vegetable oil. SAE 24-0129
Wakil A, Ahmed ZU (2012) Study on fuel properties of various vegetable oils available in Bangladesh and biodiesel production. Int J Mech Eng 2(5)
Yoshimoto Y (2001) Performance and emission characteristics of diesel engines fueled by vegetable oils. SAE 01-1807/4227

High Pressure Hydrogen Storage System Based on New Hybrid Concept

D. Duschek and J. Wellnitz

Abstract On market, high pressure storage systems have a shape of cylinder with a high specific inner diameter and length. The state of the art structure is only a metal liner or assembled with composite material, like carbon, by wrapping. The liner is used to barrier coat for hydrogen. A metal container is heavier as a hybrid structure. The rear weight is very important for emission and performance of vehicle. Therefore the relation between metal and the fibre/matrix layers define the potential of lightweight strategy. Another aspect is the capacity of gaseous storage system, because the constructed size is enormously with the result of losing convenience. The designer can reduce the container dimension with the result that the range decreased or raise the working pressure up and create more weight. The costs of manufacturing are very important, too, because the yearly availability of fibre and matrix define the material costs. The new hybrid concept of a hydrogen container depends on the lightweight potential, storage capacity, material and manufacture costs.

1 Introduction

In times of decreasing availability and rising costs for fossil fuels, new methods of energy storage have to be developed to satisfy the growing global demand for energy and the increasing consumption. In addition to this the growing amount of automobiles being registered in Asia clarifies the rising wish of the public shows for mobility. Original Equipment manufacturers (OEM) need to develop new

D. Duschek (✉)
Research-Institute of Technology and Artistic Design GmbH,
Nördliche Ringstraße 19, 85057 Ingolstadt, Germany
e-mail: daniel.duschek@itd-in.de

J. Wellnitz
Technische Hochschule Ingolstadt, Esplanade 10, 85049 Ingolstadt, Germany
e-mail: joerg.wellnitz@thi.de

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_3,

power train concepts and components to reach the goal of the United Nations Climate Conference, as a simple continuing optimization of the traditional petrol internal combustion engine (ICE) is not the most efficient way to cope the challenges of the future. Another point of view additionally to the environmental aspect pollution is the world's dependency on the oil lobby and the Organization of the Petroleum Exporting Countries (OPEC).

A lot of different concepts and approaches have been and are currently being investigated in the laboratories and research centres all over the world to find a solution for this challenge. Two mainstreams of the development of alternative energy storage can be excerpted. These are usually hydrogen storage and electrical storage. These concepts are co-existing and have their benefits and disadvantages in different fields. Considering that hydrogen is an element for fuel that appears in the nature and that a battery is a medium to store energy makes the comparison of both concepts rather complex.

2 Hydrogen Storage Systems on Market

A comparison of the different available storage strategies shows the following kind of storage systems (Godula-Jopek et al. 2012; Eichlseder and Klell 2012).

- gaseous
- liquid
- solid

Today gaseous storage is the preferred system because of the simple tank design and the resulting low initial costs. In conclusion the aim is the optimization of the energy density to volume ratio. During the last decade three different main

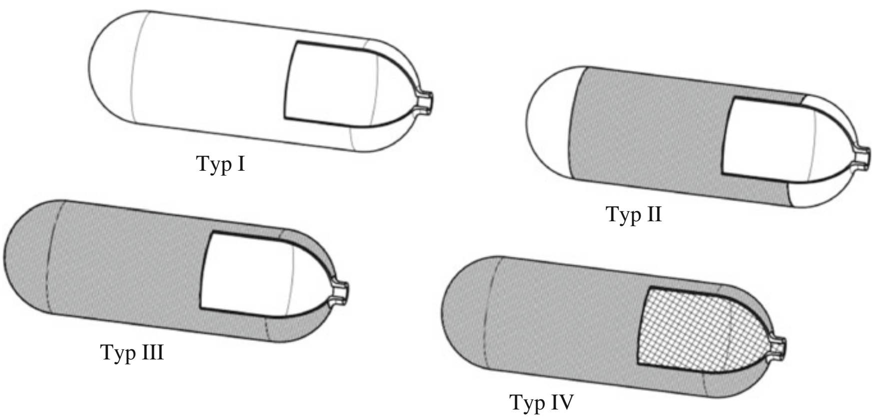


Fig. 1. Classification of hydrogen containers (European Parliament Council 2009)

concepts have been developed to increase that ratio of energy density compared to the volume. The regulation (EC) No 79/2009 of the European Parliament and of the Council describes the classification of hydrogen containers designed to use compressed (gaseous) hydrogen, Fig. 1 (European Parliament Council 2009).

- Type I: Seamless metallic container.
- Type II: Hoop wrapped container with a seamless metallic liner.
- Type III: Fully wrapped container with a seamless or welded metallic liner.
- Type IV: Fully wrapped container with a non-metallic liner.

A view into the field of pressure tank technology shows that usually today it is common practice to design a huge cylinder tank. Usually these tanks (type III) consist of an inner diffusion resistant aluminium layer and a carbon composite outside liner with the purpose of carrying the pressure loads.

The challenge is to find a compromise between maximum range, like compression ignition engine and convenience of trunk volume, Fig. 2. Typical hydrogen storage systems on market show a common system that is able to carry 4.66 kg of hydrogen at a pressure of 350 bar. The average weight of the construction tanks is 86 kg, which equals a specific weight of 18.45 kg_{tank}/kg_{H2}. Therefore, the rear weight is huge and must reduce to get a better consumption of hydrogen and driving characteristics. Current concepts tend to store the hydrogen at a higher pressure of 700 bar because of the higher mass of fuel that can be stored in the same volume compared to conventional 350 bar systems. For example, Quantum Technologies have developed a 700 bar tank system for General Motors. 2.2 kg of hydrogen can be stored in a tank of a mass of 35 kg. This equals a specific weight of 15.91 kg_{tank}/kg_{H2}. Another example of a 700 bar system is the pressure tank used in the concept car Mercedes Benz F-Cell. In conclusion it can be seen as a matter of fact in each construction, that all current technically relevant 350 bar storage systems on the market are designed as a cylinder of high diameter and have an average specific weight of 25 kg_{tank}/kg_{H2} (Eichlseder and Klell 2012).

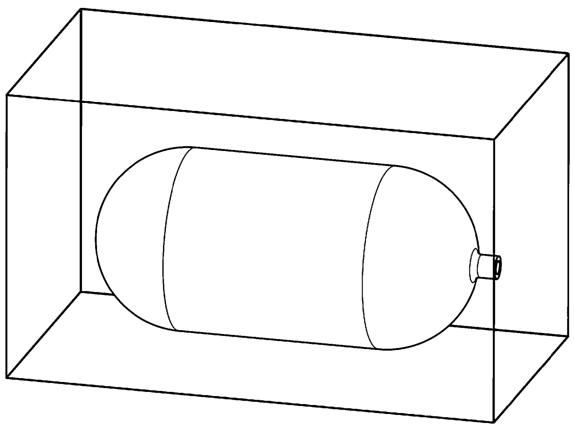


Fig. 2. Relation of hydrogen containers (3 kg_{H2}, 350 bar) and a trunk volume of a compact car (360 litres)

3 New Hybrid Concept

The challenge of the design process is to find the compromise between used constructed size, capacity and weight of gaseous storage systems.

3.1 Structure Mechanical

The mechanical structure analysis of high-pressure storage shows that internal pressure p caused axial and tangential stresses. With the vessel-equation (standard, DIN) it is possible to calculate a system under internal pressure. Fig. 3 shows the stress in tangential direction σ_t and in axial direction σ_a, which can be calculated using the vessel-equations.

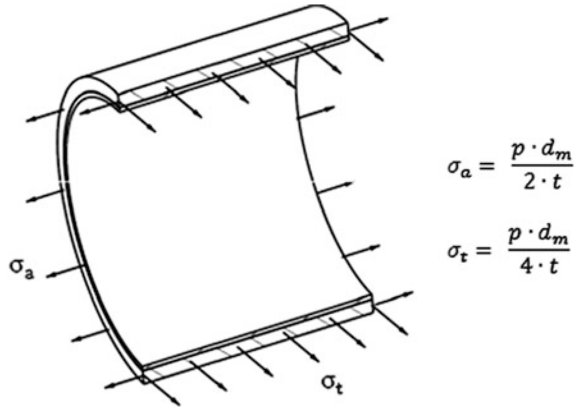


Fig. 3. Stress in a tube under internal pressure (section layer assembly)

The result of the first draft clarify that the stresses grow up proportional to increasing working pressure. The application of the vessel-equation is only valid for tubes with a fraction of the diameters of

$$d_a/d_i \leq 1.2$$

as the characteristic curves for the elastic and plastic state show only low discrepancy for the fraction of p/σ_v. Following that as a possible approach the surface structure needs to be used. For consideration of the stress for components the two dimensional state of plane stress is chosen, which is extended to the three dimensional case for further continuum mechanical analysis.

Another important theoretical factor is the influence of boundary conditions that are not considered in the vessel-equation, like effects of the end of the tube. Following the approximation parameter study can deflect from real stresses.

The definition of a safety factor can minimize the risk of failure but this causes more weight for the storage system. The challenge is to find out which parameter has a big influence to create the best solution for the new hybrid concept. For example, if the diameter of the pipe increases, the stresses in axial and tangential direction are also geting bigger. So this parameter has to be optimized. A small parameter means, the internal volume of the pipe gets smaller and the relation of mass hydrogen to mass storage system is getting worse.

The idea is to reduce the diameter, axial and tangential stress, wall thickness and in conclusion the resulting weight of the hydrogen system. But with decreasing diameter the relation between kg_{H2} and kg_{Tank} gets worse, because the inside volume of the pipes gets lower. Analysing of hydrogen storage systems show three main facts for the system parameter:

- weight
- stress
- costs

3.2 Design of the Composite Tube

The comparison of the hydrogen containers types with the same maximum working pressure shows that a type I system has more weight as a type III storage. This means, reducing weight has more potential using reinforced pipes for containers with high internal volume.

The assembly of the hydrogen system (type III) is based on three different components:

- metal (aluminium, stainless-steel, magnesium, …) for the liner
- resin (epoxy resin) and
- fibre (carbon fibre, glass fibre, basalt fibre …).

The metal component is used to define the shape of the pipe system and acts as barrier coat for the hydrogen, Fig. 4. Hydrogen is able to cause hydrogen embrittlement, which is a corrosive effect that lowers the ductility of a metallic material, as hydrogen atoms enter the metal matrix structure and recombine to hydrogen molecules. As a result of this effect not all metallic materials are acceptable as a choice for a hydrogen tank liner. Aluminium is a very suitable material, because the surface layer of the structure is an oxide-layer. The second component is the fibre material, e.g. basalt and epoxy resin. The structure depends on material properties and stresses caused by internal pressure, because the fibre material absorbs the stresses. The first calculation of wall thickness t_{ges} and number of layer based on CLT (classical lamination theory) (Schürmann 2007; Anders 2008), Fig. 5.

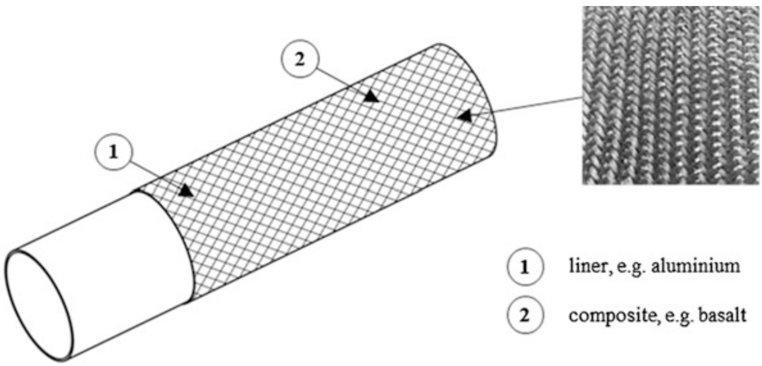


Fig. 4. Assembly of the hybrid concept

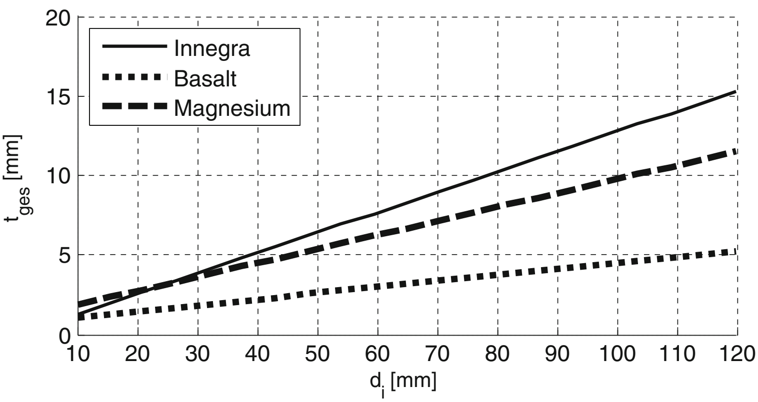


Fig. 5. Wall thickness depending on inner diameter, safety factor and internal pressure 350 bar

The wall thickness t_{ges} depending on the inner diameter d_i and the internal pressure p_i. Figure 5 shows, that t_{ges} increase with the dimension of the diameter caused of higher stresses. Therefore, the manufacturing process is very difficult and expensive, because a lot of material and manpower is used. The risk of surface defect raise up with the number of layers, because, the fibre angle can changed during winding step of each layer.

4 Conclusion

The compromise between capacity, weight of container, comfort and manufacture costs is very complicated, because some components have an influence on more as one point. The first calculation represents that the inner diameter is the most important parameter, because the stresses depend on the internal pressure and define the whole wall thickness. A view on the property of fibre shows, that the density is lower as the density of metal. The rule of mixture of the composite material helps to calculate the weight and wall thickness of the composite structure. Therefore, the lightweight potential raises up if the wall thickness of metal liner decreases.

Another critical point is the constructed size. If the inner diameter is smaller, the inner volume getting smaller too, but the comfort is raising up. For example, an inner diameter of 10 mm and a wall thickness of 2 mm are enough to absorb the stresses caused by internal pressure of 350 bar. For this case it is necessary to use fibre instead of an inner diameter of 30 mm and 1 mm metal wall thickness fibre are needed. The comparison of both clarifies the hybrid structure and resultant material and manufacture costs.

References

Anders S (2008) Sensitivitätsanalyse des Eigenspannungszustandes eines Composite - Hybrid-hochdruckbehälters, BAM - Dissertationsreihe, Band 37, Berlin

Eichlseder H, Klell M (2012) Wasserstoff in der Fahrzeugtechnik. Vieweg + Teubner, Wiesbaden

European Parliament, Council (2009) Regulation (EC) No 79/2009 of the European Parliament and of the Council of 14 January 2009 on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC (Text with EEA relevance). Regulation, OJ L 35, 4.2.2009, pp 32–46

Godula-Jopek A, Wellnitz J, Jehle W (2012) Hydrogen storage technologies. Wiley, Weinheim

Schürmann H (2007) Konstruieren mit Faser-Kunststoff-Verbunden. Springer, Berlin

Risk Optimisation of an Automobile Hydrogen System

J. Meyer

Abstract According to leading automobile manufacturers, hydrogen vehicles will be commercially available within the next few years. Up to now, a number of pre-production models have covered millions of test kilometres and proven to be sufficiently reliable for market launch. Nevertheless, there are still some reservations with respect to safety. The concerns are nourished by the fact that the physical properties of hydrogen differ significantly from the properties of conventional fuels like gasoline and diesel. Thus, the development of hydrogen vehicles requires a radical rethinking of the fuel system. In this context the question arises, which system components should be chosen and where they should be positioned in order to minimise the overall risk. The answer to this question can be given with the help of a quantitative risk analysis (QRA). The risk associated with the interrelated system components depends on a set of non-linear equations and thus requires non-linear numerical approaches. One such non-linear approach is the gradient descent method. Using this method, the safety of an automobile hydrogen system was optimised. The following article summarises the basic approach and the outcomes of the optimisation study.

1 Introduction

Driven by the changeover to renewable energy, there is an ever growing demand for hydrogen based power systems. In contrast to conventional fuels like gasoline and diesel, the production of hydrogen and its consumption is not associated with any greenhouse gas emissions and thus is considered clean and sustainable. For this reason, hydrogen will displace hydrocarbon-based fuels in the next few decades and develop into the most important fuel of our future energy network.

J. Meyer (✉)
Institut für Technik und Design GmbH (ITD), Nördliche Ringstraße 19,
85057 Ingolstadt, Germany
e-mail: jean.meyer@itd-in.de

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_4,

However, hydrogen systems are generally more complex than conventional fuel systems, especially with regard to automobile systems. This is due to the fact that hydrogen needs to be stored in gaseous state at several hundred bars, whereas conventional fuels are stored in liquid state and can be handled more easily. For this reason, the design of hydrogen vehicles requires a radical rethinking of the fuel system, especially with respect to safety. Although the reliability and safety of hydrogen vehicles has been proven in numerous tests, safety remains an ever-present aspect.

Up to now, hydrogen systems are designed on the basis of a best practices approach. In detail, a lot of effort is put into the design and the selection of system components. On the other hand, aspects concerning the interaction of these components, especially their local positioning, are often neglected. However, the design and positioning of system components has a magnificent impact on the systems safety and offers great potential for optimisation.

There are a number of analytical optimisation approaches, which enable to determine the optimum of a certain target parameter with respect to a given set of variables. Especially in the area of financial economics and financial risk management, optimisation approaches play a major role. For example, optimisation approaches are used to find the optimum parameter set, at which the benefit reaches a maximum or the financial risk is lowest.

The potential of optimisation approaches is not limited to economic and financial tasks, but is also a useful tool for technical issues, including hydrogen safety. The following summary gives an overview of the outcomes of a safety-related optimisation study concerning the design of a hydrogen system in a racing car.

2 Methods

Safety is often associated with the term "risk". In order to make a system safer, the risk associated with the operation of this system, has to be minimised. With respect to the optimisation study presented here, the term "risk" designates an area and time related probability of a lethal event due to an unintended release of hydrogen.

In this connection, the most probable reason for an unintended release of hydrogen is a damage of the hydrogen system, caused by a crash of the car. Depending on the area of the car which is affected by a crash, different parts of the system might be damaged. The consequences of the hydrogen release, in turn, depend on the amount of hydrogen and the manner in which the hydrogen is released, for example spontaneous or over a longer period of time. Both aspects, the amount of hydrogen and the manner in which it is released are determined by the system components and their design. For example, a rupture of a pipe with a small cross section and a low pressure level will lead to a small jet with manageable consequences. In contrast, a rupture of a high pressure pipe, will lead to a much more extended jet with more severe consequences. A rupture of the pressure vessel in turn will lead to an immediate release of a large amount of hydrogen and will result in even more severe consequences. In each of these three hypothetic scenarios, the amount of hydrogen and the manner of release is determined by the design parameters of the component, for example its flow diameter, its position with respect to the car body and the respective design parameters of the other components of the system. Thus, there are several parameters that can be altered and adjusted in order to lower the risk and optimise or increase the safety of the system.

The safety context of the relevant parameters is described by nonlinear functions. Nonlinear functions are functions with multiple variables, of which at least one is of higher order. In contrast to linear functions, nonlinear functions can only be solved with the help of numeric approaches. One such nonlinear approach is the gradient descent method.

2.1 Gradient Descent Method

The gradient descent method is a nonlinear optimisation approach and is based on a comparatively simple algorithm, which can be easily implemented into a software code. The basic idea of the gradient descent method is to find the minimum of a nonlinear function by stepwise approximation in direction of the steepest descent. The direction of the steepest descent is determined by the negative gradient of the function. Conversely, it is also possible to find the maximum of a function, by approaching in direction of the positive gradient of the function. Mathematically the gradient descent method is described by the following algorithm (Bronstein et al. 2012: 941):

$$x^{(i+1)} = x^{(i)} - \alpha^{(i)} \nabla f\left(x^{(i)}\right),$$

in which $\nabla f\left(x^{(i)}\right)$ designates the gradient of the function and $\alpha^{(i)}$ is the step size.

There are several methods to determine the optimum step size. One approach is to find the step size by determining the minimum of the function in dependence of $\alpha^{(i)}$(Bronstein et al. 2012: 941):

$$\min! = f\left(x^{(i)} - \alpha^{(i)} \nabla f\left(x^{(i)}\right)\right).$$

2.2 System Design

In order to simplify the risk optimisation on the basis of the gradient descent method, the original hydrogen system of the vehicle was reduced to the main components, which are required for operating the car in a race. Any pipework and components, which are necessary to refill the pressure vessel as well as the pipework and components of the venting system were neglected.

The hydrogen system comprises seven components: One pressure vessel, two pressure regulators, two shut-off valves and two pressure relief devices (see Fig. 1). Apart from the position and the parameter settings of the system components, the risk associated with the hydrogen system strongly depends on the mode of operation and the ambient conditions. For example, during a race, the risk is significantly greater, as all system components are filled with hydrogen at maximum pressure and the probability of a crash or damage of the system components is greatest. In contrast, when the vehicle is parked, the risk is much lower. In order to overcome any ambiguities, arising from the different modes of operation, it is assumed that the system is operated in normal mode, i.e. racing mode. In normal operation mode, the pressure inside the vessel is assumed to be at 350 bar and the flow rate is assumed to be at 10 g/s. In addition, all logical components are assumed to be and remain at a constant setting, which means that all valves are assumed to be and remain open. A possible malfunction of system components is not considered.

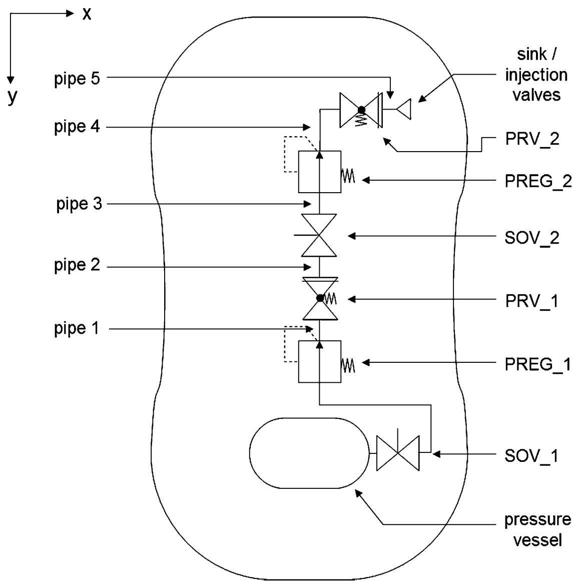


Fig. 1 Schematic diagram of the hydrogen system

2.3 Implementation of Pressure Dynamics

The local pressure inside the pipes has a strong influence on the overall system safety. In detail, the pressure determines the amount of hydrogen inside the pipes and the dynamics of an eventual release. For this reason, the pressure variations, caused by the components and the flow though the pipes, were taken into account.

The pressure losses associated with the components were implemented on the basis of the flow coefficient C_v. In this connection, it is assumed, that the pressure drop at the components and density change is comparatively small, so that the gas can be considered as an incompressible medium.

The pressure drop, caused by a component with the flow coefficient C_v, is given by the following equation (Glück 1988: 60):

$$\Delta p = \frac{\rho u^2}{2} \cdot \left(\frac{1}{C_v^2} - 1 \right),$$

in which ρ designates the density and u the flow velocity of the gas.

For the sake of convenience, it was assumed that all components show a constant, non-variable flow coefficient of $C_v = 0.9$.

The pressure drop associated with the flow through the pipes was implemented on the basis of the following equation (Glück 1988: 144):

$$p_{out} = \sqrt{p_{in}^2 - \overline{u}_{in}^2 \, \rho_{in} \, p_{in} \, \lambda \frac{l}{d}},$$

in which p_{in} designates the input pressure, p_{out} is the output pressure, $\overline{u}_{in}$ is the flow velocity at the inlet of the pipe, ρ is the density, λ is the friction factor, l is the length of the pipe and d designates the diameter of the pipe.

Depending on the local Reynolds number (Re) the friction factor λ can be calculated with different equations. For laminar flows (Re < 2,300) the friction factor is described by the following equation (Glück 1988: 49):

$$\lambda = \frac{64}{Re}.$$

For turbulent flows (Re > 2,300), the friction factor is determined in an iterative approach on the basis of the Colebrook-White equation (Glück 1988: 52):

$$\frac{1}{\sqrt{\lambda}} = -2 \log_{10} \left[\frac{2.51}{Re\sqrt{\lambda}} + \frac{\varepsilon}{3.71\, d} \right],$$

where ε designates the surface roughness of the pipe. For the implementation it was assumed that the pipe roughness shows a constant value of 10^{-5} m.

At high pressures, hydrogen shows great deviations from the ideal gas law. Therefore, the optimisation was conducted on the basis of real gas properties. For this purpose, the relation between pressure and density was approximated with the help of a quadratic function, derived from 35 pressure-density sets in the range of 1−350 bar at a constant temperature of 293 K. The datasets were gathered from the NIST Chemistry WebBook (2011).

3 Quantification of Risk

Mathematically, risk can be expressed as a product of the probability of a hazardous event and the severity or consequence.

$$risk = probability\ of\ a\ hazardous\ event \times severity\ of\ the\ event$$

In the course of the risk optimisation study presented here, the hazardous event is defined as an unintended release of hydrogen. Thus, the risk associated with this event can be expressed as a product of the probability of an unintended release of hydrogen and the associated consequences, e.g. an explosion, etc. In order to account for the probability of a crash and a damage of the system components, the local damage probability was defined as a function of the horizontal coordinate x and the vertical coordinate y (see Fig. 2). The damage probability is visualised in Fig. 2 and expressed as percentage of the overall crash probability. In this connection, a low damage probability, e.g. 10 %, means that the respective area will be affected in only 10 % of all crashes. In contrast, a high value, e.g. 90 %, means that the respective area will be affected with a probability of 90 % in case of crash. As can be seen in this Fig. 2, the crash probability is assumed to be highest in the rim areas of the car and the front section of the car. In contrast, in the back of the car, the crash probability is lowest.

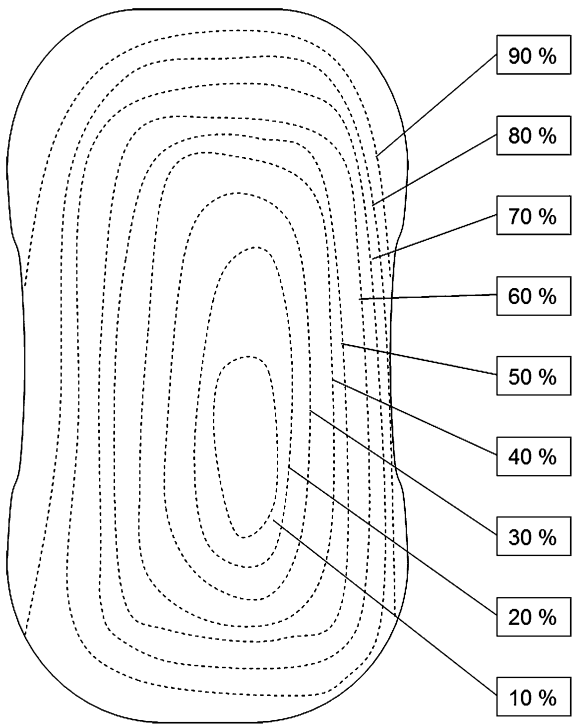


Fig. 2 Schematic diagram of the local damage probability

As mentioned above, the severity of a hydrogen release depends on the amount of hydrogen and the way it is released. For example, hydrogen can be released through a small slit, e.g. a damaged pipe. Depending of the pressure inside the damaged pipe and the slit, the release might be associated with a jet flame. In case the pressure is very low and the slit is very narrow, the hydrogen might mix the ambient air and will not ignite at all. On the other hand, a damage of the pressure vessel might lead to a rupture of the vessel and an instantaneous release of the vessel content, resulting in an explosion.

In the course of the optimisation study presented here, three types of hazards were taken into account:

- jet flame
- flash-fire and
- explosion.

In this connection, a jet flame is considered as a momentum driven flame, which is pointed into a certain direction. On the other hand, a flash-fire is considered as an ignition of an unconfined gas mixture. Finally, an explosion is characterised by an ignition of a confined gas mixture. With respect to the consequences, an explosion is considered much more severe than a flash-fire, as it is associated with the propagation of a pressure wave, which might cause building structures to collapse. In the course of the optimisation study, the severity of each hazard type was implemented in the form of an area dependent parameter, describing the hazardous area associated with the respective event. More precisely, the hazardous area is considered as the area, within which a person would suffer a lethal injury.

The hazardous area associated with a jet flame, was implemented on the basis of a graphical approach, developed by Molkov et al. (2010). The approach enables to determine the jet flame on the basis of the opening diameter and the upstream pressure. For the calculation of the hazardous area it was assumed that the jet flame has an opening angle of 10° and a person within the range of the flame will suffer a lethal injury.

For the determination of the hazardous area of a flash-fire, it was assumed that the hydrogen accumulates in a hemispherical shape and forms an ideal mixture with air at a concentration of 4 %, which is the lower flammability limit. In comparison to the consequences, which are to be expected in real life, this is a very conservative approach, as most of the hydrogen will rise up into the atmosphere due to buoyancy effects and dissolve with air before it ignites. Similar to the jet flame-related consequences, it is expected, that a person within the range of the flash fire will suffer a lethal injury. Thus, the hazardous area associated with this event is equal to the base diameter of the hemispheric cloud of gas.

Finally, the hazard associated with an explosion was implemented in the same way as the hazard, arising from the flash fire. In addition to this hazardous area, the hazard, arising from the pressure effects of the explosion were taken into account. The pressure effects were implemented on the basis of the TNT-equivalency method. The TNT-equivalency method is based on the idea, that the overpressure resulting from an explosion, can be described as a function of the chemical energy of the reaction (CPR 2005; Casal 2008).

For the determination of the hazardous area it was assumed that a person within the range of an overpressure of 30 kPa will suffer a lethal injury (CPR 1992).

Although there is a chance, that hydrogen, escaping from damaged components, dissolves into the ambient air before it ignites, it is assumed, that the hydrogen will ignite in every event, as there are a number of hot spots in the vehicle, which might serve as an ignition source.

4 Implementation

In the course of the optimisation study, the numerical approach outlined above was formulated in a Pascal-based language and implemented into a program. The program enables to set the variable parameters of the hydrogen system and to define constraints for each parameter. The constraints can be considered as limiters, which need to be defined to ensure that the optimum, which is determined with the algorithm, is technically feasible. In other terms, the parameters of some system components might be variable, but only in a certain range. For example, the position of the pressure vessel: From the safety point of view, it would be desirable to place the pressure vessel in the least endangered area of the vehicle. But this area might already be occupied with other parts, which means that the optimum system design associated with the lowest risk, cannot be realized. For this reason, the constraints are implemented, which ensure that the parameters are only varied in a technically feasible range.

In addition to the constraints a "sink pressure controller procedure" was implemented into the program. The sink pressure controller serves the purpose of monitoring and controlling the pressure at the sink of the systems, i.e. the injection valves of the engine. The basic idea of this pressure controller is to keep the pressure above a minimum level of 5 bar which is required to ensure correct operation of the injection valves. If the controller was not implemented, the optimisation process would reduce the pipe diameters to a minimum, as this is the solution with the lowest risk. This can be explained on the basis of the jet flame length. In detail, smaller pipe diameters result in a lower pressures and shorter jet flames. However, the operation of the vehicle requires a certain minimum pressure at the injection valves. For this reason the pressure controller is steadily monitoring the pressure at the valves and stops any further reduction of the pipe diameters and output pressures of pressure regulators, once the pressure falls below the predefined limit of 5 bar.

In order to ensure that the minimum pressure is also attained at the minimum state of charge (SOC), the procedure was run at the minimum state of charge, which is assumed to be reached at a pressure of 25 bar inside the storage vessel.

In addition to the sink pressure controller, a "choked flow controller procedure" was implemented. The aim of the choked flow controller is to prevent the

Table 1 Initial values, constraints and final values of variable parameters

Component	Variable parameter	Unit	Initial value	Min. value	Max. value	Final value
Pipe 1	Diameter, d_1	(mm)	8	4	10	4.01
Pipe 2	Diameter, d_2	(mm)	8	4	10	4.05
Pipe 3	Diameter, d_3	(mm)	8	4	10	4.39
Pipe 4	Diameter, d_4	(mm)	8	4	10	4.47
Pipe 5	Diameter, d_5	(mm)	8	4	10	5.28
PREG_1	Exit-pressure,	(bar)	150	100	200	112.75
PREG_1	y-position, $y_{PREG,1}$[a]	(–)	0.58	0.56	0.62	0.615
PREG_2	Exit-pressure, $p_{PREG,2}$	(bar)	20	15	25	15.72
PREG_2	y-position, $y_{PREG,2}$[a]	(–)	0.23	0.22	0.25	0.25
PREG_2	x-position, $x_{PREG,2}$[b]	(–)	0.5	0.48	0.51	0.506
SOV_2	y-position, $y_{SOV,2}$[a]	(–)	0.38	0.33	0.42	0.42
PRV_1	y-position, $y_{PRV,1}$[a]	(–)	0.5	0.48	0.52	0.52

[a] Relative vertical position with respect to car-length
[b] Relative horizontal position with respect to car-width

analytical flow velocity from exceeding the speed of sound, which is the physical maximum of the flow velocity inside a pipe. Thus, flow velocities above the speed of sound are physically invalid. For this reason, the choked flow controller constantly monitors the flow velocity in each pipe and counteracts any further reductions of the pipe diameters by the optimisation algorithm, once the local velocity reaches the speed of sound.

In the course of the optimisation process, seven parameters were considered as being variable. In addition, the diameters of the pipes were also considered as being variable. The variable parameters are listed in Table 1, together with their initial values and constraints.

5 Results

Starting from the initial conditions, defined by the original system setup, the optimisation algorithm dropped repeated 102 times. At this point, the remaining variation of the parameters was below 2 %. The final values of the optimisation are listed in Table 1.

With respect to the pipes, it can be seen, that the diameters of all pipes decreased. But only the diameter of pipe 1 decreased to its minimum value, defined by the constraints, whereas the diameters of the other pipes stopped decreasing at larger values. This can be explained by the intervention of the pressure controller procedure, which was implemented in order to ensure that the pressure at the sink or the injection valves does not fall below the critical limit of 5 bar at minimum SOC. The general reduction of the pipe diameters is due to the fact, that smaller pipe diameters result in lower pressures, shorter jet flames and thus, lower risk. For the same reason, the exit-pressure of the two pressure regulators also decreased.

Another remarkable aspect is, that all components with a variable position approximated in direction of the back of the car, as the damage probability in this area is lowest.

Although the optimisation had a significant effect on the parameter settings, the overall benefit with regard to a minimisation of risk is comparatively low. In detail, a comparison of the non-optimised system and the optimised system showed, that the overall hazardous area of all components decreased by less than 2 %. This can be explained by the fact, that the amount of hydrogen and the pressure in the storage vessel is much greater than the amount of hydrogen and the pressure in the pipes. Thus, the risk originating from the storage vessel is much greater than the risk of the pipework and the effects of the other components. This context becomes more evident when the influence of the pressure vessel is neglected. For example, when considering only the pipework and the components without the pressure vessel, the comparison of the non-optimised system and the optimised system shows, that the risk originating from the optimised system is only 16 % of the initial risk, which means, that the benefit of the optimisation is 84 % with respect to the overall hazardous area.

With regard to the influence of the pressure vessel it is interesting to note, that the SOC plays a major role. More precisely, the results presented above are based on the assumption that the vessel is at 100 % SOC, i.e. at 350 bar. But during operation, the SOC will decrease and the amount of hydrogen that might be released unintentionally will also decrease. Thus, the risk associated with the vessel will decrease with decreasing SOC. In contrast, the risk of the pipework in the medium pressure region and especially the low pressure region, in downstream direction of the second pressure regulator will remain almost the same. Thus, the overall benefit of the optimisation depends on the respective SOC and increases with decreasing SOC.

6 Conclusion/Summary

The safety relevant properties of hydrogen systems are described by multi-dimensional, nonlinear functions. Based on these functions, the gradient descent method provides a useful tool for optimising the risk associated with the hydrogen system.

For the optimisation study presented here, the gradient descent method was implemented into a software and used to determine the optimum position and settings for the components of an automobile hydrogen system. By taking constraints into account, it was possible determine a technically feasible solution.

In the next step it is planned to develop a software tool for analysing and optimising the logical correlation of the system components, i.e. their logical arrangement in the network. In connection with the optimisation approach presented above, the software tool will offer the universal ability to create safe hydrogen systems on the basis of a given set of boundary conditions and performance requirements.

References

Bronstein IN, Semendjajew KA, Musiol G, Mühlig H (2012) Taschenbuch der Mathematik, 8th edn. Harri Deutsch Verlag, Frankfurt a. Main

Casal J (2008) Evaluation of the effects and consequences of major accidents in industrial plants. Industrial safety series. Elsevier, Amsterdam

Committee for the Prevention of Disasters (2005) Methods for the calculation of physical effects, CPR 14E, yellow book, 3rd edn. The Hague

Committee for the Prevention of Disasters (1992) Methods for the determination of possible damage, CPR 16E, green book, 1st edn. The Hague

Glück B (1988) Hydrodynamische und gasdynamische Rohrströmung. Verlag für Bauwesen, Berlin

Molkov V, Bragin M, Brennan S, Makarov D, Saffers J-B (2010) Hydrogen safety engineering: overview of recent progress and unresolved issues. In: International symposium of combustion and fire dynamics, Santander, Spain

NIST Chemistry WebBook (2011) National institute for standards and technology (NIST). http://webbook.nist.gov/chemistry

Part II
Material Recycling

Finite Element Analysis of Three-Point Bending Test of a Porous Beam Emulating Bone Structure for the Development of Vehicle Side Instrusion Bars

Y. Rui, A. Subic, M. Takla and C. Wang

Abstract This paper presents three-point bending analysis of a porous beam using the finite element method. This novel porous structure emulates the structure of trabecular (cancellous) bone at the metaphysis of a rabbit. Segments of the bone were scanned using a high-resolution CT-scanner. The bone geometry was recreated and a finite element mesh was generated using software MIMICS. The finite element model of the bone structure was developed and a quasi-static three-point bending test was simulated in ABAQUS. This approach can be utilized in design of side intrusion bar of passenger car as these would be subjected mainly to a bending load during the event of a side collision. In this work, the load carrying capacity and specific energy absorption were determined when the properties of aluminium alloys 6061T6 were applied to the geometrical models of the rabbit femur metaphysis structure. This biomimetic design approach can be generally used to develop novel load bearing lightweight structures inspired by the structural properties of animal bones. Lightweight structures developed this way are expected to increase stiffness at a significantly reduced weight.

Y. Rui (✉) · A. Subic · M. Takla · C. Wang
Department of Mechanical and Manufacturing Engineering, RMIT University, Bundoora, VIC 3083, Australia
e-mail: S3312107@student.rmit.edu.au

A. Subic
e-mail: aleksandar.subic@rmit.edu.au

M. Takla
e-mail: monir.takla@rmit.edu.au

C. Wang
e-mail: chun.wang@rmit.edu.au

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_5,

1 Introduction

The main types of vehicle collisions include front, rear and side impacts as well as rollover. Notably, side impact crash is the second most common type of vehicle impacts after frontal impact. In such impacts, there is no room for large deformation of the vehicle structures and there are no other components to protect the occupant during the accidents. As a result, 25 % of serious casualties and 28 % of fatalities to vehicle occupants in Victoria of Australia occurred from side impacts (Gibson et al. 2001). Data provided by USA, UK, Japan, France, Germany, South Korea, Canada, New Zealand and the Netherlands shows that side impact fatalities are 15–65 % of 4-wheeled vehicle occupant fatalities (Belcher 2011).

Automotive manufacturers are required to meet the safety requirements against side impacts by reinforcing the doors of passenger cars with side intrusion bars. The function of the intrusion bar is mainly to improve side crash resistance and accordingly occupant safety. Design optimization and numerical simulation of automotive side door intrusion bar have been investigated by several researchers (Kwon-Hee et al. 2004; Wu et al. 2006; Li et al. 2010; Rui et al. 2013). Bending tests have been carried out to evaluate the performance of tubes as side door intrusion bar made of different materials (Mamalis et al. 2006; Rathnaweera et al. 2012).

This paper explores and applies the biomimetic design method to the development of novel porous vehicle side door intrusion bar inspired by the structural properties of rabbit femur bone. Bones have been naturally designed through evolution to provide structural support and protection of internal organs in a living body. Femur bone is subjected to bending moments during normal loading. These create both tensile and compressive stresses in different regions of the bone, which is similar to the loads applied to side door intrusion bar during collisions. The mechanical properties related to tension and compression loading of trabecular bone were investigated by several researchers (Goldstein 1987; Niebur et al. 2000; Leuven 2003; Gibson 2005; Guillén T 2011).

This work investigates the resistance and energy absorption in three-point bending test of an aluminium beam that mimics the structure of a rabbit femur bone.

2 Finite Element Model Reconstruction of Bone Structures

A rabbit femur (cancellous) bone was analysed at the metaphyses. The bone was obtained from the local slaughterhouse. A high-resolution micro-CT scanner (μCT 35, Scanco Medical AG, Bassersdorf, Switzerland; 55 kVp, 145 mA, 400 ms integration time) with a 5 μm focal spot X-ray tube as a source was used to scan the rabbit femur bone microarchitecture. Sections of the bone were scanned in the transversal plane. After scanning, the resulting 2D images were converted into the DICOM file format.

The scanned images were imported into the software Mimics v.15.0 (*materialise*, Leuven, Belgium) for three-dimensional reconstruction (see Fig. 1). Two models were extracted from the rabbit metaphysis image (see Fig. 2). One was extracted from the distal epiphysis and the other from the femur (see Table 1). The FE models were created by directly converting the voxel into a finite element mesh of 4-node tetrahedron element.

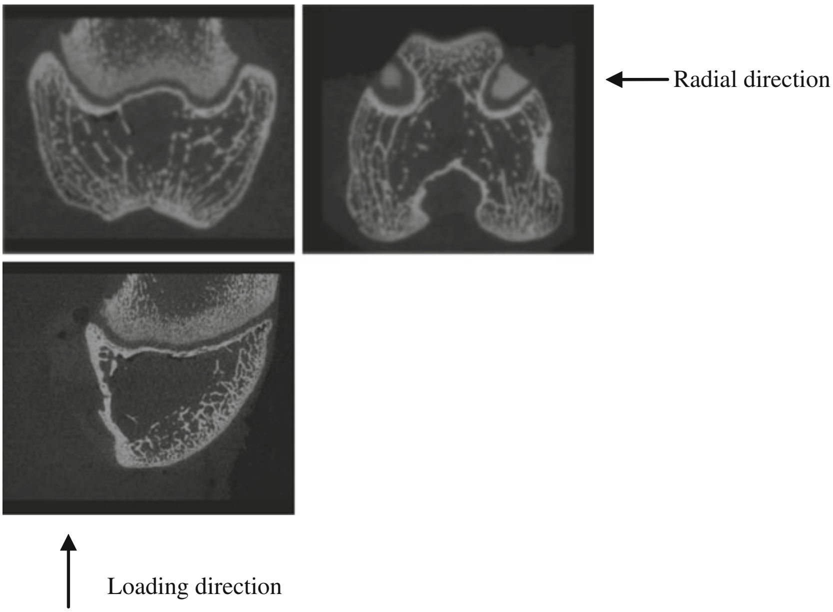


Fig. 1 Rabbit femur and distal femoral epiphysis image

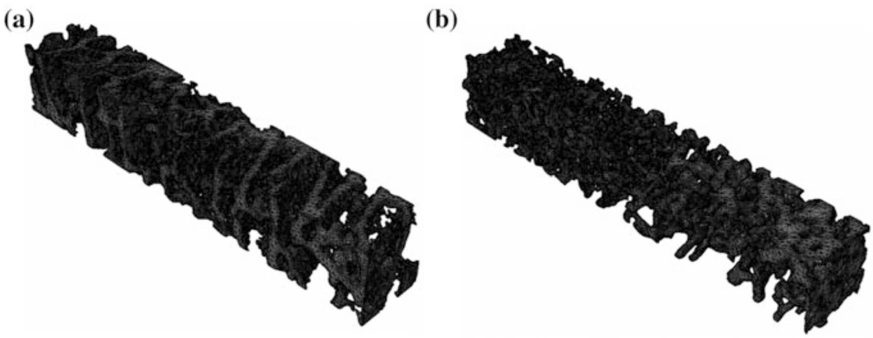


Fig. 2 Reconstructed model of **a** rabbit distal femoral epiphysis **b** rabbit femur

Table 1 Nomenclature of rabbit bone models

	Model Size (mm)	Mass (kg)
Epiphysis	1 × 1 × 6	7.58e-6
Femur	1 × 1 × 6	5.99e-6

The *Dassault Systèmes* ABAQUS software was used to simulate the three-point bending test. A rigid cylinder of diameter 1 mm was generated as the indenter. Hard contact interaction property was defined between indenter and the model. Both ends of the model were constrained in all degrees of freedoms except for displacement along longitudinal direction at the end and rotation about the lateral direction. Quasi-static indenter displacement was 1 mm. Figure 3 shows the assembled epiphysis model with rigid cylinder.

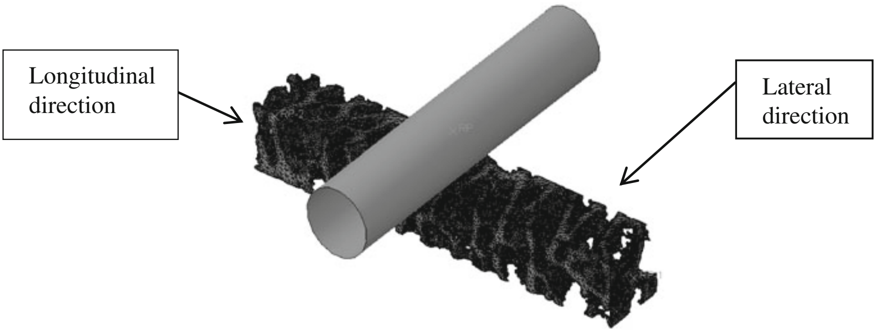


Fig. 3 Epiphysis model with *rigid cylinder assembled*

An elastic–plastic material, aluminium, with Young's modulus 68.9 GPa, density 2700 kg/m^3 and Poisson ratio 0.33 was given to the reconstructed bone model. The material plastic property was derived from the true stress–strain curve for aluminium6061 (see Fig. 4) (Groover 2008).

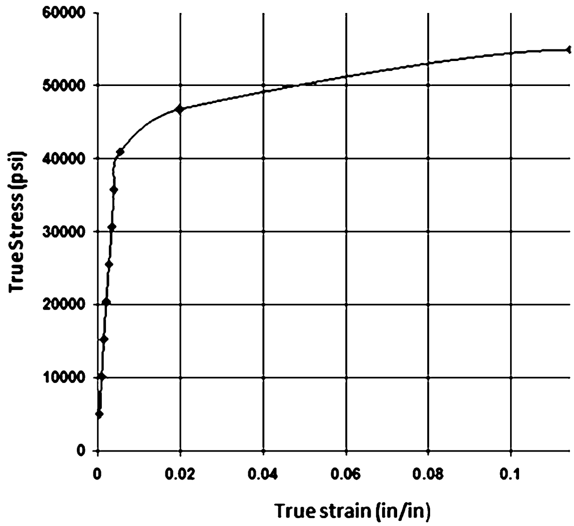


Fig. 4 True stress–strain curve of Al6061

3 Results

The energy Es absorbed by the model during the bending collapse can be calculated as

$$E_{s=\int_0^{\delta_e} F(s)ds} \tag{1}$$

where F(s) is the impact load, s is the deformation displacement, δ_e is the final displacement.

The specific energy absorption (SEA), which is defined as the energy absorption per unit mass of structural member, can be calculated by

$$SEA = \frac{E_s}{m_s} \tag{2}$$

where $m_s$is the mass of the model.

Figure 5 shows the specific energy-displacement curves of the rabbit distal femoral epiphysis and femur 1 ×1 × 6 mm models along the loading and radial directions respectively. The differences among the four curves are: (1) epiphysis structure has a higher specific energy value along both loading and radial directions than the femur structure; (2) epiphysis structure along the loading direction has a lower specific energy value than along radial direction; (3) femur structure has similar specific energy absorption ability along both loading and radial directions.

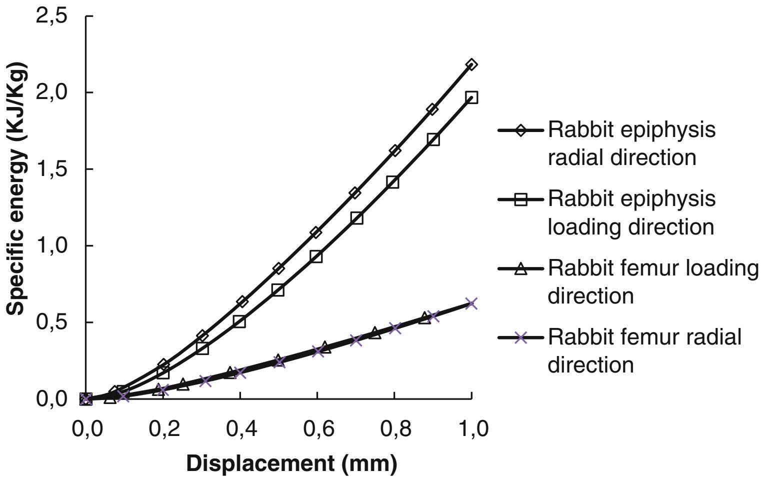


Fig. 5 Specific energy-displacement curves

Table 2 Length of displacement and energy absorbed

Models	Intrusion (mm)	Total energy absorbed (mJ)	Specific energy absorbed (KJ/Kg)
Epiphysis (loading direction)	1	14.92	1.97
Epiphysis (radial direction)	1	16.55	2.18
Femur (loading direction)	1	3.75	0.63
Femur (radial direction)	1	3.73	0.62

Specific energy in terms of the mass of all rabbit bone structural models at an intrusion of 1 mm were calculated and listed in Table 2. It shows that the specific energy absorption ability of rabbit distal femoral epiphysis structure is 3.2–3.5 times higher than rabbit femur.

Figure 6 shows the force–displacement curves of the rabbit distal femoral epiphysis and femur $1 \times 1 \times 6$ mm models along the loading and radial directions respectively. All four curves demonstrated the following key features: (1) the force first increases linearly for small displacements (elastic behaviour); (2) the force then increases slowly for larger displacement (plastic deformation); (3) the force along radial direction increases faster than along loading direction after displacement 0.5 mm.

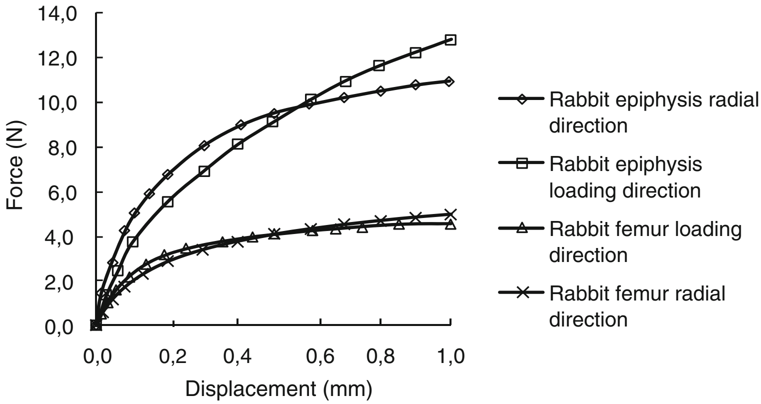


Fig. 6 Force-displacement curves

The differences for the four curves are: (1) epiphysis structure resists higher forces than the femur structure along both directions; (2) force resists difference for epiphysis structure between the loading and radial directions is bigger than femur structure.

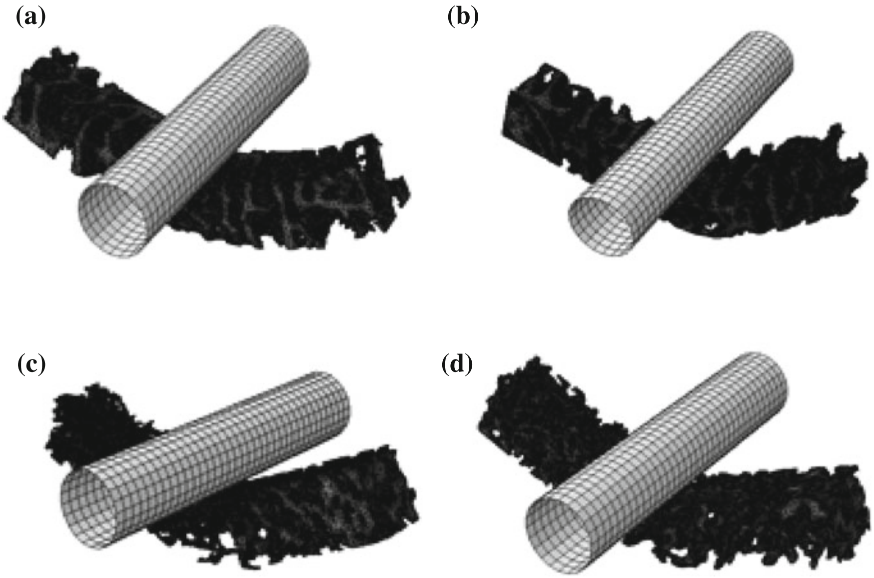


Fig. 7 Deformed shapes of rabbit models. **a** Epiphysis loading direction. **b** Epiphysis radial direction. **c** Femur loading direction. **d** Femur radial direction

Figure 7 shows the deformed shapes of the epiphysis and femur structural models along loading (z direction) and radial directions (y direction). It can be seen that the stress concentration occurred under the indenter and the areas that the thin cell walls are.

4 Conclusions

In this research, a biomimetic design approach for the development of a novel porous vehicle side intrusion bar was studied. Force resistance and energy absorption of these two types of structures made from aluminium and subjected to quasi-static 3-point bending were investigated and analysed using the Finite Element Method (FEM).

- Rabbit distal femoral epiphysis structure can absorb more energy per unit mass along both loading and radial directions than the rabbit femur structure.
- Rabbit distal femoral epiphysis structure has higher force resistance ability than the femur structure along both directions.

Through this research, a lightweight structure with good energy absorption ability was studied, which mimics the porous structure of the rabbit femur metaphysis. Lightweight structures developed this way are expected to increase stiffness at a significantly reduced weight. The new structure can be applied not only in automotive industry, but also in other areas, such as aerospace, shipbuilding etc. This biomimetic design approach can be generally used to develop novel load bearing lightweight structures inspired by the structural properties of animal bones.

References

Belcher T (2011) Pole side impact GTR: assessment of safety need: updated data collection. Australian Government Department of Infrastructure and Transport. Brussels, Belgium

Gibson LJ (2005) Biomechanics of cellular solids. J Biomech 38(3):377–399

Gibson T et al (2001) Improved side impact protection: a preview of injury patterens injury tolerance and dummy measurement capabilities. Monash University, Melbourne

Goldstein SA (1987) The mechanical properties of trabecular bone: dependence on anatomic location and function. Biomechanics 20:1055–1061

Groover MP (2008) Foundamentals of morden manufacturing: materials, processes and systems. Hoboken, USA

Guillén TZQ, Tozzi G, Ohrndorf A, Christ HJ, Tong J (2011) Compressive behaviour of bovine cancellous bone and bone analogous materials, microCT characterisation and FE analysis. J Mech Behav Biomed Mater 4(7):1452–1461

Kwon-Hee L et al (2004) Optimization of an automotive side door beam, considering static requirement. Proc Inst Mech Eng Pt D J Automobile Eng 218:51–57

Leuven KU (2003) Mechanical properties of bone. ICB, Dent

Li QF et al (2010) Optimum design and numerical simulation of automotive front side-door impact beam. Key Eng Mater 452–453:169–172

Mamalis AG et al (2006) Bending of cylindrical steel tubes: numerical modelling. Int J Crashworthiness 11(1):37–47

Niebur GL et al (2000) High-resolution finite element models with tissue strength asymmetry accurately predict failure of trabecular bone. J Biomech 33(12):1575–1583

Rathnaweera G et al (2012) Performance of advanced high strength steel and aluminium alloy tubes in three-point bending

Rui Y et al (2013) Biomimetic design of lightweight vehicle structures based on animal bone properties. Adv Mater Res 633:3–14

Wu C-H et al (2006) Optimization of side impact bar for crashworthiness. In: SAE World Congress & Exhibition, 2006

Structural Composite Elements with Special Behaviour

H. Bansemir

Abstract The properties of composites allow outstanding new designs with unknown features. Composite structures with fibre reinforced elements are widely used in the design of aerospace structures. In 1967, the BO 105, a product of the former helicopter division of MBB, now Eurocopter Deutschland GmbH, flew for the first time. This innovative helicopter was equipped with the first serial "hinge- less" rotor system. The fibre composite blades were attached to the head with the help of the "lug" element. This made possible the simple design of the rotor without damper elements. The shear stiffness is very low for unidirectional composites. In the metal world the shear modulus G is high and linked to the Young's modulus and the Poisson's ratio by the formula $G = E/2(1 + \upsilon)$. The low shear stiffness of composites allowed the "Flexbeam design" of the EC 135 with a "bearingless" and "hingeless" concept. The shear modulus G and as a consequence the torsional stiffness are the important features of this paper, they allow the given different design concepts. The mechanical behaviour of composite materials allows the design of outstanding basic structural elements such as plates and shells having a high range of different stiffnesses, in plane and out of plane. These elements are often used for the attachment of vibration absorbing structures. In this paper several applications of anisotropic structures are described and possible use is shown.

1 Introduction

The outstanding behaviour of fibre composites allows new designs with flexible elements avoiding dynamically loaded metal components. The early developments in the 60s at MBB show an intensive use of composites in the design of the

H. Bansemir (✉)
Consulting for Composites, Light Weight Structures and Knowledge Management, Geitnerweg 4, 81825 Munich, Germany
e-mail: horst@bansemir.eu

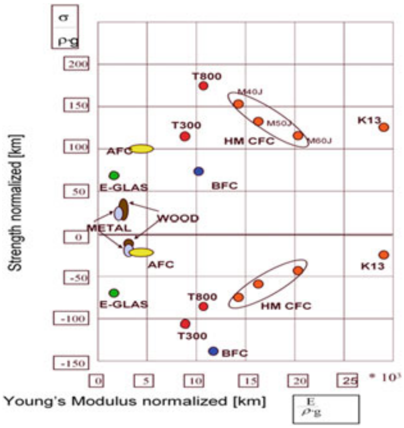
J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_6,

dynamic rotor system. The "hingeless" rotor system of the BO 105 eliminated the metallic flapping and lead-lag hinges (Bansemir 2011a). The attachment of the composite blade to the rotor head with the help of one simple lug fastened to a titanium structure allowed the transfer of the loads. The damping behaviour of this load introduction element was such that no additional damper was necessary for the dynamic lead-lag motion. This rotor system is also used in the design of the BK 117 and the EC 145 helicopters. Another rotor system was used in the design of the French-German military helicopter "Tiger" and the Indian "Advanced Light Helicopter (ALH)". The ALH was built with German Assistance. The main rotor systems use "Elastomeric Bearings" replacing conventional roller bearings mainly for the torsional motion (Bansemir 2011b). The design of the EC 135 is a "bearingless" rotor system including a "Flexbeam" with a special cross section for the torsion element. Thus the torsional ball bearings in the rotor head were eliminated saving about 70 kg weight.

The tail rotor system of the ALH is an outstanding four bladed "Flexbeam Rotor" with an elastomeric bearing for the support of the cuff, seen in Fig. 4. The vibrations of the airframe of the helicopter are reduced with special elements. A six degree of freedom "Anti Resonance Isolation System" (ARIS) is used in the ALH transport helicopter. In Fig. 3 the attachment of the rotor to the fuselage is shown with the ARIS and the schematic unit arrangement, the resonator and the flexible composite spring element (Bansemir 2011b). Several concepts for future rotor designs with elastic low flapping hinge offsets are shown in Fig. 6. In Fig. 7 "Gimbal Rotor" concept can be seen with a flexible plate membrane (Bansemir 1999). The soft elastic out of plane behaviour, together with the stiff in plane behaviour can be used for several spring elements.

2 Material Properties of Unidirectional Composites

Composites are mainly used for the design of light weight structures. The main benefit of using composites is the variety of design possibilities. In Fig. 1 on the left hand side the normalized strength and stiffness of unidirectional composites (60 % fibre volume content) divided by the specific weight factor is shown (Bansemir 2011a). The values indicate high strength and stiffness compared to the data of metals and wood. In the table on the right hand side strength, stiffness and other physical constants are given. The tension strength of the different composites is in the same range, whereas the compressive strength decreases when the stiffness is increased. The transverse stiffnesses (Young's modulus perpendicular to the fibre direction and shear modulus) are dominated by the resin properties. The shear modulus is independent from the fibre longitudinal properties. For metals the shear modulus is equal to $G = E/2(1 + \upsilon)$ with $E =$ Young's modulus and $\upsilon =$ Poisson's ratio. The result is a low value for the shear modulus for composites compared to a high value for metals, calculated by the given formula (e.g. for Aluminium the shear modulus is 27,000 N/mm^2. For unidirectional composites the value for the shear modulus is about 5,000 N/mm^2). The longitudinal Young's moduli E of the unidirectional materials vary from a value lower than Aluminium to more than twice the value of steel. The thermal expansion coefficients and the thermal conductivities of the composites also differ from those of the metals (Schürmann 2004).



Fiber type	S2-Glass	T300	M55J	K13
	Properties of unidirectional composites			
$E_{\parallel}$ N/mm²	54000	133000	300000	500000
$E_{\perp}$ N/mm²	14000	10800	6400	5700
$G_{\#}$ N/mm²	5400	5700	3900	3500
$\sigma_{\parallel Zug}$ N/mm²	1690	1610	1860	2100
$\sigma_{\parallel Druck}$ N/mm²	1220	1810	835	410
$\alpha_{T\parallel}$ E-6 1/K	6,5	0,4	-0,7	-1,4
$\alpha_{T\perp}$ E-6 1/K	35,8	42	35,2	32,2
$\lambda_{T\parallel}$ W/Kcm (293K)	0.01	0.05	0.544	8
$\lambda_{T\parallel}$ W/Kcm (4K)	0.002	0.0003		

Fig. 1 Properties of unidirectional fibre composites with 60 % Vol (Bansemir 2011a)

3 The Transport Helicopter "Advanced Light Helicopter " with the Anti-Resonance Isolation System

The Indian transport helicopter was designed with a complicate vibration isolation system. It includes spring systems and resonators for connecting the rotor system to the fuselage structure. The shown composite plate spring (right side of Fig. 2) is soft in the out of plane direction and stiff in the in plane direction (Figs. 2 and 3). The resonators are connected to the main gearbox and to the fuselage, they should contra-act the vibrations of the rotor. In flight, the resonator vibrations are in correlation with the rotor vibrations. Eight spring elements provide the right stiffness of the resonator. Four ARIS resonators including four masses provide the complete ARIS System (Bansemir 2011b).

The goal of the ARIS system is to provide a high comfort standard for the passengers.

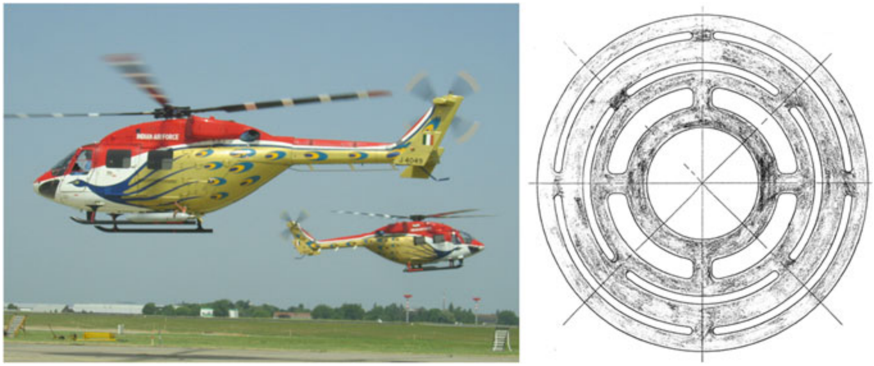


Fig. 2 The Indian multipurpose helicopter Dhruv with the composite spring element

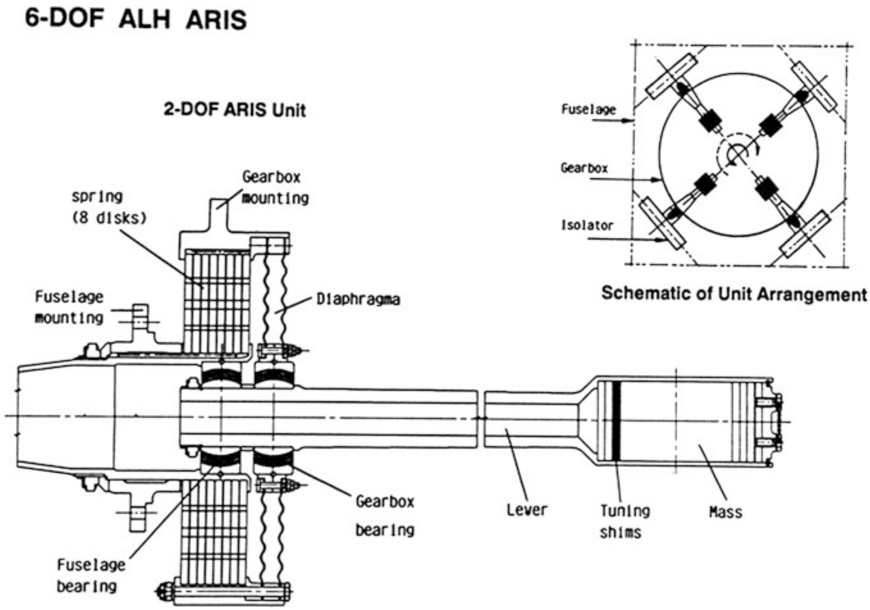


Fig. 3 The resonator of the "Anti-Resonance Isolation System" of the indian multipurpose helicopter

4 The Bearingless Tail Rotor of the ALH Transport Helicopter

As can be seen in Figs. 4 and 5 the carbon composite cuff provides the pitch angles to the blade. But the cuff is connected and supported to the blade glass fibre composite spar with elastomeric bearings or flexible composite support structures.

These structural elements again are soft in out of plane direction and stiff in plate direction. The low torsional stiffness provides the out of plane flexibility (Bansemir 2001).

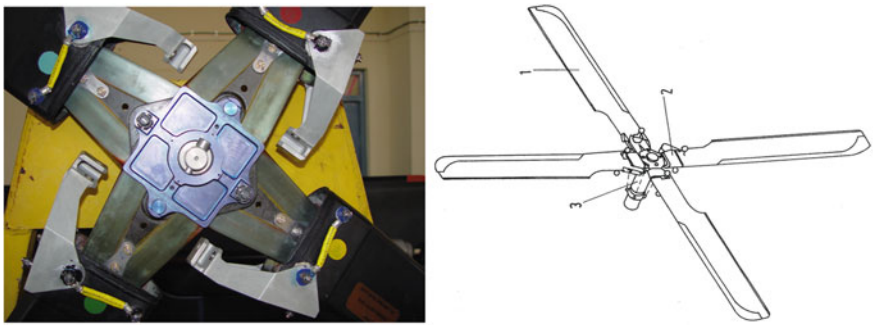


Fig. 4 The tail rotor of the indian multipurpose ALH helicopter system (Bansemir 2001)

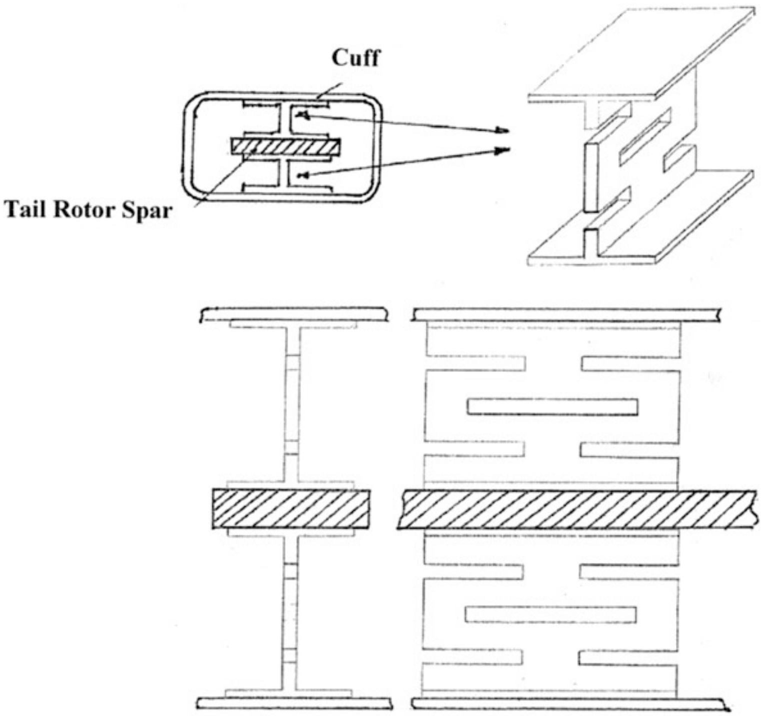


Fig. 5 The flexible composite support of the tail rotor of the Indian ALH helicopter system

5 The Flexible Composite Main Rotors "Flex Beam" and "Flex Plate"

The torsional flexibility can be used for the design of future rotor systems such as shown in the Fig. 6 (left). The four main spars of the "Flex Beam" concept are connected with the help of two torsion elastic beams to four hold down points. The result is a flexibility in flapping direction. The spars can be connected to an inner ring in order to provide some specially defined additional stiffness (Bansemir 1998, Bansemir and Bongers 1999).

On the right hand side of Fig. 6 a sketch of the "Flex Plate" system is shown. The outer ring of the design is fastened to four hold down points. The design provides some flapping flexibility. The pitch of the blade is provided by a special element connected to the blade (Fig. 6).

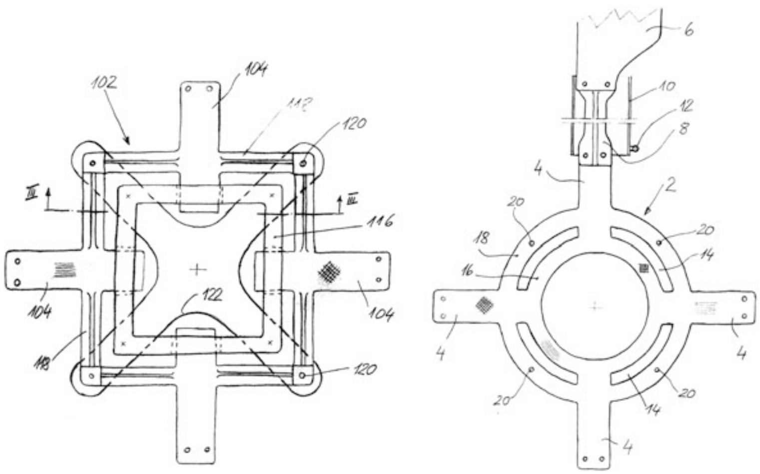


Fig. 6 The flexible composite main rotors "Flex Beam" and "Flex Plate" system (Bansemir 1998)

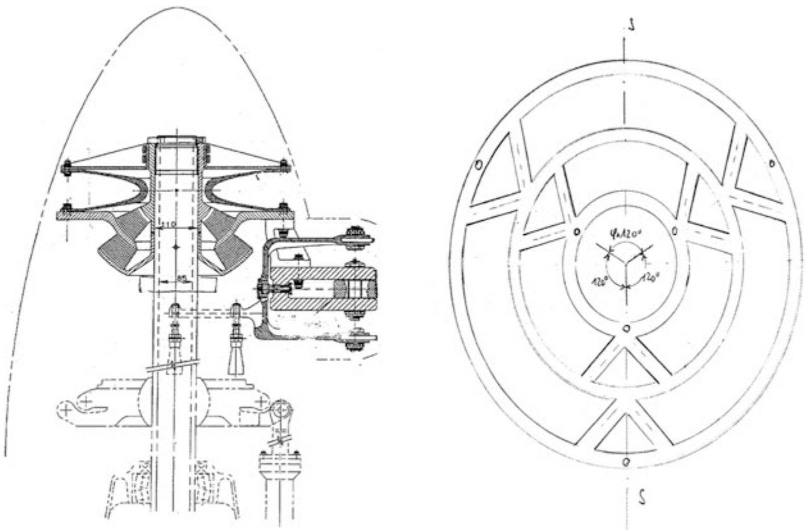


Fig. 7 The “Gimbal Rotor” with a flexible composite membrane (Bansemir 1999)

6 The “Gimbal Rotor” with a Flexible Composite Membrane

The “Gimbal Rotor” is often used for helicopters allowing the stiff rotor to move on a rotor mast. A soft out of plane membrane and the bearings are the connections between the rotor and the mast. The left figure shows a concave membrane with elastomer bearings. The membrane in the right figure provides the flapping flexibility. The connecting beams of the membrane are positioned such that a “homokinetic hinge” is generated.

7 Flexible Composite Membrane Springs of Vibration Resonators

As shown in Fig. 8 resonators are shown with plate shaped composite springs. The configurations allow a positioning of the resonators in complicate structured cabins. With a special piezoelectric arrangement an adaptive resonator design can be the result (Bansemir 2004).

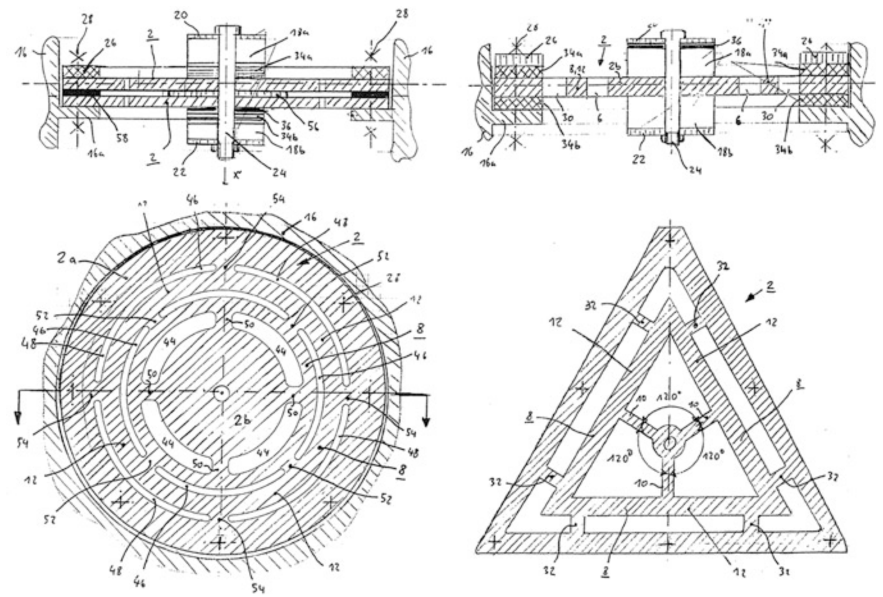


Fig. 8 Flexible composite membrane springs of vibration absorbers (Bansemir 2004)

8 Flexible Composite Elements for the Attachment of Flaps to Wing Structures

The attachment of small flap structures is often performed with metallic ball bearings or metallic elements. These are susceptible to corrosion and as a consequence to fatigue. Composite small structural element can provide high cycle dynamic deflections and torsional angles (Fig. 9).

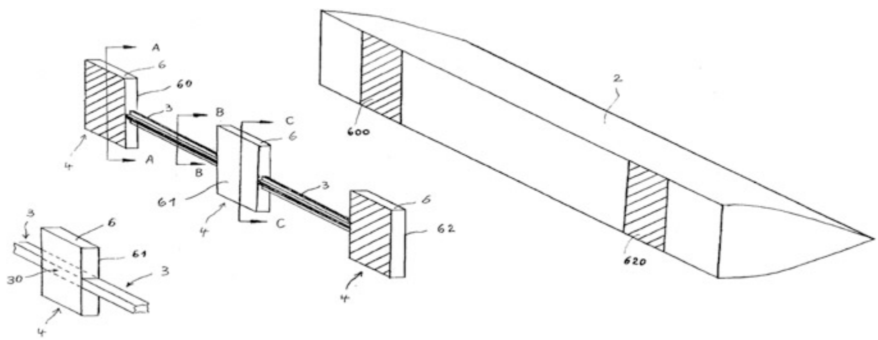


Fig. 9 Flexible composite blade attachment system (Bansemir and Klöppel 1999)

9 Flexible Composite Bearingless Seat Hinge Systems

Car seats usually have a high weight, often because a high amount of metallic bearings and local elements is used. Flexible fibre-composites can be used to insure the flexibility of car seats in several directions. In Fig. 10 a hinge seat system is shown. The out of plane flexibility is reached in Fig. 10 due to the structural longitudinal beams loaded in torsion due to the connecting arms (Bansemir and Vullriede 1999).

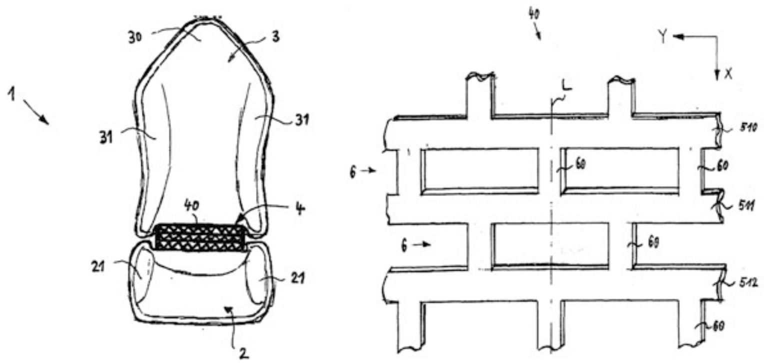


Fig. 10 Flexible composite bearingless seat hinge system (Bansemir and Vullriede 1999)

10 Conclusion

The outstanding mechanical behaviour of fibre-composites allows the design of special structural light weight concepts which could not be realized with metal materials. In this paper the low shear modulus of the unidirectional fibre composite is used for the design of an important structure like the “Flex Beam” rotor of the multipurpose helicopter EC 135. Other special concepts are shown, like the cuff bearing of the Indian helicopter “Dhruv”, plate spring elements of the Anti Resonance Isolation System (ARIS) of the same helicopter, future Rotor concepts, plate resonators, wing bearings and flexible car seats.

Future design concepts could use other outstanding features like the thermal conductivity and the thermal expansion. The value for the thermal conductivity of the carbon composite K13 is much higher than the value for metallic copper. Furthermore outstanding possibilities of designing with composites will allow us to integrate electrical elements into the structures to improve their abilities.

References

Bansemir H (2011a) Design of basic structural composite elements. In: ICSAT2011, Greenville

Bansemir H (2011b) Querelastische Feder- und Sandwichkomponenten als Grundelemente verschiedener Bauweisen, Technisch-wissenschaftliches Seminar: Hochleistungsstrukturen im Leichtbau in Luft- u. Raumfahrt, Fahrzeugen, Sonderkonstruktionen, Themenschwerpunkt im Herbst 2011, 23. Nov. (TU München): Leichtbau in frühen Konzeptphasen

Bansemir H (1999) Kupplungsmembran. Patentschrift DE 19961071 B4, Date of registration: 17 Dec 1999

Bansemir H (2001) Spring component and support Bearing for helicopter Tail Rotors and support structure for use in Outer Space. Patent Nr. US 6305640 B1, Date of Patent: 23 Oct 2001

Bansemir H (1998) Mehrblattrotor für ein Drehflügelflugzeug. Patentschrift DE 19701403 C 1, Date of publication: 26 Feb 1998

Bansemir H (2004) Mechanischer resonator. Patentschrift DE 10 2004 001 470 B4 2005.11.03, Date of registration: 8 Jan 2004

Bansemir H, Vullriede S (1999) Einteiliger Schalensitz in Leicht-bauweise. Patentschrift DE 19961070 C1, Date of registration: 17 Dec 1999

Bansemir H, Klöppel V (1999) Verbindungsmittel zum Verbinden einer beweglichen Klappe mit einem Flügel eines Luftfahrzeuges. Offenlegungsschrift DE 19909257 A1, Date of registration: 3 Mar 1999

Bansemir H, Bongers B (1999) Schwingungstilger für einen Hubschrauber und Verwendung einer Batterie als Masse eines Schwingungstilgers. Patentschrift DE 18748707 C 1, Date of registration: 21 Jan 1999

Schürmann H (2004) Konstruieren mit Faser-Kunststoff-Verbunden. Heidelberg, New York, ISBN 3-540-40283-7

Patents of Nature

T. Brodbeck

Abstract Innovations are constantly in demand, not only in engineering. Nature's living organisms also have to prove themselves again and again. Over the course of millions of years, they have continuously developed new strategies, materials and techniques to prevail against their competitors. So why shouldn't engineers draw their inspiration from nature? No matter if on land, in the water, or in the air: Nature's patents work brilliantly, there is no copyright, and they hod endless surprises. There are many cases where engineering is already inspired by nature today: 1. Self-cleaning surfaces designed following the example of lotus leaves; 2. Drag-reducing surfaces designed on the model of sharks' dermal denticles; 3. Lightweight rims designed like diatoms; 4. Mussel glue as an ideal adhesive; 5. The atomic adhesion of geckos; 6. Nacre (mother of pearl) as an ideal composite material; 7. Spider silk is superior to the best high-tech materials; 8. Lignin as an alternative to plastics; 9. Self-sharpening knives following the basic patent of beaver teeth.

1 Lotus Leaves as a Model for Self-Cleaning Surfaces

It was an unwritten dogma in engineering: The smoother a surface, the easier it is to keep it clean and the easier it is to clean it. However, biologist Wilhelm Barthlott observed that a couple of rain drops were enough to rinse off any dirt from lotus leaves. Not even the tiniest dust particle could hang on to the leaves. When examining the leave surface, he discovered that lotus leaves are microstructured. Due to tiny papillae, which also have hydrophobic qualities, bacteria,

T. Brodbeck (✉)
Mainzer Str. 165, 55743 Idar-Oberstein, Germany
e-mail: thbrodbeck@aol.com

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_7,

fungi, and algae cannot cling to the leaves. By now, there are numerous patents that are based on this lotus effect: From facade paint shining like new after every rain shower, to self-cleaning clothing and the protection glasses of road toll cameras which no longer have to be cleaned.

2 Shark Scales

2.1 As a Model for Drag-Reducing Surfaces

Biologist Prof. Wolf-Ernst Reiff proved another engineering law to be wrong. Engineers previously thought that the smoother a surface, the more low-drag. However, fast swimming sharks have rough scales. Due to microscopic grooves in the shark scales, fewer vortices occur, ideally decreasing the drag by up to 15 %. The Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM is currently developing low-drag surfaces via innovative lacquer systems, namely sharkskin effect for large structures! (Bechert et al. 1997).

2.2 As a Model for Innovative Anti-Fouling Coatings

Fouling, i.e. the growth of bacteria, algae, and mussels, is a huge problem in shipping—both commercially and ecologically. Due to the fouling growth, the ship's weight and therefore its drag are increased. Subsequently, the ships are slower, consume more fuel, and cause more CO_2 to be released into the atmosphere. Up until a few years ago, highly toxic ship coatings were used as anti-fouling measure. However, these are banned globally by now.

Bionic scientist Prof. Antonia Kesel noticed, though, that sharks are not affected by algae and barnacles. Based on her research and together with a lacquer manufacturer, she developed an anti-fouling coating on the model of sharkskin (Liedert et al. 2007).

3 Diatoms as a Model for Sturdy Rims

When building their shells, diatoms have to find the right balance between a construction that is as light as possible yet highly sturdy. Many engineers have the exact same problem. Biologist Dr. Christian Hamm from the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven transfers the diatoms' construction principles for light yet sturdy structures to technical applications. The reasons for lightweight design solutions are the same in technology and nature.

In both cases the aim is to save expensive materials or to reduce the weight, or both. The first rims based on the model of the tiny diatoms exist already. These rims ensure better road holding due to increased stability. Furthermore, they are significantly lighter (Hamm 2006).

4 Mussel Glue as an Ideal Adhesive

The future belongs to gluing. Modern composite materials do not like it when you drill holes into them, and you cannot weld them. This only leaves gluing. There are many advantages, though: An adhesive connection is lighter, more stable and more flexible—IF you have the right adhesive. But using an adhesive connection can still be treacherous: The surface has to be extremely clean and cannot be tainted with fat, dirt, humidity or even silicone residues. In addition, the glue should be non-toxic. Nature, on the other hand, solved a lot of the problems millions of years ago: Mytilus mussels use their byssus threads to attach themselves under water, near freezing point, and to any surface even if it is very dirty—and even Teflon—without fail! Amazingly, the bio-adhesive they use is also non-toxic and completely recyclable.

The research group headed by Aránzazu del Campo from the Max Planck Institute for Polymer Research in Mainz drew their inspiration from this mussel glue. They developed a new class of adhesives which are water-resistant, self-healing, reacting with surfaces, degradable under light and also bio-compatible (Arzt 2006).

5 The Atomic Adhesion of Geckos

For a long time, it was a mystery why geckos can climb up on glass walls or walk on ceilings. Only in the last few years, using state-of-the-art analysis methods, the patent of geckos' adhesion forces could be solved: The animals use atomic forces to cling to the surface. With nano-fine structures on their feet, the geckos establish a very close contact to the surface they walk on. Geckos do not use suction cups to cling onto surfaces as smooth as a mirror, they use countless tiny hairs on their feet. The so-called van der Waals forces make this possible. Individually, these "dispersion interaction forces" are rather weak, though; that is why the gecko has millions of tiny hairs in each foot, which together generate enough power to carry him. Nowadays, scientists are able to mimic the principle and to develop surfaces which are better than the adhesive qualities of nature's model by a dozen times (Schreiner et al. 2011).

6 Nacre as an Ideal Composite Material

Nacre is an ideal composite material: light, unbreakable, and heat-resistant. In addition, it looks nice and over 90 % of it consists of a material which is available almost unlimitedly: Calcium carbonate, i.e. chalk. But how does the mussel build such a resistant material from soft chalk?

It was the research group around Dr. Dirk Volkmer, Chair of Solid State and Material Chemistry at the University of Augsburg, who finally solved this mystery. Crucial for the process is "liquid chalk", i.e. Calcium carbonate which is prevented from crystallizing. This discovery brings us a step closer to developing new materials which possess the same desired characteristics as nacre.

Potential applications range from corrosion-resistant coatings to scratch-proof car paints and lightweight design materials to innovative bone substitutes (Evans et al. 2001; Menig et al. 1999).

7 Spider Silk as High-Tech Material

With over 25,000 kg/cm^2, the tensile strength of the golden orb-web spider's dragline is three times the strength of Kevlar fibres and at least five times the strength of steel. Some gossamer is twice as elastic as nylon and can be tripled in length. That is why these high-performance fibres from nature could be applied in many areas of technology and industry. The start-up company Amsilk, based in Munich and headed by Thomas Scheibel, succeeded where various major corporations failed in spite of decades of research: They manufactured artificial spider silk (Slotta et al. 2011).

8 Lignin as an Alternative to Plastics

Petroleum as raw material for plastic is getting scarcer and more expensive. Therefore, it is time to look for alternatives. Preferably right there in nature. Wood as composite material mainly consists of cellulose and lignin, which, after cellulose, is the second most common polymer in nature. Lignin is a by-product of the pulp industry, amounting to approx. 50 million tons per year globally. Up until now, lignin, accumulating during paper manufacturing, was considered waste and burnt. However, the small innovative company Tecnaro succeeded in merging lignin with natural fibres (flax, hemp or other fibre plants). Thus receiving a fibre-reinforced plastic which is workable upon heating and which can be processed, just like synthetically manufactured thermoplastic, to mouldings, panels or plates, using conventional polymer processing machines. By now, there are steering wheels made of this natural—or artificial?—Wood, but also musical instruments, jewellery and toys.

9 Self-Sharpening Knives Following the Basic Patent of Beaver Teeth

The industry still works mainly by milling, filing or cutting parts off of big objects. In order to do this you need knives. And knives get blunt. This is a serious problem as it causes idle times, rejects, and material costs. In nature, however, there are ever-sharp cutting tools like the teeth of beavers or rats. Their teeth consist of two materials—the smoother dentin and a layer of extremely hard enamel—the hardest substance known in biology. These two substances vary in how strongly they wear off, thus keeping an ever-sharp bite edge.

For a few years now, there have been industrial knives following the model of rodent teeth. And for a few weeks, there now has been a knife for domestic use: Fissler's bionic knife has two degrees of hardness and its sharpness is based on the same principle: One side of the blade has a special patented, ultra-hard coating which makes the front of the blade nearly as hard as a diamond. During daily use, steel and coating behave like the beaver teeth's dentin and enamel. Resharpening of the bionic knives is not necessary. The difference in how strongly the two sides of the blade wear off makes the bionic knives not only sharp but ever-sharp (Berling et al. 2007).

10 Conclusion/Summary

The examples mentioned above are only a fragment of the wide, almost immeasurable repertoire of nature's patents. Engineers develop interference colours modelled on the bright example of butterflies. A desert lizard inspires extremely low-friction and wear-resistant surfaces. Engineers optimize components by copying the growth of trees and the principles of evolution. And new air foils are still developed by studying the flight of birds. For over hundreds of millions of years evolution has developed organisms that adapt perfectly to survival conditions. This means nature's patent office is a real treasure trove for engineers and scientists who, during their work, are looking for new, innovative, unconventional but still practical solutions. You are all invited to get inspired by nature's example.

References

Arzt E (2006) Biological and artificial attachment devices: lessons for materials scientist from flies and geckos. Mater Sci Eng C 26(8):1245–1250

Bechert DW, Bruse M, Hage W, Meyer R (1997) Biological surfaces and their technological application—laboratory and flight experiments on drag reduction and separation control. In: Paper # AIAA-1997–1960, presented at AIAA 28th fluid dynamics conference, Snowmass Village, Colorado

Berling J, Rechberger M (2007) Knives as sharp as rat's teeth. In: Research News 1. Fraunhofer Institute for Environmental, Safety and Energy Technology, Oberusel

Evans AG, Suo Z, Wang RZ, Aksay IA, He MY, Hutchinson JW (2001) Model for the robust mechanical behavior of nacre. J Mater Res 16:2475

Hamm C (2006) Das Leben im Plankton: Überleben durch Leichtbaustrukturen. In: Blüchel KG, Malik F (eds) Faszination Bionik: Die Intelligenz der Schöpfung

Liedert R, Kesel AB (2007) Giftfreies Antifouling nach biologischem Vorbild. In: Kesel AB, Zehren D (eds) Bionik: Patente aus der Natur, Bionik-Innovations-Centrum, pp 99–106, Bremen

Menig R, Meyers MH, Meyers MA, Vecchio KS (1999) Quasi-static and dynamic mechanical response of Haliotis Rufescens (Abalone shells). Acta mater, pp 2383–2398

Schreiner PR, Chernish LV, Gunchenko PA, Tikhonchuk EY et al (2011) Overcoming lability of extremely long alkane carbon–carbon bonds through dispersion forces. Nature, pp 308–311

Slotta U, Spieß K, Scheibel T (2011) Spider Silk In: Jarvis SP Mostaert AS (eds) The functional fold. Useful amyloid structures in Nature, pp 73–90. Pan Stanford Publishing, Singapore

Structural Health Monitoring for Carbon Fiber Resin Composite Car Body Structures

S. Herrmann, J. Wellnitz, S. Jahn and S. Leonhardt

Abstract Structural Health Monitoring (SHM) is an emerging field of research in the area of lightweight design. The introduction of expensive carbon fiber resin plastic materials in the automotive industry may in the future justify the application of a monitoring of the load bearing structure via sensors to save weight and costs. Reasons for this additionally lie in the brittle and complex failure behavior of carbon fiber materials. The authors in this paper aim to give an introduction into the principle of Structural Health Monitoring (SHM), basics of fatigue of fiber resin composite materials as well as the possible application of these principles for the automotive industry. In addition to this an SHM concept and further results of the experimental research work since October 2011 are depicted. The investigations and experiments leading to this paper have been supported by Honda R&D Europe (Deutschland) GmbH with a research grant.

1 Introduction

Close research regarding to Load Monitoring or Structural Health Monitoring (SHM) shows that in the automotive area little public domain research projects are yet existing. The aim of this paper is to give a brief introduction into the world of

S. Herrmann (✉) · J. Wellnitz
Technische Hochschule Ingolstadt, Esplanade 10, 85049 Ingolstadt, Germany
e-mail: stefan.herrmann@thi.de

J. Wellnitz
e-mail: joerg.wellnitz@thi.de

S. Jahn · S. Leonhardt
Honda R&D Europe (Deutschland) GmbH, Carl-Legien-Str. 30, 63073 Offenbach, Germany
e-mail: steffen_jahn@de.hrdeu.com

S. Leonhardt
e-mail: sven_leonhardt@de.hrdeu.com

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_8,

Structural Health Monitoring and the fatigue behavior of fiber resin composite materials, regarding to possible demands of the automotive industry. In addition we will give an overview about the results of the research work concerning Structural Health Monitoring at the Technische Hochschule Ingolstadt (THI) since October 2011. THI is visible in the academic field by applied science and its research in applications for SHM systems. We integrated our activities concerning SHM into the focus point “vehicle mechatronics”. By our tradition we have a strong connection to the local aircraft and automotive industry. The investigations and experiments leading to this paper have been supported by Honda R&D Europe (Deutschland) GmbH with a research grant.

Still a main challenge is the combination of knowledge of SHM systems and composite fatigue life prediction at the same time. Our focus in the area of composite design lies on the calculation of the material and development of fatigue life prediction methods. Interesting for the scientific community is the layer specific measurement of the occurring multi-axial loads and stress states on anisotropic fiber resin composites. In the aircraft industry several experimental research programs have been conducted in this regard, but most of them concerning a different focus. Focus has been placed on design allowables and not on in situ monitoring and judgment of events that have occurred during the usage of the part. Data has been evaluated offline by post processing. Aircraft industry designs its composite laminates guidelines for Compression After Impact (CAI) and First Ply Failure. Composite laminates are in these cases not even close to their effective life expectancy, because of their slow and predictable crack growth. For parts that are not subject to foreign object damage most applied safety margins can be judged as exaggerated.

1.1 Introduction to Structural Health Monitoring (SHM)

The term Structural Health Monitoring (SHM) describes the usage of sensors and actors to gain information about the life status of a technical structure or the materials it is made of. Every technical structure is subject to applied loads, material degradation and fatigue, adverse environmental conditions or misuse loads. All of the aforementioned activities have an impact on the health state of the structure and may also determine its remaining durability and the safe life of operation. The original idea of SHM is based on bionic principles, as most natural structures are able to sense applied loads and operational conditions. As well natural structures, such as bones, are also able to react to applied loads. Following this SHM is a technique for the in situ evaluation of a technical structure and a topic closely related to the emerging field of adaptronics. Further connections are given to the topic of Non-Destructive-Testing of materials and structures. We classify three steps of complexity in SHM between

- Operation or usage monitoring,
- Load monitoring and
- Structural Health Monitoring.

Goal of SHM is the collection and processing of measurement values that are able to describe these damaging phenomena and to make conclusions about their significance for the mechanical state of a structure or part. All of this is conducted during the operation and without destroying the structure. SHM is a nowadays emerging design technology and it is by its heritage used in the field of engineering. Typical applications of SHM are structures like:

- bridges,
- buildings,
- railroad tracks,
- pipelines,
- wind turbines and
- aircrafts.

In these examples SHM is applied for the purpose of guaranteeing the safe operation of the structure. In the special cases of aircrafts and wind turbines it is also used for an extension of the operational life or lightweight design. So far SHM has rarely been shown for automotive applications, such as for body-in-white structures. Here we see a big potential of this emerging technology. For more detailed introductory information into the topic of SHM the reader may review (Balageas et al. 2006; Adams 2007; Farrar 2007).

1.2 Need for SHM in the Automotive Industry

The use of composite materials is increasing inside the automotive industry. Yet a use of composites in the main loaded structural parts of the body-in-white is still rare, especially in larger production scale vehicles. A noteworthy exception are BMW's i3 and i8 vehicles as well as the Alfa Romeo 4C, which are using CFRP monocoques using thermoset resin systems. Reasons for this rare application lie in the available manufacturing methods, cost structures, carbon fiber supply, structural integrity after crash, repair, insurance, acoustics, impact behavior and the difficult prediction of the lifetime properties of the composite part and its joining technology.

Composite materials show completely different failure modes in comparison to metals, due to the material anisotropy and the different constituent parts. The part design has to make allowance for this, which often results in oversizing of the respective components. Composite materials are rarely used at the full level of their capabilities and a material degradation during the life expectancy of the part is not accepted. Reason for this is to guarantee the safety of the user under all relevant circumstances, such as heavy duty usage or misuse events. In common structures this is dealt with by adding unnecessary material and weight. When the user decommissions a car with a traditional steel or aluminum body, the body-in-white structure shows no mentionable signs of degradation. This paradigm may be set into question in the future: why cannot an automotive body be subject to cracks and material degradation? In the ideal lightweight automotive design all parts of the automobile will fail at the same time after their desired life expectancy. The change of this existing paradigm can open new lightweight design horizons and to reach this a constant monitoring of the structural state is necessary.

The idea of using strain gauges, Fiber-Bragg-sensors or piezoelectric elements to monitor the health status of a load carrying structural part is not all new. Nevertheless the idea of using these data in an algorithm in situ and classifying them for prediction of the remaining fatigue life of a composite structure is new. We call this a combination of event- and condition-monitoring. This has not been shown in detail, particularly not in the context of body structures in the automotive industry. A use of the strain and stress data is given in delivering design criteria and parameters during the development of a given part. Introduction and broader use of composite materials and the not yet common practical knowledge of all failure criteria and lifetime properties offer opportunities for the use of SHM. The latter lie in the safe application of fiber resin composite materials for structural loaded parts, costs savings and lightweight design (see Fig. 1).

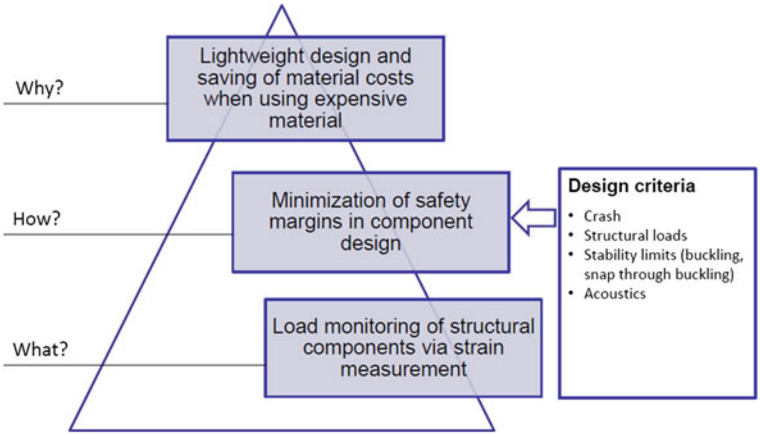


Fig. 1 Reasons for the introduction of a Structural Health Monitoring System

Fiber resin plastic (FRP) materials exhibit a different failure mechanism than metals. In contrast to having a well defined fatigue limit and ductile failure, current research suggests that FRP features no fatigue limit and has a brittle failure behavior (Keller and Vassilopoulos 2011).

To cover these uncertainties, carbon fiber composite parts are dimensioned in the automotive context by using design criteria taken from the aircraft industry without questioning them. Usage of a load monitoring system combined with a fatigue life prediction of the part can be a good option to make a significant step forward to the vision of an automobile body with slim dimensioned parts. In addition the introduction of a SHM system for automobile structures offers new possibilities to guarantee a safe function of novel load carrying FRP parts for the customer. The current approach of conservative design rules would be partly compensated by permanent monitoring of the structure.

Today's practice of a typical design of components for the worst possible customer and covering of all misuse cases can be questioned. Why reward the worst imaginable customers and penalize decent drivers with added weight? When we use SHM we learn about the real occurring loads during the operation of the structure. SHM and fatigue life prediction enable safe operation of the desired product or part without having the need for high safety margins. Before part breakdown the user will be warned early enough, because of the beneficial crack growth and failure behavior of composite materials. Currently it is still unclear how much material can be removed from the body structure without losing all of its operational capabilities.

1.3 Business Case Behind SHM for the Automotive Industry

Since the 1980s in the aircraft industry the philosophy of damage tolerance and material degradation during its operation emerged. This design standard emerged from the former fail-safe philosophy, which is characterized by multiple load paths embedded in the structure. All current automobiles are designed with the principles of safe-life or at least fail-safe. Usage of damage tolerance is uncommon. When in the future we want to apply bionic principles to our design this does not make any sense at all. Nature in its design allows a certain failure rate and also a natural degradation of its materials during operation. The reader will find more information and detail about aspects of damage tolerance design and structural integrity in Reifsnider and Case (2002) and Grandt (2004).

When we introduce a new class of materials for wider application in our products, this change offers chances for a change of paradigms. With the introduction of expensive carbon fiber resin composite materials for load-bearing structures in the industry, we get the chance for a change of our design principles in the direction of damage tolerance. When we are certain about the exact load a structure needs to bear and allow crack growth and material degradation during the lifetime of the part, then we are able to lower the safety margin of the structure during the design phase. This results in lower material cost of the expensive material used.

Placing focus on manufacturing methods used in the automotive industry versus the aviation industry, we see that scales are much higher and cost targets are lower. While the aircraft industry is familiar with thermoset resin systems and a no-fail

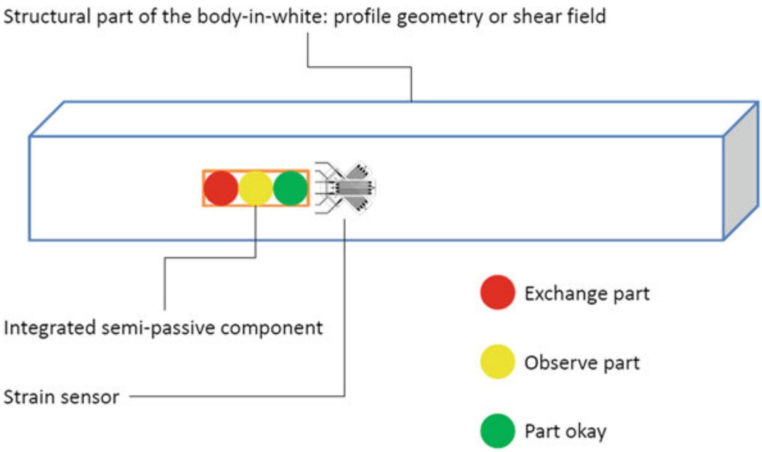


Fig. 2 Sketch of the vision and idea of the Structural Health Monitoring system

and no-void strategy, the automotive industry aims for a wider use of fiber reinforced composites with thermoplastic resins, such as polyamide. If a monitoring system for fighter aircraft may lie at around 5–6 € per aircraft, we aim at a cost target of 0.50 € per produced automobile unit. We need to recognize and consider these cost goals early in the design process of the SHM system. It makes sense to go for a very simple system design, which we call semi-passive (see Fig. 2). This successful development of the described SHM system offers the potential of a quick market introduction of FRP based structural lightweight parts. Thus automotive industry could achieve substantial weight reduction for a broad range of their products. This could be one important contribution to reduce CO_2 emissions furthermore.

2 Main Part

It is often mentioned that composite materials are uncritical in fatigue in opposition to metals. This is the case for typical tension–tension loads in the fiber direction, which are indeed uncritical for composite laminate structures in comparison to metals. However, in case of compression stresses this statement is not true (Talreja and Singh 2012). Even though composites show a slow crack growth and warning signs of upcoming catastrophic failure, fatigue plays an important role. When we think of component design including crack growth and material degradation during operation, it is even more important to know at which point of time the part catastrophically fails. Failure in this case means that the remaining strength is lower than the applied load. Intentional material degradation gets also relevant when we want to lower safety margins for more extreme and user safe lightweight design.

2.1 Terms and Definitions

We will introduce some necessary terms of the area of fatigue. Also we will give more detail to the term S–N-curve (Wöhlerkurve) for composites as a function of the load direction of the composite laminate structure.

Several load and stress cases can be applied to components. These are described by the stress ratio R. It describes the quotient between the minimum stress σ_{min} and the maximum stress σ_{max} of a load cycle. Therefore we distinguish between tension–tension, tension–compression and compression–compression cycles. Further relevant parameters in this regard are the mean stress σ_m and the load amplitude σ_a. For further information please review Keller and Vassilopoulos (2011) or Haibach (2006). Fiber resin composite materials are always more sensitive in regard to fatigue to compression than to tension cycles.

Most material properties like the tensile or compressive strength of a composite specimen are derived using uniaxial stress states. In real world applications multiaxial stress states occur. This makes fatigue life prediction complex for fiber resin composites, as their mechanical properties such as stiffness and strength differ in every direction of the composite, due to the material anisotropy. Contributing to the complexity is the existence of variable amplitude loading cycles.

We describe fatigue behavior of a material with S–N-curves or Constant Life Diagrams (Haigh-Diagrams). For metal materials it is sufficient to determine one S–N-curve per stress ratio R, as the material is isotropic. Fiber resin composites have anisotropic material properties. When we use fiber resin composite laminae or laminates we have to identify more than one S–N-curve per stress ratio, depending on the off-axis angle of the applied load. Typical angles are 30°, 60° and 90°. The anisotropism of the material properties, the different failure modes, the lack of a plastic range and also the layer structure of the composite make fatigue life prediction more complex in comparison to metals.

Whereas the S–N curve usually only delivers values for a discrete number of stress ratios R, with the Constant Life Diagram (CLD) the user is able to interpolate between the stress ratios that have been tested in experiments. Real load cases occur with stress ratios that have not been tested in the experiment. Damage in composite materials is prone to compression or tension–compression cycles. For example one decides to test a composite material with $R = -1$ (tension–compression) or $R = -1.66$, which can be said to be the most harmful stress ratios in practical application. Knowledge about this can be used in the Design of Experiments process. The aim then is to lower the necessary amount of experiments that one wants to conduct to describe the fatigue behavior of a polymer composite material.

In conclusion this shows that for the prediction of the remaining life of a component the presence of an anisotropic material, variable load amplitudes and changing load directions represent the worst and most complicated case. We already see that a fatigue life prediction of a composite material has to be conducted layerwise, if we want to be flexible concerning the layer structure and unless we want to design our components using predefined standard layups.

2.2 Main Idea of Our SHM System

Development focus of our SHM or load monitoring system is a high simplicity of the system design and the used parts. There are no actuators built into the structure of the composite laminate. All sensors are passive. The SHM system is working on the outer layer of a classical fiber resin composite laminate. In its first stage it only delivers information about the load history and the health status of the composite structure. When we analyze today's SHM systems we see that most of them show a complicated system design. A part of them combine multiple measuring principles and sensors, which is good when we look at the measured data and all the options that we are capable to use it for. We are able to spread the monitoring to several different failure modes and damaging events. In our view the disadvantage of this approach is that the SHM system gets highly complicated, the computing units get more expensive and at some point the SHM system is erased from a series production for issues like e.g. its price. More complexity in the system also means a higher probability of false alarms of the system, which has to be prevented concerning reliability of the system.

For a composite laminate fatigue life prediction algorithm we focus on a simple approach similar to the Palmgren–Miner rule existing for metal materials. Yet we know about the given assumptions of the Palmgren–Miner rule such as losing the sequence information of the loads and the challenges of using constant amplitude S–N curves. Different measuring options exist for the prediction of the failure of a structure. One option is the continuous measuring of all occurring loads. As a benefit this enables an exact monitoring of the structure. The disadvantage is the resulting data volume and the therefore low processing speed. The second option is the measuring of values that exceed a certain predefined threshold. This lowers the recorded data volume and also the necessary requirements for the processing of the data. Currently it is hard to decide which load cycles to leave out and where exactly to set the threshold, so in our experiments continuous monitoring of all occurring loads is preferred.

2.3 Fundamental Hypotheses in Structural Health Monitoring

When users want to monitor the health state of a structure, the following hypotheses, which have been set up by Worden and Farrar (2007), have to be considered. For reasons of their importance for the project they shall be repeated at this point:

- Hypothesis I: All materials have inherent flaws or defects.
- Hypothesis II: The assessment of damage requires a comparison between two system states.

- Hypothesis III: Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage present and the damage severity can generally only be done in a supervised learning mode.
- Hypothesis IVa: Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information.
- Hypothesis IVb: Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions.
- Hypothesis V: The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system.
- Hypothesis VI: There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability.
- Hypothesis VII: The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation.

These hypotheses are currently matter of discussion inside the SHM scientific community worldwide. For the special case of load and event monitoring, as used in our system, we judge hypotheses III and VII as irrelevant. We see that in SHM the perfect system cannot exist and that compromises have to be made concerning the preciseness of the prediction of the health state, signal noise, price etc. This confirms our thought that the leveling rule for first simple versions of SHM systems has to still be kept relatively low. For the automotive industry we really have to focus on the simplicity and reliability of the system, focus on usage of less information than more.

2.4 Relevant Researchers in the Field

Closer research regarding the topic of Load Monitoring or Structural Health Monitoring (SHM) shows that in the automotive area little public domain projects yet exist. Typical applications for load monitoring are military aircrafts like Tornado or Eurofighter (Molent and Aktepe 2000). The Eurofighter is equipped with an SHM and load monitoring system (Hunt and Hebden 1998, 2001; Stolz and Neumair 2010). Fraunhofer LBF in Darmstadt, Germany, has been doing research on a similar and interesting project to our with a Kayak paddle including a load monitoring unit (Kloepfer 2013).

2.4.1 Researchers in the Area of SHM

SHM is a new emerging research topic. Yet several publications, journals, books, conferences and also magazines exist until now. The most known magazine is "Structural Health Monitoring—an international journal" by SAGE Publications with its editor Fu-Kuo Chang at Stanford University. This journal has been starting in July 2002. Several names gained reputation during the last years. For the areas of buildings and similar structures Daniel Balageas, Claus-Peter and also Alfredo Güemes are specialists in the field. In the area of bridges Helmut Wenzel is a well known practitioner (Wenzel 2009). Further specialists are Charles R. Farrar and Keith Worden (Farrar and Worden 2013). Concerning adaptive structures and SHM also David Wagg may be mentioned (Wagg et al. 2007), as well as Douglas Adams. Christian Boller, Holger Speckmann and Nobuo Takeda are working on the monitoring of aerospace composite structures. In adaptronics Holger Hanselka can be mentioned. All of the aforementioned persons are publishing on a regular basis.

2.4.2 Researchers in the Area of Failure Criteria and Composite Fatigue

During the last years fatigue of composite materials gets into the focus of research. In previous years questions in the area of composites arose in the direction of manufacturing methods, stress analysis and simulation. Research on composites has been driven by the military, aircraft and aerospace industry. Due to the high security standards and complex certification in the aircraft industry, focus has been rarely placed on fatigue and more on the avoidance of voids and delaminations in the structure during manufacturing. Aircraft carbon composite laminates are designed not to show fatigue effects during their operation. Therefore they are loaded well below their capabilities, usually at stresses below 200 MPa. This means that these fiber resin composite materials will probably never come even into the region of suffering fatigue damage during their operation. Once again we see that for a proper introduction of composite materials for structural applications in the automotive body, we have to shift the paradigm to higher loads and permitting voids, crack growth and the occurrence of delamination during operation. The slow and predictable crack growth of fiber resin composite materials is a big benefit at that point in comparison to metals.

In the area of composite failure, research has been conducted since the 1970s. Uncountable static failure criteria for composite laminae (plies) and laminates have been elaborated and assessed over time, most of these criteria focus on one special failure mode of the composite. Talreja and Singh (2012) distinguish between micro-damage mechanics (MIDM) and macro-damage mechanics (MADM) approaches. Following this we distinguish between microscopic and macroscopic failure criteria.

Macroscopic failure or fatigue criteria on the level of the composite laminate have the benefit that they are comparably easy to understand, as they represent a rather phenomenological approach. Simply speaking, after conducting some mechanical tests with a pre-designed composite laminate it is possible to assess, when the laminate actually fails in static or dynamic cases. The effort for modeling is comparably low. The big disadvantage lies in the fact that a prediction gets difficult, once properties of the laminate design are changed, such as the fiber volume fraction, type of fiber, type of matrix or the layer buildup sequence/ply stack. No consideration of the influence of micromechanical differences inside the laminate is done. Following this tests have to be redone or descriptive theories have to be used to predict the influence of these changes.

One of the currently most promising methods for the prediction of composite failure is the multi continuum approach developed by Hansen et al. (Hansen and Garnich 1995; Mayes and Hansen 2004; Nelson et al. 2012). This approach divides the composite material into its constituent substances, such as e.g. carbon fiber and the polymer matrix. This makes sense as both components show a totally different fatigue behavior. Fatigue in the composite is matrix dominated, whereas e.g. carbon fiber is regarded as not critical regarding fatigue during the component lifetime. During the Second World-Wide Failure Exercise, which ended in 2012, failure criteria for fiber resin composite materials have been evaluated and correlated to experimental data from multi-axial material tests (Hinton and Kaddour 2012). Among other approaches, multi continuum theory has been shown to be applicable with acceptable accuracy during this research.

All of these failure criteria for composite laminates have in common, that they are designed to predict the static failure of a laminate. When it comes to fatigue damage, several models exist. The residual strength of the composite lamina decreases during its operation and so does the residual stiffness. When it comes to fatigue of composites, much work is still needed to fully understand the field. A lot of good and necessary work in that area has been done by Keller and Vassilopoulos (2011). One further challenge exists in the fact that for fatigue life prediction, laminates cannot be handled the same way as single laminae. In case of a single ply failure the load is redistributed over the remaining plies of the laminate, instead of a sudden complete laminate failure. Here a differentiation is necessary.

2.5 Sensor Technologies

Different sensor technologies have to be taken into account for an SHM system, depending on the requirements to accuracy, price and scope of the system. In SHM strong focus is set on the correct acquisition of the measuring data and the post processing of the latter. Typical sensor technologies are:

- Strain gauges,
- Fiber-Bragg-Sensors,
- Carbon fiber sensors,
- Carbon nanotubes,
- Vibration based techniques,
- Piezoelectric sensors,
- Electrical resistance methods and
- Lamb waves.

Benefits and disadvantages of each of these methods are broadly discussed in the aforementioned literature, such as Balageas et al. (2006). For an automotive context most of these methods are not yet suitable, either in regard of the complex working principle, the technology readiness level or the pricing structure.

2.6 Experiments Conducted

THI and the Institute for Applied Research started a new focus area with SHM. This work was supported by Honda R&D Europe (Deutschland) GmbH. Under the scheme of the Honda Initiation Grant Europe (HIGE), a research grant was allowed to provide funding to support the research on SHM systems for CFRP car body structures. Several experiments have been conducted during the course of the HIGE project, which will be explained in more detail in the following.

2.6.1 Load Recording Drives

During August 2012 load collectives of Aluminum cross beams and a steel race seat fixation of an Audi TT race car of Technische Hochschule Ingolstadt have been recorded on Nürburgring and Nordschleife (see Fig. 3).

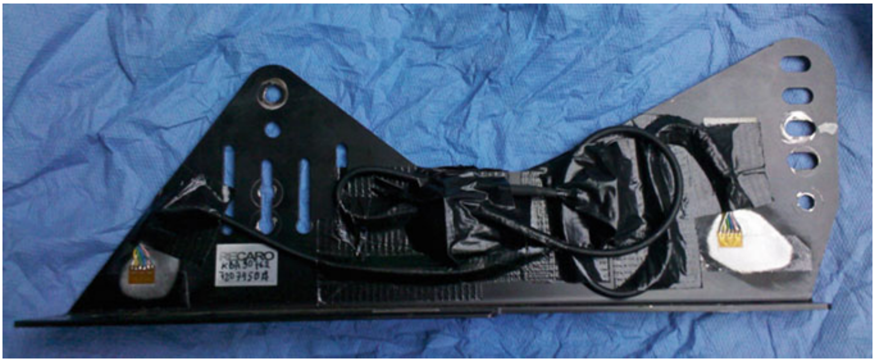


Fig. 3 Strain gauge equipped steel seat fixation for recording drives on the Nordschleife

We derived these load collectives using conventional strain gauges of HBM (RY103-3/120) and a HBM QuantumX measuring amplifier. During the recording drives a GPS unit and a three-axis accelerometer were also connected to the measuring amplifier. While conduction of the measurement drives we controlled the whole system via a remote desktop connection between the data logger and its HBM CatmanEasy software and a laptop computer. Afterwards we analyzed the recorded data in National Instruments DIADEM (see Fig. 4). The aim has been to acquire load recording data that later could be analyzed and evaluated for design, fatigue and algorithm purposes.

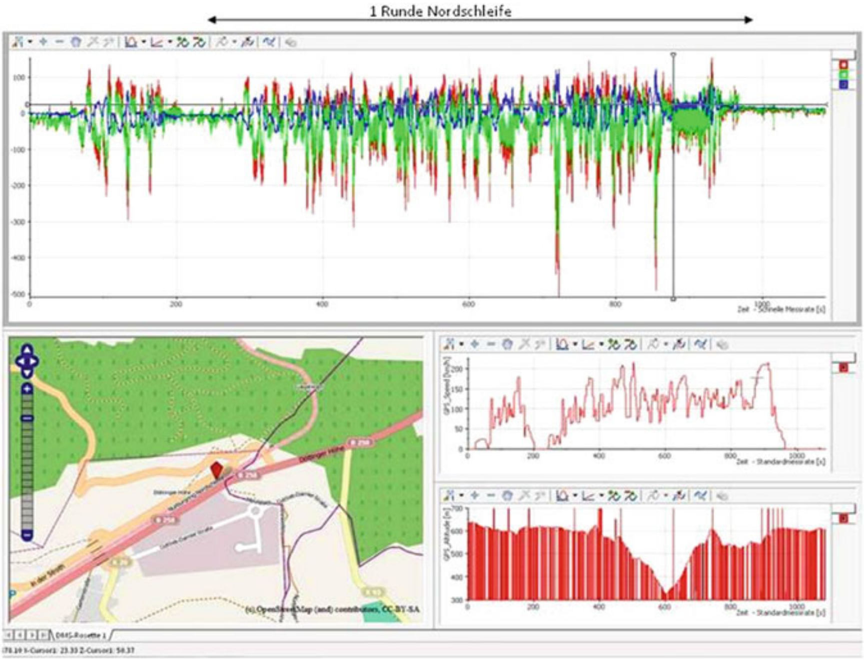


Fig. 4 Signal analysis of the strain gauge measuring data in combination with GPS positioning

For the measurements the Wheatstone bridge consisted of a half-bridge including a measuring strain gauge and a separate temperature compensation strain gauge. The influence of temperature changes during the measurement drives inside the car are noteworthy and need further attention to ensure a sufficient quality of the measuring signals. As expected, the temperature changes cannot be easily corrected by the use of a compensation strain gauge.

Our measurements show that strain gauges applied on real body-in-white parts deliver processible strain data, which we can later use in a fatigue life prediction algorithm concept. We used the drives at Nürburgring and Nordschleife to create a block load collective for the steel seat fixation. Nürburgring and Nordschleife have been chosen for the test drives because the track represents a possible worst case of the vehicle use, except from misuse incidents similar to the crossing of road curbs.

2.6.2 Signal Analysis

We analyzed the derived signals after the recording drives. Goal has been conducting a rainflow analysis of the recorded data and deriving a block load collective. All signal analysis and further signal preparation for the processing in our fatigue life prediction algorithm concept has been conducted using the software

National Instruments Diadem and partly Microsoft Excel. We created a rainflow-classification of the data as well as a block load spectrum during the project progress (see Fig. 5). We derived the main stresses and principal directions as well as know-how about the necessary signal processing steps.

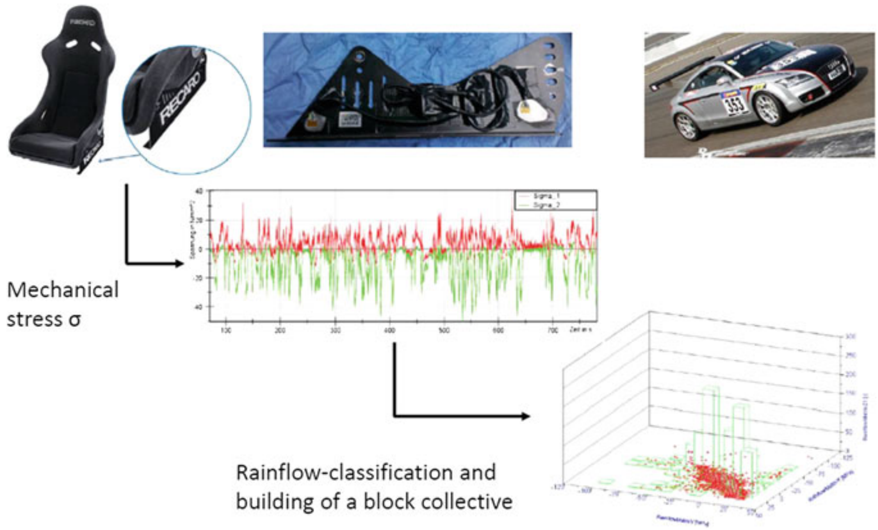


Fig. 5 Measuring drive on the Nordschleife with determination of a load collective and building of a block collective. Conducted at the example of a race seat fixation

Also we determined the general stress distribution and principal directions in the part as a function of time. In the seat fixation we found two predominant directions of stress given in the part, which were in the line of connection between the fixation points of the part and perpendicular to this direction. These directions—representing the spots where the strain gauges on the part have been applied—could comparably easy be located by visual inspection of the part. This is a great benefit for elaborating recommendations for suitable strain gauge sensor positions on the part. Nevertheless the user has to be cautious about where to place the strain gauges depending on the eigenmodes and natural frequencies of the component.

Our measurements show that the relevant maximum frequency of the structural loads is below 10 Hz. This low maximum frequency enables us to lower the recording frequency and therefore limit the occurring amount of data that needs to be stored and processed in a monitoring unit.

For using the strain signal in the algorithm it is necessary to post-process the data after the data acquisition. As mentioned, analysis of the acquired data shows that further attention needs to be given to the temperature compensation of the strain gauge measurements, as well as to a consideration of possible outlier values. During the project we handled the occurring temperature drifts of the recording drives with a fourth order polynomial. In a next step we will acquire the measurement signal and post process the signal in situ on an embedded rapid prototyping system.

2.6.3 Calculation, FE Analysis and Composite Design

Following measurement and signal analysis we built up a CAD model of the steel race seat fixation. We modeled the CAD model of the steel variant of the seat fixation in FE analysis using ANSYS. Also we modeled the loads to the seat fixation, which occurred during cornering of the car. After this, a validation of the simulation results using measurement data and an analytic calculation took place. Later, we modeled the carbon fiber resin composite seat fixation and conducted a layer-wise FE-analysis and structural optimization of the part, including the validated and refined boundary conditions. We created a suitable for production plybook of the optimized part for the later manufacturing of a demonstrator part and the fatigue experiments (see Fig. 6).

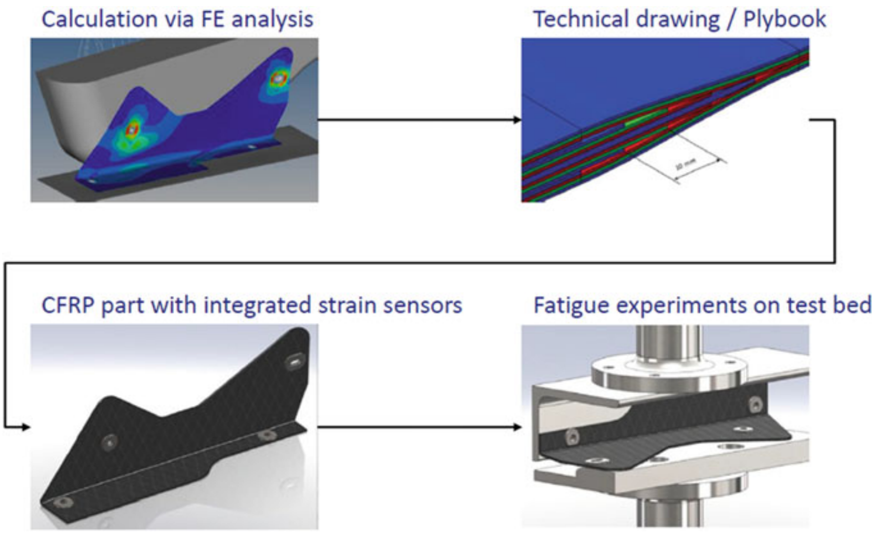


Fig. 6 Process of fatigue evaluation on the example of a fiber resin composite race seat fixation

Three methods exist for the modeling of a composite part: micromechanics approaches, a layer-wise calculation as well as the view of the composite as a homogenous body. In our case the calculation has been done layer-wise to be able to make predictions about the failure of each layer separately. Micromechanic approaches can be relevant to our project in the future, but currently they are still computationally very intensive. Being able to compute the composite laminate as one solid part would have benefits concerning the simplicity and velocity of the calculation, but too many details get lost during the modeling process.

Composite calculation and fatigue evaluation software was reviewed during the course of the project. Among these programs have been Siemens Fibersim, Ansys Composite PrepPost, Altair HyperWorks Optistruct, ALAN (Advanced Laminate Analysis) by RWTH Aachen, eLamX by TU Dresden as well as the software packages by FireHole Composites containing multicontinuum theory. For the FE analysis of the composite part we used the tool HyperWorks Optistruct.

2.6.4 Prototype and System Architecture

As a first step we created a general overview system design of the SHM concept. For further details we generated a function structure including block diagrams. Another question that we needed to resolve is finding a decision on which sensor technology is the best suitable alternative for the measurement of the strain on the composite part. Fatigue lifetime of classical strain gauge sensors can be defined to a minimum of 10^7 load cycles at a maximum strain amplitude of 1,000 μm/m, which we rate as sufficient for the application in a SHM system. It has to be kept in mind that the de-facto strains of strain gauges applied on an anisotropic material like e.g. carbon fiber resin plastics are always higher than the displayed value of the strain. One has to be aware that high strains of the strain gauges on the laminate are caused through the limited elastic modulus of the carbon fiber laminate (compared to steel sheet metal). This can lead to pronounced fatigue of the strain gauges through the occurring high strains on the surface of the laminate. Newest developments in strain sensor technology also focus on a change of the material of the wiring of the sensor to e.g. carbon filaments. But these technological challenges are only one side, another side is given by common resentments, such as the fact that the position of a sensor may always act as an imperfection or void inside a composite laminate. In the future, further good arguments need to be found for SHM to debilitate these resentments.

Various types of strain gauges are available on the market. We consider classic metallic strain gauges to be the best option for our SHM prototype. The main reasons are the high costs of their main opponent: optical interrogators. Optical interrogators offer several benefits when larger distances between measuring unit and strain gauge have to be covered. Also their benefits lie in their insensitivity in regard to electromagnetic shielding and better fatigue behavior in the area of high cycle fatigue. For other applications, where the costs for a SHM system would be small compared to the total product costs—such as in the aircraft industry—these optical strain gauges are still very interesting. But in opposition to strain gauges we expect optical systems stay at the current price level in the medium term. Price reasons are also responsible for the decision to integrate textile strain gauges that are applied on a fleece and can therefore be integrated on top or between layers of the composite laminate material.

Classical strain gauges are one suitable technique for measuring mechanical strain, which provides the possibility to scale up the production for entering a mass market. The price ratio between optical and classical strain gauges can currently be described by a minimum of 10:1, rather 100:1. Classical strain gauges offer potential for future price drops, as they represent a well known technology. Nevertheless it has to be mentioned that application of strain gauges is still a time consuming procedure. Future focus will be put on options for automating the process of the strain gauge application. In addition, the SHM sensors shall not be within areas which are easily accessible to the customer during day-to-day use of the vehicle.

The broad temperature range between −40 and +80 °C in the automotive industry requires dedicated temperature compensation measures, self compensation is definitely not sufficient. An option to cope with the temperature compensation challenge is the manufacturing of the complete part including sensors and running of measurements inside a climate chamber and taking these measurements into account mathematically. This makes a temperature sensor on the part necessary. The behavior of strain gauge measurement needs to be evaluated further concerning the occurrence of zero-point drifts. Further handling of this will be important and is part of the next evaluation of the signal post processing.

2.6.5 Manufacturing of Carbon Fiber Resin Composite Parts

After the design process, prototype parts of the strain gauge equipped seat fixation were manufactured, which matched the geometry of the original steel part concerning their geometry (see Fig. 7). This also means that the applied loads to the composite part have been comparable to the steel original.

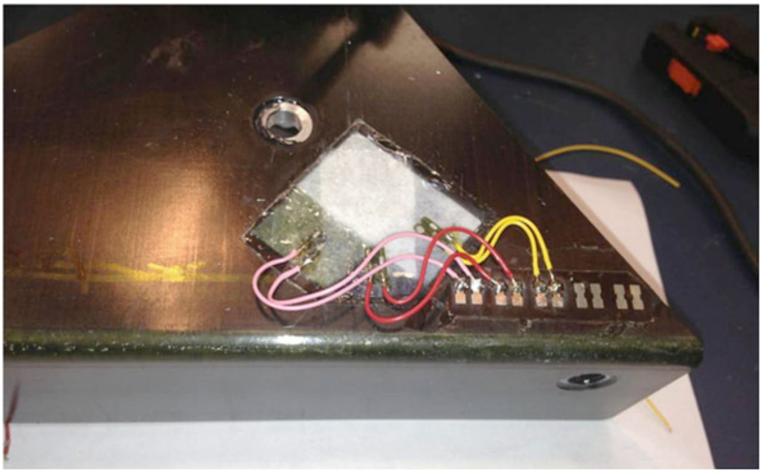


Fig. 7 Carbon fiber resin plastic seat fixation equipped with textile strain sensors

For the manufacturing of the parts thermoset prepreg material was used. The used fiber is Torayca M40 and the matrix system is an Epoxy resin system (E201/E201S by SGL Group). M40 fiber has been used to create maximum stiffness of the part. The prepreg layers have been grouted. One specialty of the manufactured composite part is that the layup is not quasi-isotropic, as it consists only of +45°, −45° and 0° plies. Reasons for this lie in the results of the finite element analysis. Another reason is given in the fact that the goal was to examine the behavior of a non quasi-isotropic laminate structure in the prototype test bed runs.

For the prototype parts stitched strain sensors were applied on the top layer of the laminate, which was beneficial for visual examination of the sensor technology, the necessary wiring and inconsistencies during the manufacturing process. The thickness of the sensor patches is one focus area for future improvements of the sensor technology.

Metal inserts were included to ensure a good load transmission of auxiliary forces into the laminate. In our case glued inserts for the necessary bolt joints have been designed in Aluminum. Regarding to the prototype status of the part and the low requirements concerning corrosion, this material was sufficient.

2.6.6 Creation of a Fatigue Life Prediction Algorithm Concept

During the project a first design of a fatigue life prediction algorithm was elaborated. Fatigue life prediction for composite materials is complex and highly discussed inside the scientific community. Currently there is no best-practice approach to the in situ prediction of fatigue life of composite laminates. Reasons lie in the lack of a unified failure criterion for fiber resin plastics. Our algorithm concept had to suffice several requirements. As the SHM concept shall be kept simple it was a goal to keep the structure of the algorithm simple and understandable as far as possible. The developed method should be similar to the life prediction of metals, one example can be given in the Palmgren–Miner rule.

In the longer term we want to be able to use and process real-time strain data of the sensors, currently it is possible to post process given data. The fatigue life prediction algorithm had to be able to recognize multi-axis stress states with variable amplitudes and mean stresses. As well a requirement has been basing the algorithm concept on the classical laminate theory. We realize this is in a modular structure, where it is possible to calculate the plane stress state of each separate layer of the composite laminate structure. Further requirement was providing a possibility for easy modification of each unidirectional composite layer structure and buildup sequence. For a first design we based the algorithm on multi continuum theory to take into account the more relevant influence of the matrix on the fatigue properties of the laminate. We assumed that partial-damage caused by fatigue is caused proportional to the damage index value of a static failure criterion.

Not a requirement of the algorithm concept was the provision for different failure modes like interlaminar shear, fiber pull-out and crack growth at pin joints. These phenomena have to be taken into account phenomenologically with further experiments. For first validation of the concept we used the designed CFRP seat fixation in a test bed experiment. Using multi continuum theory provides the opportunity to simplify the fatigue life prediction by reducing the number of needed S–N-curves. Nevertheless derivation of the necessary static and dynamic material constants is not a trivial issue.

2.6.7 First Validation Experiments and Test Bed Analysis

A first validation of the design allowables of the composite prototype part and of the fatigue life prediction algorithm concept was conducted to see whether the algorithm concept is able to work and to post process data. To gain knowledge about this fatigue testing was conducted at the stress-laboratory of the Technische Hochschule Ingolstadt (see Fig. 8).

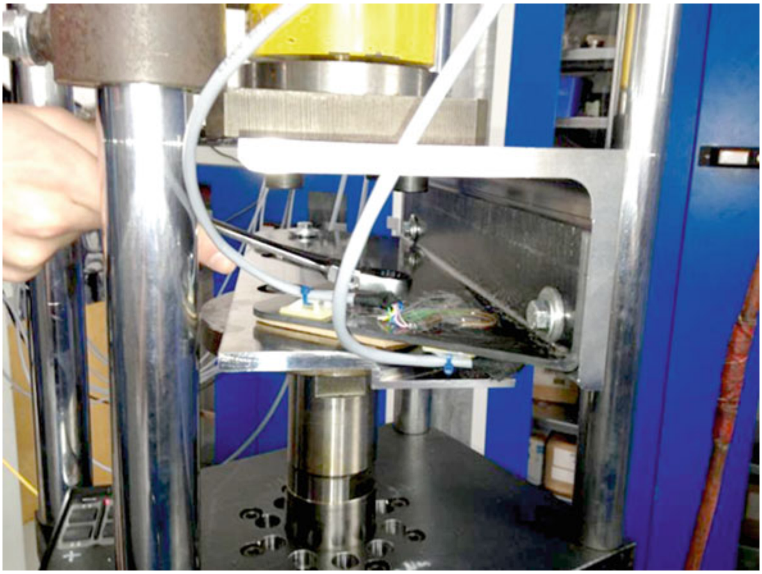


Fig. 8 Installation of the CFRP prototype part at the test bed of the stress-laboratory at Technische Hochschule Ingolstadt

The composite prototype part has been tested concerning its strength and fatigue properties. To achieve this aim the prototype has been installed on a unidirectional hydraulic pulsing cylinder and tested in static load cases and also with dynamic fatigue cycles. A measure to assess the declining of the mechanical properties was the reduction of part stiffness. After the experiment the obtained data and results were implemented into the fatigue life prediction algorithm concept. During the test bed validation the strain data have been monitored and recorded on a separate laptop computer via a HBM strain gauge measuring system. The strain data have then been processed offline by the algorithm concept. To limit the complexity of the test bed validation, constant tension–compression load amplitudes were used. The applied maximum load has been increased during the course of the test bed run to find coherence between the applied load and the behavior of the applied failure criterion for each ply.

For all material properties, data sheet values, calculations or suitable assumptions were taken, as the used thermoset resin system is a common standard material. During future evaluations we will focus more on the deduction of material properties and specifications, both static as well as dynamic. Starting values for calculations can be e.g. found in Kaddour and Hinton (2012), Soden et al. (1998, 2002). The static behavior of the composite part laminate could be predicted in a good manner.

Regarding to the dynamic behavior a simplified and assumed S–N-curve was chosen. The CFRP prototype part has been very resistant in regard to catastrophic failure. In our experiments it was not possible to achieve global part breakage, due to load limits of the test frame. However, in the experiment a significant decrease of the stiffness of the part was measured. A quasi-ductile behavior and stress redistribution inside of the laminate could be observed. The major stiffness decrease occurred when delaminations in the part formed, which was always accompanied by an audible acoustic emission of the laminate.

3 Conclusions

During the project an extensive literature research of the state of the art in regard to Structural Health Monitoring and the lifetime and fatigue properties of fiber resin composite laminates were conducted. A Structural Health Monitoring system prototype concept was developed for the needs and demand of the automotive industry in cooperation with Honda R&D Europe (Deutschland) GmbH. Next steps of research were defined. Also a fatigue life prediction algorithm concept was developed, based on the classical laminate theory and state of the art failure criteria. Measuring drives were conducted on the Nordschleife and load collectives were recorded. Afterwards composite prototype parts have been manufactured and tested in first test bed validation runs.

Our thesis still is: the usage of first-ply-failure of composite laminates, which is used in the aircraft industry for defining the failure of the composite laminate, can be much too conservative for usage in the automotive industry. Further potential for material reduction and lightweight design is given. A discussion of the use of a less conservative criterion for the part design, such as remaining strength, and acceptance of material degradation during operation of the component seems more suitable. In combination with monitoring the load history of a car body part this can create additional weight saving benefits.

Prediction of the remaining life of anisotropic fiber resin composite materials is still a very ambitious and challenging goal, as the failure modes are diverse and complex. The question still is, whether it is possible to rely on one failure criterion for an approximation of the remaining life of a composite part. Progress in this regard is visible inside the scientific community and more and more experiments are conducted. Concerning cost targets strain gauges can still be judged as a suitable solution for monitoring part stresses. Still one challenge is the derivation of all static and dynamic micromechanical material constants for the chosen composite material.

Acknowledgments Special acknowledgments go to Johannes Stöckl. Further acknowledgments to Reinhard Weigl, Gerald Sitzmann, Maximilian Beck and Philipp Cervenka. Thank you very much for your effort and support!

References

Adams D (2007) Health monitoring of structural materials and components: methods with applications. Wiley, Chichester

Balageas D, Fritzen C-P, Güemes A (2006) Structural health monitoring. Iste Publishing Company, London

Farrar C, Worden K (2007) An introduction to structural health monitoring. Philoso Trans R Soc A 365:303–315

Farrar C, Worden K (2013) Structural health monitoring—A machine learning perspective. Wiley, Chichester

Grandt A (2004) Fundamentals of structural integrity: damage tolerant design and nondestructive evaluation. Wiley, Hoboken

Haibach E (2006) Betriebsfestigkeit. Springer, Berlin

Hansen A, Garnich M (1995) A multicontinuum theory for structural analysis of composite material systems. Compos Eng 5(9):1091–1103

Hinton M, Kaddour A (2012) The background to the Second World-Wide failure exercise. J Compos Mater 46:2283–2294

Hunt S, Hebden I (1998) Eurofighter 2000: An integrated approach to structural health and usage monitoring. In: RTO AVT specialists' meeting on "Exploitation of structural loads/health data for reduced life cycle costs"

Hunt S, Hebden I (2001) Validation of the Eurofighter Typhoon structural health and usage monitoring system. Smart Mater Struct 10:497–503

Kaddour A, Hinton M (2012) Input data for test cases used in benchmarking triaxial failure theories of composites. J Compos Mater 46:19–20

Keller T, Vassilopoulos A (2011) Fatigue of fiber-reinforced composites. Springer, London

Kloepfer J (2013) Entwicklung eines load-monitoring-systems für Sportgeräte. http://www.adaptronik.fraunhofer.de/de/projects/paddel.html, 06.2013

Mayes J, Hansen A (2004) Composite laminate failure analysis using multicontinuum theory. Compos Sci Technol 64:379–394

Molent L, Aktepe B (2000) Review of fatigue monitoring of agile military aircraft. Fatigue Fract Eng Mater Struct 23:767–785

Nelson E, Hansen A, Mayes J (2012) Failure analysis of composite laminates subjected to hydrostatic stresses: a multicontinuum approach. J Compos Mater 46:2595–2634

Reifsnider K, Case S (2002) Damage tolerance and durability of material systems. Wiley, New York

Soden P, Hinton M, Kaddour A (1998) Lamina properties, lay-up configurations and loading conditions for a range of fibre-reinforced composite laminates. Compos Sci Technol 58:1011

Soden P, Hinton M, Kaddour A (2002) Biaxial test results for strength and deformation of a range of E-glass and carbon fibre reinforced composite laminates: failure exercise benchmark data.

In: Tsu-Wei Chou (Ed.): Composites Science and Technology, Vol. 62, Elsevier Science Ltd., Kidlington, Oxford, UK
Stolz C, Neumair M (2010) Structural health monitoring, in-service experience, benefit and way ahead. Struct Health Monit 9:209–217
Talreja R, Singh C (2012) Damage and failure of composite materials. Cambridge University Press, Cambridge
Wagg D, Bond I, Weaver P, Friswell M (2007) Adaptive structures: engineering applications. Wiley, Chichester
Wenzel H (2009) Health monitoring of bridges. Wiley, Chichester
Worden K, Farrar C, Manson G, Park G (2007) The fundamental axioms of structural health monitoring. Proc R Soc A 463:1639–1664

Material Composition and Revenue Potential of Australian End of Life Vehicles Using Machine-Based Dismantling

E. El Halabi, M. Third and M. Doolan

Abstract To date, little is known about the recyclability of End of Life Vehicles in Australia. This study, the first of its kind, attempts to fill the gap by presenting data collected from the dismantling of 1,115 ELVs at an Australian auto-recycler using an excavator-based multi-dismantling machine. The dismantled components grouped by rough metal content are compacted and weighed before being sold to the respective recycling markets. The findings are put into perspective by comparing them with available data from Europe. The material composition of the Australian fleet is aggregated to highlight the call for the auto recycling industry, which relies on revenue from the sale of used parts, to adopt machine-based dismantling as a value-added activity. This business strategy has the potential to significantly benefit the industry's sustainability by capitalising on overlooked revenue streams.

1 Introduction

Each year in Australia around 610,000 End of Life Vehicles (ELV) are dismantled and sold as parts and materials for profit. The automotive parts recyclers or dismantlers undertaking this business activity rely on other revenue streams in order to supplement their revenue, such as mechanical repairs and servicing, and second-hand car trade (El Halabi and Doolan 2012). The industry is made up of approximately 793 firms having a total of $1.1 Billion Australian in revenue and $96.2 Million in profit IBISWorld (2011). In recent years the industry has

E. El Halabi (✉) · M. Doolan
Australian National University, Canberra, Australia
e-mail: ezzat.elhalabi@anu.edu.au

M. Third
Total Auto Recyclers, Melbourne, Australia

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_9,

experienced stagnant growth which can be effectively regarded as a decline when taking into account the shrinking of the workforce and the number of operators, coupled with a substantial growth in population, the automotive fleet, and related industries (El Halabi and Doolan 2013). Some operators have focused on increasing revenue from scrap metal sold to metal recyclers by dismantling components (e.g. catalytic convertors, radiators and others) that contain higher valued materials like platinum (Pt), aluminium (Al) and copper (Cu). The more profitable but labour intensive process led a small number of recyclers to invest about $500,000 in multi-dismantling machinery (i.e. excavator, compactor, and storage bins). At a rate of two ELVs per hour, the excavator-based dismantling machine manned by a sole operator could remove the needed components using mechanical force of a clamp arm and a wide jaw (Fig. 1). The various parts, now grouped in piles by rough metal content, are compacted and supplied to scrap metal recyclers at several folds the price paid for scrap ELVs.

Fig. 1 An excavator-based multi-discmantling machine

The authors undertook a dismantling trial at a reputable auto dismantling yard located in Melbourne to address a major data gap on Australian ELVs hindering further research, and to assess the potential of the industry to adapt more substantial dismantling processes. In this paper we present the results from the dismantling of 1,115 ELVs over the first three months of 2013. We provide an overview of the handling of these ELVs, the dismantling, and the weighing processes as well as the data collection method. We then contrast the results with ELV dismantling data from Europe. We also aggregate them over the Australian automotive fleet and highlight the revenue potential for auto recyclers from adopting machine-based dismantling.

2 Dismantling, Weighing, and Data Collection Method

In this section we detail the flow of ELVs dismantled for this study (Fig. 2). We also highlight key assumptions and constraints made about the data. ELVs, specifically chosen for their parts value, are sourced from salvage car auctions, direct from public, used car dealers, local councils, and car towing service operators. Upon arriving into a holding yard, the ELVs are inspected, inventoried, and then moved into a processing hangar for depollution and removal of quality parts. Where applicable, fluids (i.e. coolant, hydraulic fluids, engine oil, gearbox and differential oils, and fuel) are drained while Air Conditioning (A/C) gas and Liquid Petroleum Gas (LPG) are extracted. The batteries, wheels/tyres, tow bars, and catalytic convertors are also removed. Parts deemed to be in high demand, good condition, and high value are dismantled (e.g. engines, transmissions, door mirrors, audio equipment, etc.). These parts, including useable batteries and wheels/tyres, are tagged and warehoused for sale as quality used parts.

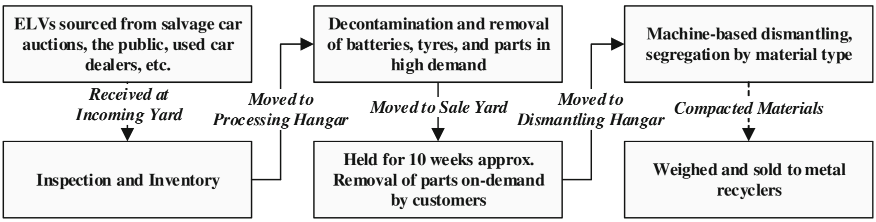


Fig. 2 An overview of the movement of ELVs from procurement to dismantling

The ELVs are then placed into a sale yard where walk-in customers dismantle parts as required. The 650-ELV yard stock is rotated on a daily basis. Every day 20 ELVs that had been on display for 10 weeks are replaced with newly acquired ones and moved to a dismantling hangar where an excavator-based multi dismantling machine is used to break them apart. The components removed earlier during the depollution process and from the machine-based dismantling are grouped by rough metal composition, pressed into bales using a compactor, and then weighed on an industrial scale. With the exception of the left-over tyres that are disposed of through tyre recyclers for a fee, the bales are sold to their respective recycling markets including metal recyclers and catalytic convertors recyclers.

Data relating to the make, model, year of manufacture, transmission type and kerb weight is entered into a database at the initial inspection stage. After the machine-based dismantling stage, weight data for various bales types is collected and aggregated. It is worthwhile noting that the kerb weight data relies on third party databases like the International Dismantling Information System (IDIS) (http://www.idis2.com. Accessed in Mar 2013) because currently the incoming ELVs are not weighed.

3 Results, Observations, and Discussion

The aggregate dismantling results are divided by the sample size (1,115) to average material weights and potential revenue per ELV (Figs. 3 and 4). The value of scrap materials is calculated using the market prices in the state of Victoria as of March 2013. Furthermore, a conservative estimate of 17 kg per ELV is used for captured fluids as no measurements are currently taken. Recovered fuels (i.e. petrol, diesel, and LPG) are consumed in the forklifts and trucks on site. The remaining fluids sold to fluid recyclers at a negligible rate are excluded from revenue calculations.

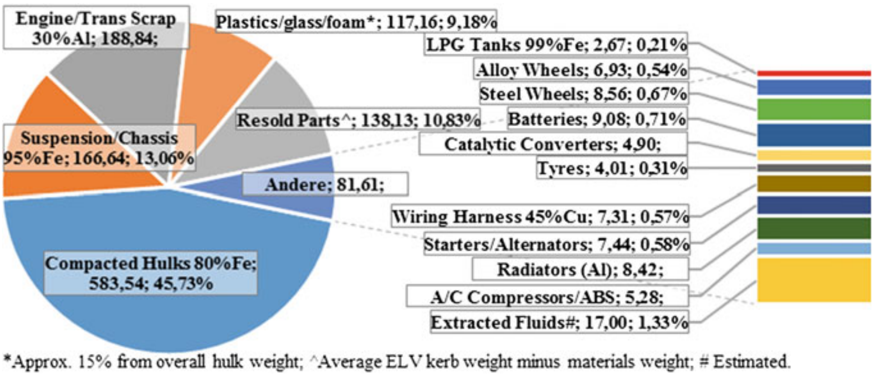


Fig. 3 Aggregate material/component composition per ELV in kg

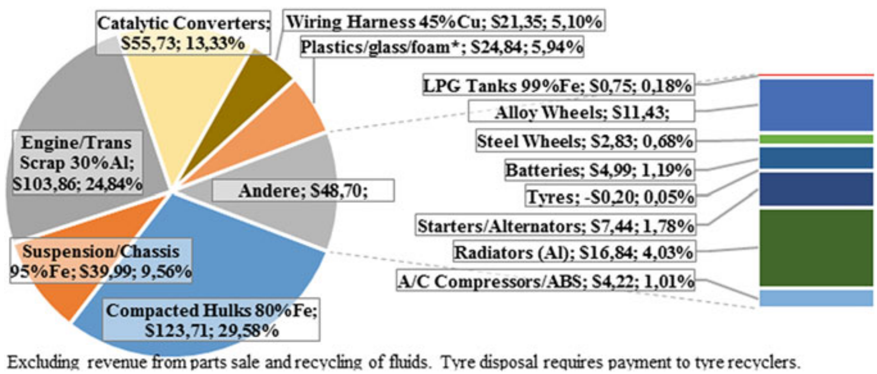


Fig. 4 Aggregate revenue from selling scrap materials/components in Australian Dollars

On average, a processed ELV is 17.4 years old (Fig. 5). It has a kerb weight of 1275.92 kg (median 1,312, standard deviation 251.33) of which, 138.13 kg (10.83 %) sells as used parts while the rest 1,120.79 kg is sold/disposed of as materials to scrap metal, tyres, battery and fluids recyclers. Assuming that the plastic/glass content ends up in landfill, the resulting overall reuse/recycling rate is 90.82 %. The estimated recoverable metal content[1] is 999.62 kg (78.35 %). As scrap, each ELV revenues $417.78. The top ten make (65 %) of the sample positively correlate (0.84) with the top ten prevalent makes in the state of Victoria.[2] While the correlation is unintended, it could be attributed along with the relatively high re-use rate, to the business model seeking to maximise revenue from selling used parts by selecting the most popular makes. From a scrap value perspective, the four most valuable components are: catalytic convertors (due to precious metals content like Pt), wiring harnesses (Cu), radiators (Al and Cu), and alloy wheels (Al). Combined, they only make 2.46 % (27.56 kg) of the ELV weight as scrap materials weight but a substantial 25.21 % ($105.34) in revenue (Fig. 6).

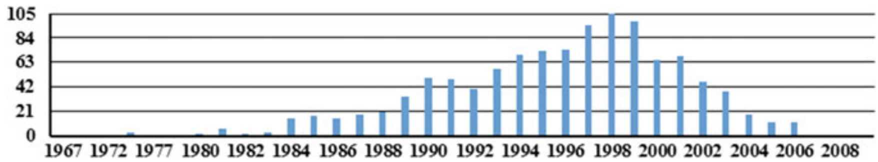


Fig. 5 Sample distribution by year of manufacture

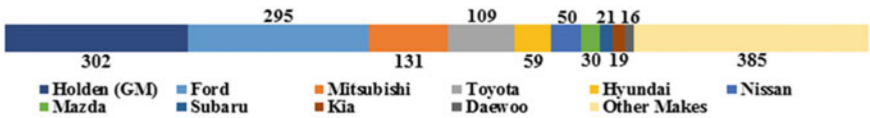


Fig. 6 Top ten makes in the sample by number of ELVs

Based on the results, we find that Australian ELVs are on average 30.63 % heavier, 2.5 years older and contain 3.86 % more recoverable metals than those in the UK (Weatherhead and Hulse 2005). Moreover, it is at least possible at a small scale to achieve a reuse/recycling rate in Australia similar to that in best-practice countries like Denmark (90.5 %) (Eurostat 2013). These observations should be treated with caution, however, because as mentioned earlier the sample is skewed towards maximum revenue potential from used parts.

[1] Both ferrous and non-ferrous, excluding from batteries and tyres.

[2] Based on cars made between 1971 and 2009 registered in Victoria (http://www.idis2.com. Accessed in Mar 2013).

The typical practice in the industry with regards to supplementing the low price paid by metal recyclers for scrapped ELVs, about $150 per unit, is to sell highly priced components separately (i.e. manually removed batteries, catalytic convertors, radiator, and alloy wheels). The combined revenue in this case would be $238.99 per ELV, assuming that auto recyclers net $88.99 for those components based on figures from our trial. Thus, the calculated revenue differential from having machine-based dismantling is $173.80 per ELV. Taking this figure further, if 20 % of auto recyclers (159 out of 793) handling 80 % of ELVs (488 k out of 610 k) were to adopt machine-based dismantling as a value-added activity, the annual industry revenue and profit[3] could increase by $84.8 Million (7.71 %) and $28.3 Million (29.4 %) respectively (IBISWorld 2011). The proposed scenario is plausible in terms of daily throughput, about 13 ELVs per dismantler, with adequate spare processing capacity.

It is important to note that the revenue estimate does not take into account the fluctuations of scrap metals prices, as dictated by international prices and currency exchange rates, and the resulting damping of increased supply of segregated scrap metals on the local market. Furthermore, the analysis ignores machinery costs, subsuming them as part of an ongoing investment that a relatively large recycling firm could make to maximise its revenue potential from an overlooked stream. There is scope to take this study further beyond the current limitations. First, the data collection process needs to go over a longer period and in other Australian states to identify the trends, if any, in ELV composition. Secondly, the weight data could be more accurate by including the actual ELV weight prior to dismantling as opposed to kerb weight sourced from third party databases. Lastly, it would be interesting to assess the amount of recyclable materials (e.g. glass and plastics) that could be recovered at the dismantling stage in the absence of legal requirements like in Europe (European Parliament 2010).

4 Conclusion

The paper addressed a major data gap on Australian ELVs by presenting the results of a first-in-kind dismantling trial, including age, weight, make, material/component composition, and revenue potential from the sale of materials as scrap. We contrasted the results with data from other countries and highlighted the significance of machine-based dismantling, as a value-added activity, for auto recyclers seeking to maximise their revenue and profit potential.

Acknowledgments This original research was proudly supported by the Commonwealth of Australia through the Cooperative Research Centre for Advanced Automotive Technology (AutoCRC) and the Australian National University (ANU).

---

[3] Assume additional profit at 1/3[rd] the revenue differential.

References

Australian Bureau of Statistics (2012) Motor vehicle census, cat. no. 9309.0, Canberra

El Halabi E, Doolan M (2012) New insights into the Australian automotive recycling business. In: 4th international conference on sustainable automotive technologies, Melbourne

El Halabi E, Doolan M (2013) Operational challenges in the automotive recycling business: A system dynamics perspective.Re-engineering manufacturing for sustainability. Springer, Singapore

European Parliament (2010) End of life vehicles: legal aspects, national practices and recommendations for future successful approach. Study by DG internal policies, policy department A: Economic and scientific policy

Eurostat (2013) End-of-life vehicles: reuse, recycling and recovery, totals. http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/key_waste_streams/end_of_life_vehicles_elvs

IBISWorld (2011) Industry report F4624 motor vehicle dismantling and used part dealing in Australia

Weatherhead T, Hulse D (2005) A study to determine the metallic fraction recovered from end-of life vehicles in the UK. Report to the department of trade and industry

The Usage of Lightweight Materials in Hazardous Areas: Flex-Metal-Mesh

E. Wilhelm and J. Wellnitz

Abstract The usage of lightweight materials is in general highly preferred due to better mechanical behaviours of the materials (e.g. fibres). Besides this, the possibility to influence economic effects in a positive way is also important, which can be realised in saving material costs due to a certain weight reduction or focussing on fuel consumption reduction especially in the transportation sector. So the main industry sector has a certain interest to support the research and adaptation or rather replacement of state of the art materials with lightweight material. This paper shows a possibility to implement a metallic lightweight material, called Flex-Metal-Mesh, within the protective sector, which is rather reluctant to change standard materials and to adopt new developments. Therefore, the challenge is to convince people that this system fulfils the wanted requirements and is working in a proper and reproducible and therefore in a reliable way. For this reason, the potential of the here mentioned system was investigated in various experimental tests and simulation procedures. The focus of the following documentary deals with the validation aspect of such a system.

1 Introduction

In the area of lightweight materials most people think of transportation and the decrease of fuel consumption to combat the upcoming global warming. Besides this, new developments and the usage of lightweight materials in hazard areas play a big role as well, because humans or human lives respectively are involved

E. Wilhelm (✉)
Institute for Technology and Artistic Design GmbH (ITD), Nördliche Ringstraße 19, 85057 Ingolstadt, Germany
e-mail: eva.wilhelm@itd-in.de

J. Wellnitz
Technische Hochschule Ingolstadt, Esplanade 10, 85049 Ingolstadt, Germany
e-mail: joerg.wellnitz@thi.de

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_10,

directly, which gives an insight of the mentioned sensitive matter. There are interactions of these two fields visible, see armouring vehicles.

Of course, it is always easier to work with known materials and concepts, because this supports a basic security. In addition, the manufacturing process, the mechanical behaviour as well as the availability of established materials is known in detail. We need to balance this kind of disadvantage of lightweight materials to overcome existing doubts.

The here presented protection system consists of metal, indeed a well-known basic material, facilitating its acceptance. At the same time the configuration of the single elements is different from anything else. For this reason, the acceptability and the understanding is the true challenge in this case.

2 Key Data of Flex-Metal-Mesh

Flex-Metal-Mesh (FMM) describes a chain meshwork, which consists of a large number of welded metal rings with a well-defined geometry. The 4 in 1 arrangement of the mesh is known as the European or king version, which means that every single ring is connected with four neighbouring rings (see Fig. 1; left).

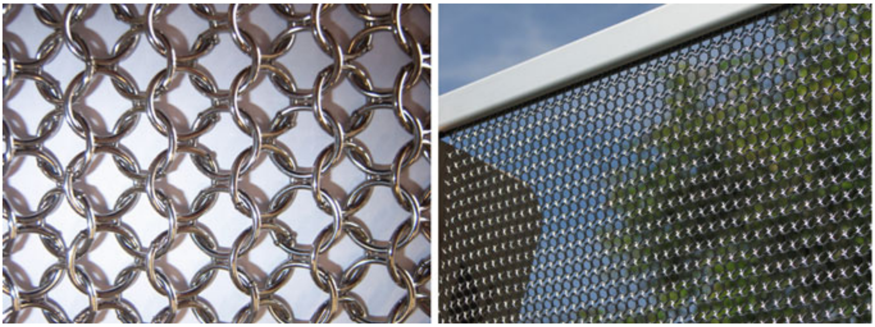


Fig. 1 4 in 1 arrangement of the rings within a meshwork; transparency of Flex-Metal-Mesh

A summary of the main properties and advantages of FMM are listed below:

- variable ring dimensions; outer ring diameter Ø = 3.6–12.0 mm,
- tensile strength with respect to the dimension up to $R_m \approx 1000$ N/ring,
- low mass per unit area of m = 1.21–4.65 kg/m^2,
- high deformation capacity (>50 %),
- high energy absorption due to plastic deformation,
- transparency (56–63 %),
- very good free-form and flexible behaviour,
- metallic and non-metallic bulk commodity,
- properly engineered manufacturing process,
- easy product access—serial production.

3 Experimental Studies

In the past many different experimental studies have been undertaken for a better understanding of the behaviour of the FMM. The potential of the here presented protection system was investigated under various conditions.

The following tests have been carried out so far:

Tensile test

- one ring
- varied rows of rings
- investigation of planar mesh
- force-deflection
- stress-strain relations

Penetration test

- variable energy levels
- wire treatments
- plastic deformation
- test following the regulations of VPAM, HOSDB. Fig. 2

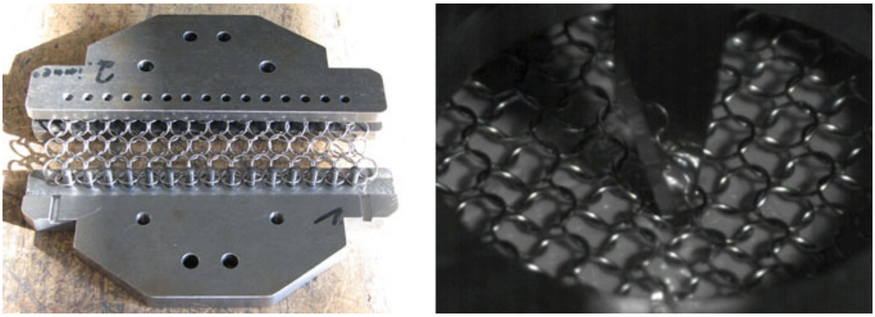


Fig. 2 Exemplary tensile test configuration (*left*); penetration test scenario (*right*)

Blast wave

- investigations regarding turbulences
- (peak) pressure measurements
- suspension behaviour

Fragments

- window blast test
- secondary debris
- test following the GSA standards

Impact

- large impactor with low speed
- small impactor with high speed
- energy absorption
- meshwork movement
- realisation of suspension. Fig. 3

Fig. 3 Impact configurations: test situation (*left*); mesh application on site (*right*)

These entire test series verified the potential of FMM in a traceable way. The experimental research demonstrated for impact scenarios, that a large impactor and the depending movement of the FMM show very good results and trace the FMM exactly within its technical capabilities.

For this reason, the theoretical research focusses on this application, too. So the total amount of results forms the foundation for the theoretical approach and validation of a reliable simulation model.

4 Theoretical Approaches

The main theoretical approach is to focus on the holistic system and not to consider each single ring and its momentary behaviour; this is valid by focusing on a large area mesh (e.g. $A > 2\ m^2$). Moreover, the following internal approaches have been agreed:

- high displacement
- less deformation.

In addition, a substitute model represents the FMM following the membrane theory. In general this theory includes the following simplifications and requirements:

- lateral dimensions are much greater than the thickness,
- the holistic system is pliable, bending stiffness and bending torque are very small, deflections are therefore neglected,
- force transmission in a compatible manner,
- the structure is classified as amorphous,
- a membrane works only under pre-stress.

Typical examples for a membrane are the balloon or the soap bubble. Taking into account the knowledge of these and other systems a substitute model of the FMM is underway.

Besides the holistic amount of experimental data, an impact test series under ideal, reproducible conditions and measurements have been completed.

Material and impactor; suspension

- RG12 $\times$ 1.3 mm; L $\times$ B = 400 mm $\times$ 400 mm
- four types of spherical masses m = 103 g/174 g/512 g/845 g
- fixed support around the mesh.

Recorded dimensions

- drop height
- weight of impactor.

Outputs

- High speed videos
- Measurement of maximal deflection in the centre-average value
- Validation data.

All this information was feed into a LS-Dyna/HyperMesh model with an initial configuration set to start the validation. Fig 4

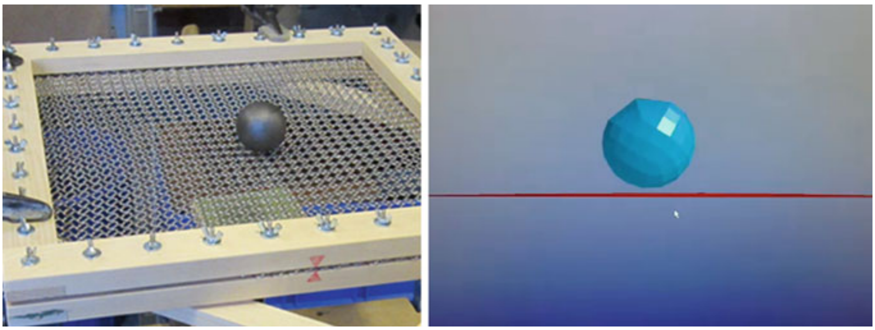


Fig. 4 Experimental test situation (*left*); initial HyperMesh model of the experimental test (*right*)

The final goal of the theoretical work is to create a reliable simulation model, verified on wide-ranging testing results. So complex situations and scenarios can be predicted and further applications can be proved without the usage of time and cost consuming experiments and customer inquiries can be handled in a forwardlooking way.

5 Conclusion/Summary

Studies have shown that a system consisting of the lightweight material Flex-Metal-Mesh has a clear potential due to the usage in hazard areas.

The experimental tests of this protection system verify especially the potential of Flex-Metal-Mesh concerning protective effects, substantial potentials for the debris containment as well as for protection devices within several speed and impactor mass regimes.

The generated experimental information was used to set up a simulation model according to the requirements of the membrane theory. Within this simulation large area impacts and the realistic behaviour of the mesh should be realised.

In general, Flex-Metal-Mesh provides significant advantages, which are the awareness level of the basic material—metal, the variance of parameter and shape, the availability of the system due to series production, high transparency and therefore less mass per unit area as well as the potential to serve diverse application areas.

Within its potential the FMM will supply its strength wherever special material properties and characteristics are demanded.

A Dynamical Life Cycle Inventory of Steel, Aluminium, and Composite Car Bodies-in-White

P. Stasinopoulos and P. Compston

Abstract This paper presents a dynamical life cycle inventory study of the Australian car-fleet energy consumption when the steel in car bodies-in-white is replaced with aluminium or a composite material. The results show that both lightweight BIWs have net energy benefits over steel BIWs. The energy benefits of composite BIWs are greater than for aluminium BIWs because energy consumption during the production and use stages is lower for composite BIWs. The results also suggest that the energy benefits to the fleet might be limited by competition from steel BIWs, which, together with the growth in the car fleet, prevents the car-fleet energy consumption from declining.

1 Introduction

Car manufacturers apply light weighting strategies, such as material substitution, to decrease the fuel consumption of cars. For many lightweight materials, net energy benefits emerge only if the higher energy investment in material production is recovered, through fuel savings in driving, before the car is retired.

The aim of this paper is to make progress towards a life cycle assessment (LCA) method that can account for changes in resource consumptions and environmental impacts over time. LCA has been used to calculate the possible energy benefits of many structural car components. Most studies compare a single current-model (usually steel) component with the equivalent lightweight component (Puri et al. 2009). A few studies, all life cycle inventory (LCI) studies, consider the whole car fleet to account for the transition from steel components to lightweight-metal components (e.g. Cáceres 2009; Das 2000; Field et al. 2000; Stasinopoulos et al. 2012b).

P. Stasinopoulos · P. Compston (✉)
Research School of Engineering, College of Engineering and Computer Science,
The Australian National University, Canberra, ACT 0200, Australia
e-mail: paul.compston@anu.edu.au

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_11,

This paper builds on these studies by including a limit on the adoption of lightweight components and by comparing a non-metal material. The limit reflects the ability of car buyers to choose the car that best suits their requirements. Specifically, the study uses System Dynamics methods (Sterman 2000) to compare the Australian car-fleet energy consumption when the steel in car bodies-in-white (BIWs) is replaced with aluminium or carbon-fibre reinforced polypropylene (composite).

2 Methods

This LCI study builds on a previous fleet-based LCI study of car BIWs (Stasinopoulos et al. 2012b) by modifying the SD model. It also uses LCA data from an Australian LCA study of car door skins (Puri et al. 2009), which follows ISO 14040 (Standards Australia & Standards New Zealand 1998). The SD model, constructed using the stock-and-flow modelling software STELLA™ (version 9.1.2), performs dynamical computations by allowing parameters to affect their own values through feedback loops. The computed values are then used to calculate LCI data in a Microsoft Excel spreadsheet.

2.1 Model

The dynamical models of previous fleet-based studies include the *turnover* accumulation structure—the flow of components into and out of the car fleet. Turnover causes long delays in the diffusion of lightweight BIWs into the car fleet and in the change in the fuel consumption of cars. The models also include the *recycling* feedback structure—the recycling of materials from end-of-life components back into new component production. Recycling causes a decline in the energy consumption of component production.

These models assume that the adoption fraction of lightweight BIWs grows linearly from 0 to 100 %. This assumption is modified in the present SD model via the *adoption* modification. The adoption modification limits the adoption of lightweight BIWs based on the total costs of ownership (TCO) of steel cars and lightweight cars. This enhancement partly represents the response of manufacturers to the risk of changing from a well understood material, such as steel, to a poorly understood material, such as novel composites. The adoption fraction of lightweight BIWs adjusts towards the fraction given by: 1 − TCO of lightweight car/(TCO of steel car + TCO of lightweight car). The TCO of a car is equal to the car price plus the fuel cost over the useful life; maintenance costs are ignored. Car prices in the model differ due to the BIW mass and engine power, which is adjusted such that all cars have the same power-to-weight ratio. All material prices grow with increasing fuel price, and the composite-material price also declines with increasing production experience. The adoption modification also assumes

S-shaped adoption (Gargett et al. 2011; Grübler 1991). Figure 1 shows the present SD model, highlighting the feedback loops of the turnover and recycling structures, and the adoption modification.

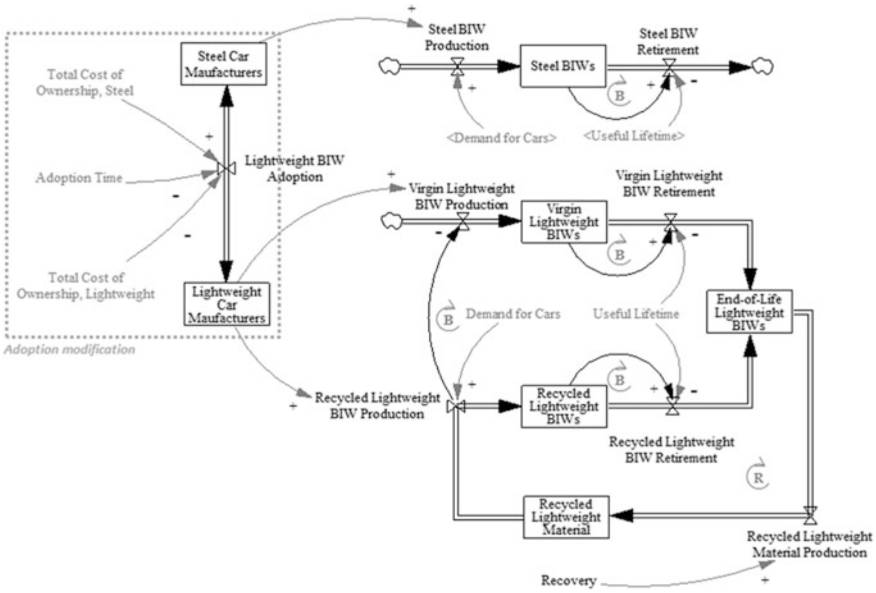


Fig. 1 The system dynamics model, highlighting the feedback loops of the turnover and recycling structures, and the adoption modification. The boxes represent stocks (e.g., 'Steel BIW'). The *double-lined arrows* represent flows (e.g., 'Steel BIW Production'). The 'tap' symbols represent flow rates (e.g., rate of 'Steel BIW Production'). The 'cloud' symbols represent unlimited source and sink stocks that lie outside the system boundary. The text elements (e.g., 'Demand for Cars') represent ancillary parameters. The *single-lined arrows* represent influence links (e.g., 'Demand for Cars' affects 'Steel BIW Production'). The plus (+) and minus (−) signs on the *arrows* indicate link polarity. An *encircled R* indicates a reinforcing feedback loop. An *encircled B* indicates a balancing feedback loop

2.2 Data

Table 1 shows the parameter values used in the SD model and in the calculations of the life-cycle energy flows. The values are adapted from Stasinopoulos et al. (2012a, b), unless otherwise indicated.

3 Results and discussion

The SD model simulates three scenarios. The *baseline* scenario assumes that car manufacturers continue to produce steel BIWs. The *substitution-aluminium* scenario assumes that car manufacturers adopt aluminium BIWs (starting in 2010) and

Table 1 Assumed parameter values

Parameter	Steel	Aluminium	Composite	Units
BIW mass	430	300	230	kg
BIW recycled content	25	10, 10+	0+	%
Car mass	1720	1590	1520	kg
Car fuel consumption	0.523	0.545	0.558	l/100 km/100 kg
BIW fleet, initial	6 million	0	0	BIWs
BIW manufacturers, initial	100	0	0	% of production capacity
Adoption time	n/a	20	20	y
Demand for cars[(a)]				
Initial	387,000	387,000	387,000	BIWs/y
Final	1,720,000	1,720,000	1,720,000	BIWs/y
Driving intensity	15500	15500	15500	vehicle-km/y/car
Useful lifetime[(b)]	22	22	22	y
Recovery	n/a	90	90	%
Total cost of ownership				
Initial (2010)	58,000	54,900	54,300	$
Final	96,900	92,500	90,300	$
Energy flow, production[(c)]				
Virgin	35.2	190	102	MJ/kg
Recycled	19.0	57.5	77.4	MJ/kg
Energy flow, use[(c)]	2.47	2.57	2.64	kJ/km kg

[(a)] Calibrated such that the simulated car fleet corresponds with the car registrations in Australia between 1980–2010 (Australian Bureau of Statistics 1979–2012), given the useful lifetime. The calibrated value is consistent with the new car registrations in Australia between 1980 and 2010 (Australian Automotive Intelligence 2010, pp. 28–29)
[(b)] The minimum age to which 50 % of cars in Australia lived during 1998–2007 (Australian Automotive Intelligence 2010, pp. 28, 44)
[(c)] Acquired using the same method as in Puri et al. (2009)—from LCA software SimaPro, GaBi Demo, and GREEN 1.7

recycle end-of-life aluminium BIWs into new BIWs. The *substitution-composite* scenario involves the same intervention, except that manufacturers adopt and recycle composite BIWs. The simulations cover the past 30 years, for which some reference data is available, and the next 70 years, during which the effects of the dynamics can be observed. In Figs. 2 and 3, the shapes of the curves are more important than the absolute values.

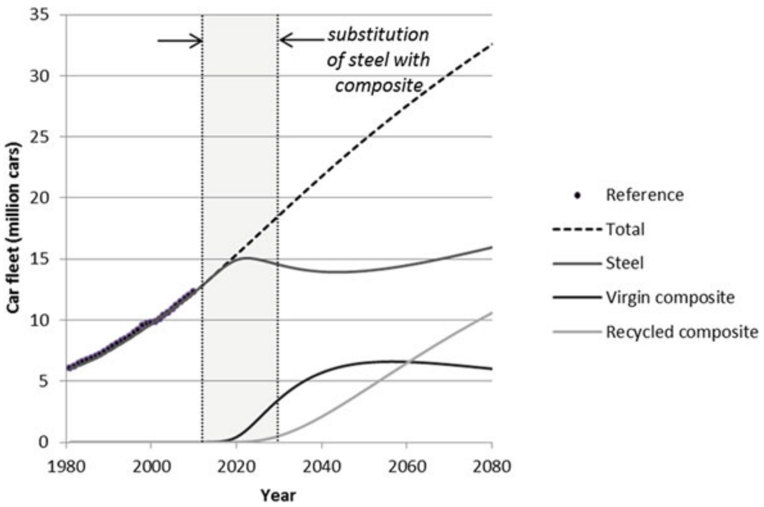


Fig. 2 Distribution of cars in the fleet under the substitution-composite scenario. Reference data are historical data

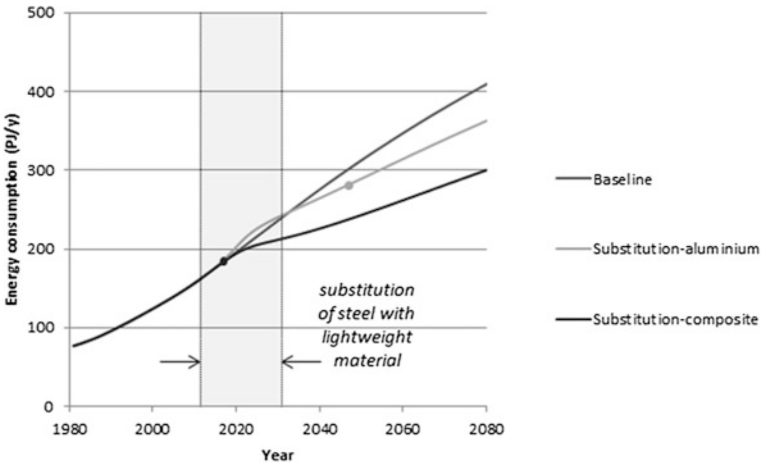


Fig. 3 Life-cycle energy consumption of the car fleet under the baseline, substitution-aluminium, substitution-composite scenarios, calculated using data computed by the SD model

Figure 2 shows the computed values of the stocks of steel, virgin composite, and recycled composite BIWs under the substitution-composite scenario. These values are similar under the substitution-aluminium scenario. Figure 2 also shows reference data for the car fleet (Australian Bureau of Statistics 1979–2012; Bureau of Infrastructure, Transport and Regional Economics 2011). Under all scenarios, the assumed growth in demand for cars produces growth in the car fleet from 6 million cars to 33 million cars over 100 years.

Simulations show that aluminium BIW production reaches full adoption at 52 % of market share and composite BIW production reaches full adoption at 53 % of market share. Under both scenarios, the TCO of the lightweight car is slightly less than that of the steel car because the high unit costs of the lightweight materials are more than offset by the corresponding cost savings in materials and fuel. In 2030, when lightweight BIWs reach full adoption, the fleet contains only 22 % lightweight BIWs because the slow rate of turnover limits the opportunities to replace end-of-life steel BIWs. Recycling affects the proportions of virgin and recycled lightweight BIWs, but not the proportion of total lightweight BIWs, in the fleet.

Figure 3 shows the calculated annual life-cycle energy consumption of the BIW fleet under the baseline, substitution-aluminium, and substitution-composite scenarios. The energy consumption, the sum of the primary energy flows, is dominated by petroleum consumption during the use stage.

Under all scenarios, the car-fleet energy consumption grows at all times but is lower for the substitution-composite scenario than for the substitution-aluminium scenario at all times after 2010. This result differs from that of Stasinopoulos et al. (2012b), who simulate a brief period of declining energy consumption, because the limit on lightweight BIWs prevents the energy benefits from fully offsetting the growth in the car fleet. The energy benefits of aluminium BIWs emerge in 2045, the same year computed by Stasinopoulos et al. (2012b), because the smaller stock of aluminium BIWs requires less energy to produce but also recovers proportionately less energy during use. The energy benefits of composite BIWs emerge in 2017, sooner than for the aluminium BIWs because energy flows during the production and use stages are lower for composite BIWs.

4 Conclusion

This paper builds on previous fleet-based LCI studies to increase the relevance of the results to decision-making processes. The SD model considers the more likely scenario that lightweight BIWs, if adopted, will share the market with steel BIWs. Under this limiting scenario, the long-term energy benefits are smaller because the car fleet contains fewer lightweight BIWs. The SD model and LCI calculations also consider a composite material, which is representative of the novel materials and polymers that car manufacturers are increasingly adopting. Compared with the energy benefits of aluminium BIWs, those of composite BIWs emerge much sooner and are about twice as large in the long-term.

Acknowledgments This original research was proudly supported by Australian National University and the Commonwealth of Australia through the Cooperative Research Centre for Advanced Automotive Technology. The authors thank Barry Newell and Haley Jones for their assistance in the development of the SD model and their useful comments and advice in the development of this paper.

References

Australian Automotive Intelligence (2010) Australian automotive intelligence yearbook 2010, 9th edn. Australian Automotive Intelligence, Melbourne

Australian Bureau of Statistics (1979–2012) 9309.0: Motor vehicle census. Commonwealth of Australia, Canberra

Bureau of Infrastructure, Transport and Regional Economics (2011) Australian infrastructure statistics yearbook 2011. Commonwealth of Australia, Canberra

Cáceres CH (2009) Transient environmental effects of light alloy substitutions in transport vehicles. Mater Des 30(8):2813–2822

Das S (2000) The life-cycle impacts of aluminum body-in-white automotive material. J Min Met Mater Soc 52(8):41–44

Field F, Kirchain R, Clark J (2000) Life cycle assessment and temporal distributions of emissions: developing a fleet-based analysis. J Ind Ecol 4(2):71–91

Gargett D, Cregan M, Cosgrove D (2011) The spread of technologies through the vehicle fleet. Australasian transport research forum 2011 proceedings, 28–30 Sept 2011 Adelaide, Australia

Grübler A (1991) Diffusion: long-term patterns and discontinuities. Technol Forecast Soc Chang 39(1–2):159–180

Puri P, Compston P, Pantano V (2009) Life cycle assessment of Australian automotive door skins. Int J Life Cycle Assess 14(5):420–428

Standards Australia & Standards New Zealand (1998) Australian/New Zealand standard: environmental management—life cycle assessment—principles and framework, AS/NZS ISO 14040:1998, Standards Australia & Standards New Zealand

Stasinopoulos P, Compston P, Jones HM (2012a) A system dynamics approach to understanding the influence of lightweight materials on the development of fuel efficient cars. In: Wellnitz J, Subic A, Leary M, Koopmans L (eds) Sustainable automotive technologies 2012: proceedings of the 4th international conference. Springer Berlin, pp. 33–38

Stasinopoulos P, Compston P, Newell B, Jones HM (2012b) A system dynamics approach in LCA to account for temporal effects—a consequential energy-LCI of car bodies-in-white. Int J Life Cycle Assess 17(2):199–207

Sterman JD (2000) Business dynamics: systems thinking and modeling for a complex world. McGraw Hill, Boston

How New Things Come Into The World

T. Brodbeck

Abstract How New Things Come Into The World! From the hand axe to the automobile; from the idea that the Earth rotates around the Sun to self-cleaning surfaces; from bronze via iron and steel through to innovative composites—brilliant ideas, ground-breaking inventions, unprecedented techniques, and new materials have determined human life from time immemorial. However, while the hand axe was the universal tool 1.8 million to 50,000 years ago, nowadays a new tool is required every two to three years, say a new operating system, to ensure we can work efficiently: See Windows 8. Product cycles have become shorter, too. A new cell phone every year, and new car models are released every three to four years, or at least completely overhauled versions. Developers today are under enormous pressure in terms of innovation. But is there some common ground, something uniting, which can be extracted from the history of innovation? This presentation tries to find an answer to that very question, focusing on the development of the car and its current challenges, with bionics offering numerous solutions. With amusing and illuminating examples from history, psychology, art and literature the secret of fantasy, creativity and hence of innovation will be unravelled.

1 Introduction

The development of the car is a success story, at least until now: Cars can be found on the moon, in the air, on water and on all six continents, including Antarctica. They are fuelled by gasoline, diesel, petroleum gas, wind, pressurized air, hydrogen or by batteries and turbines.

T. Brodbeck (✉)
Biologist, Media Producer and Executive Coach, Mainzer Str. 165,
55743 Idar-Oberstein, Germany
e-mail: thbrodbeck@aol.com

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_12,

But it is exactly this success that now endangers their survival. The writing is on the wall: Pollution, climate change, diminishing resources, super jams.

What we need are new ideas! Innovations for the coming car generations. And these innovations are required soon, as the times in which an operating system—like the hand axe for example—is being used for over 1.5 million years after its invention are long gone. New car models are released every three to four years, or at least completely overhauled versions. It is a curse, because it forces the industry to come up with massive investments and innovations in very little time. At the same time, it can also be a blessing, because new fuel saving technologies and security concepts can be introduced to production very quickly. This means that both the consumer and the environment can profit.

But how do new things come into the world? Let's have a look at history first—maybe we can learn something from it already.

2 Distrust Authorities

2.1 Nicolaus Copernicus

Martin Luther's opinion about the lateral thinker was clear: "The fool wants to turn the whole art of astronomy upside-down! However, as Holy Scripture tells us, so did Joshua bid the sun to stand still and not the earth".

Contrary to common belief, the propagation of the heliocentric system was not viewed as heresy in Copernicus' time, but at best as the chimera of a confused mind. After all, the geocentric system seemed to be much more in agreement with common sense than a moving Earth. If it was moving, there had to be a 'head wind', it was thought. After all, the Earth is moving with a speed of almost 2000 km/h and is 'flying' around the Sun with more than 100,000 km/h.

And finally, the most important astronomers of his time used complex calculations and up to 80 epicycles to develop a system which showed the Earth in the center of the solar system—in mathematically correct terms (Vollmann 2007).

2.2 Albert Einstein, Georges Lemaître and Max Born

A pamphlet entitled "100 Authors against Einstein" was published as late as (Israel 1931), in which not only the National Socialists, but also many Jewish professors argued vehemently against the theory of relativity, which was already scientifically established at the time. But even Einstein fundamentally erred in many sciences. He wrote to fellow physicist Max Born in 1926: "Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the 'old one'. I, at any rate, am convinced that He does not throw dice."

Einstein erred, until this day, no quantum physics prediction has been refuted: God throws dice after all.

The priest Georges Lemaître published his big bang theory in 1927. His colleagues smiled at his work for years. Albert Einstein went as far as to call the priest's theory 'abominable', and tried to invalidate it with all means. Among other things, it was because of Lemaître that Einstein introduced the cosmological constant.

2.3 Max Planck

It was in 1874 when high-school graduate Max Planck asked Philipp von Jolly from Munich whether he could recommend to study physics instead of mathematics or music. Jolly commented on Planck's interest in physics with the remark that 'in this field, almost everything is already discovered, and all that remains is to fill a few unimportant holes'—an opinion held by many physicists at the time. It was for the better that Planck did not listen to the expert's advice. In doing so, he opened the doors to a completely new and unexpected science, namely quantum physics.

2.4 Wilhelm Barthlott

All four attempts of presenting the phenomenon of self-cleaning surfaces, the so-called lotus effect, in a dedicated publication were dismissed by the consultants of renowned magazines, giving the same reason each time: It contradicted the textbooks and the extensive array of related literature. One of the consultants replied that the lotus effect only existed in the author's fantasy world. But doctrines are not rules—they are opinions. Dozens of dependent patents regarding the lotus effect have by now been registered or granted, and a true lotus obsession has come over manufacturers of self-cleaning surfaces. Thanks to his patents and his insistence Barthlott now is a rich man.

2.5 Some More Mistakes from Scientists and Experts

In 1825, experts and professors in the Parliament of England seriously claimed that passengers would suffocate in trains driving at speeds above 30 km/h, animals would die of fear from the locomotive whistles and chickens would stop laying eggs (Asimov 1990).

In 1943, former IBM CEO Thomas Watson postulated: "I think there is a world market for maybe five computers."

In 1977, Ken Olsen, president and founder of the computer manufacturer DEC, said in a truly non-trend-setting statement that 'there is no reason for any individual to have a computer in their home'.

And in 1993, who told his employees—who numbered quite a few—that 'the Internet is just a hype'?

Microsoft co-founder and Harvard drop-out Bill Gates. He thus ordered his employees to look after other things first.

What can we learn from that? The world does not wait for innovations—most often the world rather fights everything new, unknown, and genius!

3 Who Brings New Things Into The World?

3.1 Genius and Madness: A Close Liaison

Very often it is not the busy, well adapted, normal, low-key individuals but the loners and misfits who bring new things into the world. To put it more scientifically: Those who suffer from Asperger syndrome, schizophrenia, autism, savant syndrome, and very often also narcissism and egomania.

3.1.1 John Forbes Nash, Jr.

Nobel Prize in Economics for his works in game theory.

Diagnosis: Schizophrenia.

3.1.2 Isaac Newton

Newton was unable to put up with criticism of his publications and thus withdrew more and more from the scientific community and focused on his alchemical experiments. A fight with English Jesuits in Liège in 1678 was the last straw and Newton suffered a nervous breakdown. His mother died the following year. For six years, until 1684, Newton was in a phase of isolation and self-doubt.

Diagnosis: Late-onset schizophrenia.

3.1.3 Wolfgang Amadeus Mozart

Wolfgang Amadeus Mozart was off his rocker, too. It was impossible for him to sit still for longer periods and he liked to speak in an inappropriate manner at court. In letters he would suddenly write absurd rhymes and sign with ‘Sincerely yours, Süssmaier Scheißdreck’, which literally translates along the lines of ‘Sweetmeyer Shit’.

Diagnosis: Tourette syndrome.

3.1.4 Baron Karl-Friedrich von Drais

Let us see what Major Tulla has to say in a report on Drais’ running machine, commissioned by the Department of the Interior of the Grand Duchy of Baden:

We can thus not attach any significant purpose to von Drais’ man engine whatsoever, because everybody who has feet can use these for a change of location much better in the way they are used naturally, and we believe that such a machine could only be of any use to the human being if fitted for disabled people or those without feet, but in this case the operation would need to be set in motion with the hands to allow the machine to give to such people the power of movement they lack… It is for these reasons that I must doubt the overall practical use of the running machine.

The inventor of the dandy horse, the archetype of the bicycle, uses alcohol to drown his frustration about the lack of understanding and the foolishness his machine is met with. He suffers from persecutional mania in the end. Drais is incapacitated in 1851 and dies within the year.

Diagnosis: Alcoholism and paranoia (Bürgin 1998).

3.1.5 Rudolf Diesel

The inventor the diesel engine owes its name to was indeed a great engineer, but he was lacking a talent for business. Bad speculations, excessive demands and financial worries lead to a mental breakdown, followed by a stay in a mental home. Diesel’s bouts of depression peak in the planning of his suicide. He burns mountains of files and jumps from a steamer into the North Sea in 1913. The following lines were found among his notes: “There is no saying more false then the one about the genius who brings himself to do something. 99 out of 100 masterminds perish undiscovered, and number 100 only barely manages to accomplish something amidst untold difficulties.”

Diagnosis: Depression.

3.1.6 Psychological Explanation

According to Wolfgang Maier, psychiatrist with the University of Bonn, some disorders include the creative ability to think associatively and unconventionally. Inversely, people with creative talents are said to be susceptible to derail emotionally. The rate of authors and artists who suffer affective disorders such as depression is thus above average.

Genius and madness are connected more closely than initially thought: Researchers have discovered a gene which seems to be responsible for both creativity and insanity. The positive side effect is that this hereditary factor is sexy.

Daniel Nettle of Newcastle University and Helen Keenoo (Nettle 2006, Nettle 2005) of the Open University in Milton Keynes published a study in the journal 'Proceedings of the Royal Society B'. The result: The more creative a person is, the more distinct are their schizotypal traits—and the more active is their love life. On average, the most creative artists were found to have considerably more partners than their uncreative peers. According to the researchers, this was true for both the men and the women surveyed. Nettle and Keenoo believe creativity to be a decisive factor in the selection of partners, which more than outweighs the disadvantages linked to the higher susceptibility to schizophrenia.

3.2 Women Who Bring New Things into the World

3.2.1 Bertha and Karl Benz

Karl Benz's motor vehicle would surely not have become a success without his wife Bertha. She was brave enough to drive the vehicle her husband constructed, with her two sons in the passenger seats. The way from Mannheim to Pforzheim and back covers a total distance of 180 km/h! And that across field paths, across country. This long-distance test was the automobile's breakthrough. Because on no account was the world waiting for the car. Karl Benz is believed to have said something along these lines:

And then suddenly, doom—in the form of the first breakdown. The driver alights, kneels down and tinkers. People gather, smile, and laugh. Amazement and admiration turn into pity, mockery, and scorn. Just like here for the first time, a debate of destructive criticism spreads with every glitch in the town and later outside, in the villages. 'Gadgetry, with nothing and nothing else to come of it', some said. 'How can one sit on such an unreliable, pathetic and loud machine box? There are horses all over the world with the most elegant carriages and hackney coaches on top', others remarked. The 'experts' said it was 'a pity about the man; he is going to ruin himself and his business with this crazy idea'. And an innocent man from Berlin gave the well-meant advice 'if I had a smelly box like that, I would stay at home…

3.2.2 Mary Anderson

Even before Henry Ford's first car went into production, the American Mary Anderson (1866–1953) invented the windshield wiper in 1903. She observed in New York, in bad weather, how motorists stopped their cars and got off in order to improve visibility and manually free their windshields from rain drops or snowflakes. This gave her the idea of an automatic wiper, to avoid drivers having to get out in the cold and wet.

3.2.3 Hedy Lamarr

Neither GSM cell phones nor notebooks would exist today, if actress Hedy Lamarr, born Hedwig Kiesler in Vienna, Austria on November 9, 1914, and the American avant-garde musician George Antheil (July 8, 1900–February 12, 1959) had not met at a dinner party in Hollywood in the summer of 1940.

On the basis of Hedy Lamarr's technical suggestions, a tap- and interference-proof device for radio controlling torpedoes was developed. This was later used as the basis for the radio communication of cell phones and the wireless communication of notebooks.

4 What Can We Use for Inspiration?

4.1 Nature

Why not use something for inspiration that has been functioning brilliantly for millions of years and that has not been protected by patents for quite a while? Some examples:

- Self-cleaning surfaces designed following the example of lotus leaves.
- Drag-reducing surfaces designed on the model of sharks' de mal denticles.
- Lightweight rims designed like diatoms.
- Self-sharpening knives following the basic patent of beaver teeth.
- Mother of pearl and spider silk are superior to the best high tech materials.
- Airbag folding using origami design.
- The beaked salmon's skin produces less friction than glass, steel, or nylon.
- Mussel glue is an ideal adhesive.
- Interference colors modelled on the bright example of butterflies.
- The atomic adhesion of geckos.

4.2 Literature

Many famous scientists were inspired by literature when it comes to their inventions. This is because fantasy is on the forefront of every invention and every discovery. "Imagination is more important than knowledge. For knowledge is limited" is one of Albert Einstein's best-known sayings. It is without doubt that writers live on their imagination.

4.2.1 Jules Verne

Jules Verne inspired scientists, tinkerers and inventors like no other writer of his time. It is not a coincidence that the world's first nuclear-powered submarine, the American USS Nautilus, was named after Captain Nemo's futuristic submarine from the novel *'Twenty Thousand Leagues under the Sea'*. When Werner von Braun got his hands on Hermann Oberth's book *'The Rocket in Interplanetary Space'*, the utopias he absorbed from Kurd Lasswitz and Jules Verne's *'From the Earth to the Moon'* became a bit more real. He made an effort to improve his up to then modest achievements in mathematics in order to understand the book about the specialist subject.

4.2.2 Erich Kästner

The description of a Utopian cell phone in literary dates back to 1931. It can be found in the children's book *'The 35th of May, or Conrad's Ride to the South Seas'* by Erich Kästner (1931). In one paragraph, Kästner describes the following scene: A man traveling on the sidewalk suddenly stepped onto the pavement, pulled a telephone receiver out of his coat pocket, said a number out loud and then called his wife to tell her that he would be an hour late for lunch. "I want to go to the laboratory first. Goodbye, darling!", he said, then put his pocket telephone away, stepped back onto the moving belt, read in a book and continued his journey.

4.2.3 Erwin Schrödinger

Nobel laureates James Watson and Francis Crick confirmed that they took a little book entitled *'What Is Life?'* by quantum physicist Erwin Schrödinger as their inspiration for their work on the discovery of the genome, the deoxyribonucleic acid.

4.2.4 Roger Bacon

Roger Bacon (born 1214) was a monk and scholar of the Middle Ages. He was the first to express the idea of an independently (*auto*nomously) moving vehicle: "[…] carriages can be made so that without an animal they may be moved […]"

4.3 Arts

On first sight it may seem that art and science or technology have little in common. Yet it is certainly worthwhile to be inspired by art. This is because a closer look reveals many similarities.

4.3.1 Leonardo da Vinci and Isaac Newton

Both da Vinci and Newton dissected and analysed nature in order to draw conclusions—to calculate and understand the world and to construct new things. Newton wrote his epochal work ‘Opticks’, and da Vinci concerned himself with the structure of the eye. Da Vinci discovered that the retina displays images upside down. These findings were the basis for his construction of the first camera obscura. Leonardo da Vinci: “Art is the Queen of all sciences communicating knowledge to all the generations of the world.” To him, “mechanics is the paradise of the mathematical sciences, because by means of it one comes to the fruits of mathematics.”

The science of Leonardo da Vinci is a visualised one. Painting and drawing to him were graphic tools which allowed for such materialization, together with the pragmatic and concrete representation of abstract theory. All of this leads to a strange blend of layers of reality and abstraction, thought and vision, art and science, of which he was seeking a synthesis. Knowledge that did not pass all sense cannot create a truth other than a harmful one, to rephrase one of his quotes.

4.3.2 What is Colour? Eugène Chevreul, Vincent van Gogh and Albert Einstein

Besides Newton’s *‘Opticks’* and Goethe’s *‘Theory of Colours’*, Chevreul’s *‘De la loi du contraste simultané des couleurs’* is regarded as one of the most important works in colour theory.

With the three primary colours red, yellow, and blue Chevreul developed a chromatic circle with 23 secondary colours for every primary colour, resulting in a circle of 72 colours. He also developed colour scales for successive brightening up and shading. His main works greatly influenced the developments in the art industry and modern painting.

Vincent van Gogh developed a new colour theory; he felt constantly in-between two thoughts, the first about material worries, a constant seesaw just to make ends meet, and the second thought devoted to the study of colours. He always felt as if he had to discover something (Michels-Wenz 1990, Shlain 2007).

“For the rest of my life I want to reflect on what light is” Albert Einstein

“The real subject of every painting is light” Claude Monet

5 Question Your Own Insights

5.1 Transatlantic Flight: Charles Lindbergh?

Lindbergh was not the first to complete a transatlantic flight. In fact, he was the 67th person to do so; John Alcock and Arthur Whitten Brown were the first to fly an aircraft non-stop across the Atlantic as early as 1919. A few days later, the English air ship R34 made its way non-stop from England to Mineola/New York and, after landing, back again non-stop (Krämer 2006).

5.2 Engine Powered Flight: The Wright Brothers?

Jacob Brodbeck (born on October 13, 1821 in Plattenhardt, Germany, died on January 18, 1910 in Luckenbach, Texas) was a German-American aviation pioneer and the draftsman of the aircraft which allegedly was the first in aviation history to successfully fly in 1865. In the US, Brodbeck is known as a Father of US Aviation. This was long before the Wright brothers took off on their maiden flight in the Wright Flyer Kitty Hawk in 1903.

5.3 Automobile: Carl Benz?

The Frenchman Étienne Lenoir patented an operational gas engine in 1860. Three years later, he drove a hippo mobile, a street vehicle powered by a gas engine, from Paris to Joinville-le-Point.

In 1881, Gustave Trouvé presented the first fully operational electric car suitable for daily use on the electricity trade fair in Paris—5 years before Benz's patent was filed. Numerous electric cabs were found on the streets of New York in 1899, before gas became cheaper and the combustion engine started its triumphal procession.

It is often said that Vienna-resident Siegfried Marcus, a mechanic born in Malchin, Mecklenburg, was the man who actually built the first automobile in 1875, long before Carl Benz and Gottlieb Daimler. The Marcus myth is based on a mistake though: Apparently, early chroniclers confused an automobile Marcus built in 1888 with a construction he had put on the streets in 1870. This was indeed early, but it was merely a type of pushcart with an auxiliary engine.

6 Conclusion/Summary

Can we study imagination or fantasy? No. And yes. By occupying oneself with things not directly connected to the specialty subject, the work, the actual problem. That can be arts, literature, philosophy, or any different science. Or, in the words of Prof. Dr.-Ing. Grabe, Head of the Geotechnical Engineering and Construction Management Institute of the Hamburg University of Technology: “It is the process of creation engineers are actually fascinated about. A deeper understanding of mechanics and material behaviour alone is not an adequate prerequisite, yet a useful one. Intuition and imagination make the difference. Only when these two are added, creativity begins.”

It is possible—and necessary—for us to doubt the opinion of authorities again and again. And to challenge your own opinion, your own knowledge—in order to create space for something new.

And at all times, this sentence by Paul Feyerabend (1986) seems valid: “Given any rule, however ‘fundamental’ or ‘necessary’ for science, there are always circumstances when it is advisable not only to ignore the rule, but to adopt its opposite.”

References

Asimov I (1990) Wenn die Wissenschaft irrt. Bastei Lübbe Publishing, Cologne

Bürgin L (1998) Irrtümer der Wissenschaft. Gondrom Publishing, Bindlach

Feyerabend P (1986) Wider den Methodenzwang. Suhrkamp Publishing, Berlin

Israel H, Rukhaber E, Wienmann R (eds) (1931) Hundert Autoren gegen Einstein. Voigtländer Publishing, Leipzig

Kästner E (1931) Parole Emil. Hanser Publishing, Munich. New published (1998)

Krämer W (2006) Irren ist menschlich. In: Vom Urknall zum Bewusstsein, pp 347–355

Nettle D, Clegg H (2006): Schizotypy, creativity and mating success in humans. Proc R Soc B 2006 273 1586 611–615 doi:10.1098/rspb.2005.3349, pp 1471–2954

Nettle D, Keenoo H (2005): Schizotypy, creativity and mating success in humans. Proc R Soc B 2005 doi:10.1098/rspb.2005.3349

Shlain L (2007) Art and physics. Harper Perennial Publishing, New York

Michels-Wenz U (1990) van Gogh. Feuer der Seele. Insel Publishing, Berlin

Vollmann W (2007) Uncentering the Earth, Phoenix, London

Part III
Manufacturing and Management Costs

Laser-Assisted Tape Placement of Thermoplastic Composites: The Effect of Process Parameters on Bond Strength

C. M. Stokes-Griffin and P. Compston

Abstract The manufacturing process for high performance composite materials is typically slow due to labour intensive lay-up processes followed by long cure cycles of thermosetting resins. Thermoplastic materials be can processed by fusion bonding, a welding process based on the diffusion of polymer molecules across the bond interface at elevated temperatures. This process can be orders of magnitude faster than a typical thermoset cure. Furthermore, when coupled with a placement technology such as automated tape placement (ATP) or filament winding, the composite can be bonded in situ as it is placed. The part is ready for finishing as soon as placement or winding has completed. This approach shows much potential for flexible and automated manufacture of lightweight and high performance automotive structures, including high pressure storage vessels for gaseous fuels. The placement rate must be maximised for production, however maintaining composite quality is nontrivial due to the highly dynamic behaviours at the nip point. A small parametric study was performed to investigate the effects of laser power and consolidation force. A laser-assisted tape placement system was instrumented with temperature and pressure sensors so as to measure the temperature and pressure profiles experienced at the bond interface in the nip point region. The recorded temperature and pressure profiles were fed into a bonding model to predict the resulting strength. Mechanical tests were performed on Carbon/PEEK lap shear samples and compared with strength predictions.

1 Introduction

The high specific strength and stiffness of fibre-reinforced polymer composites makes them an attractive choice of material for use in lightweight and high performance structures. Traditionally the manufacturing process for such materials is

C. M. Stokes-Griffin (✉) · P. Compston
Research School of Engineering, College of Engineering and Computer Science,
The Australian National University, Canberra ACT 0200, Australia
e-mail: chris.stokes-griffin@anu.edu.au

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_13,

too slow and costly for use in mass produced vehicles. However there are some automotive components such as compressed natural gas (CNG) tanks where the cost benefit of using composites is favorable compared to metals. The production rate and recyclability are still limiting factors.

Traditional composites manufacture is slow due to labour intensive layup processes followed by long cure times of thermosetting resins. Additional costs for pre-impregnated materials and autoclave cure must be considered for high performance composites. Technologies such as filament winding, automated tape placement (ATP) have the ability to eliminate the labour intensive layup process, however the long cure cycles still remain.

Composite materials with a thermoplastic matrix can be processed by fusion bonding, a welding process based on the diffusion of polymer molecules across the bond interface at elevated temperatures. This process can be orders of magnitude faster than a typical thermoset cure. Furthermore, when coupled with a placement technology such as automated tape placement (ATP) or filament winding, the composite can be bonded in situ as it is placed. The part is ready for finishing as soon as placement or winding has completed. This process shows a lot of potential for mass production of composite materials.

The process is also much cleaner as no solvents are involved. End of life credentials are also better as the thermoplastic composite can be melted and reformed.

The thermoplastic tape placement process is an attractive manufacturing technique as it is faster, cleaner and automated. While research has been conducted in the area, the process has not yet reached maturity. A complete understanding of the process and ability to accurately predict material quality in real processes is required in order for industry to adopt the technology.

1.1 Laser-Assisted Thermoplastic Tape Placement

Hot gas gun heat sources have been traditionally used for the in situ thermoplastic tape placement process (Sonmez and Akbulut 2007; Tierney 2006; Khan et al. 2010). In more recent times, high power diode lasers have emerged (Barasinski et al. 2010; Schledjewski and Miaris 2009; Grouve et al. 2012) as they can deliver much higher heat fluxes allowing for higher placement rates and have near-instantaneous response which is ideal for process control. Limited research has been conducted on the laser-assisted tape placement process.

The laser-assisted tape placement process is described by Fig. 1. A pre-impregnated composite tape is delivered to the surface of previously placed layers (substrate). A near infrared (NIR) laser is shaped into a rectangular spot using optics. This is aimed at the tape and substrate, melting the surfaces as they approach the nip point. The melted surfaces are pushed together by the consolidation device, resulting in a bond. Layers are formed by placing multiple tapes side by side. Parts are made by building up laminates layer-by-layer.

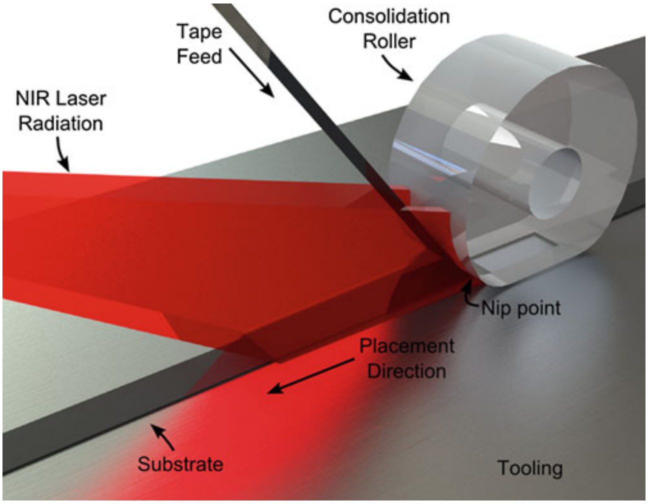


Fig. 1 A diagram of the laser-assisted tape placement system used in this study

2 Bonding Model

The bonding process is the source of strength development and is based on the diffusion of polymer molecules across the bond interface, a process known as healing. Healing will only occur if the surfaces are in intimate contact. The bond strength development process is therefore modeled by combining healing and intimate contact development models.

2.1 Intimate Contact

As real surfaces are not truly flat, the initial contact is limited to asperities. As temperature and pressure are applied the material softens and begins to flow increasing the level of intimate contact between the surfaces. In this study the Mantell and Springer (1992) non-isothermal adaptation of the simplified rectangular wave model was used to predict the level of intimate contact:

$$D_{ic}(t_b) = g^* \left[\int_0^{t_b} \frac{P_{app}}{\mu_{mf}} dt \right]^{1/5} \tag{1}$$

where t_b is the bonding time and P_{app} is the pressure applied to the interface. g^* is an empirically determined geometric parameter where 0.29 was the value assumed in this study as used in similar work (Tierney 2006; Mantell and springer 1992).

μ_{mf} is the temperature dependent fibre-matrix viscosity for a AS4/PEEK composite (Mantell and Springer 1992) :

$$\mu_{mf} = 132.95\left(\exp\frac{2969}{T(K)}\right) \tag{2}$$

2.2 Healing

Healing is the inter-diffusion/reptation of the polymer chains across regions of the interface that are in intimate contact. The rate of healing is highly temperature dependent. Yang and Pitchumani (2002) formulated a non-isothermal model of reptation theory from first principles. This model has been shown to correlate well with experimental data for non-isothermal conditions (Tierney 2006; Khan et al. 2010; Yang and Pitchumani 2002; Yang and Pitchumani 2003) :

$$D_h = \left[\int_0^t \frac{1}{t_w(T)}\,dt\right]^{1/4} \tag{3}$$

where D_h is the degree of healing which is proportional to the strength of the interface. T is the temperature of the interface and t_w is the weld time, the time required under isothermal conditions to achieve full interfacial strength. Khan et al. (2010) used the following temperature dependent expression for PEEK:

$$t_w(T) = 2 \times 10^{-5}\exp^{43{,}000/RT} \tag{4}$$

where R is the universal gas constant.

2.3 Coupled Bonding Model

Healing only occurs on areas in contact. For each increment of newly formed intimate contact, a separate healing process starts. Full bond strength occurs when the last increment of intimate contact has formed and has subsequently healed completely. Mathematically the degree of bonding D_b can be represented by:

$$D_b(t_h) = \int_0^{t_{ic}} D_h(t_h - \tau)\frac{dD_{ic}}{d\tau}\,d\tau \tag{5}$$

where t_{ic} and t_h are the times of last intimate contact formation and total healing time respectively. The strength prediction is calculated by multiplying the degree of bonding by the ultimate strength which is assumed to be 89.16 MPa (Schledjewski and Miaris 2009).

3 Experimental Method

Suprem™ T 60 % v/v AS4/PEEK-150 0.15 × 12 mm unidirectional prepreg tape was used in the experimental work. A single tape was placed onto another on top of aluminium tool at room temperature, forming a 2 ply unidirectional laminate. Process parameters were chosen to investigate the effects of laser power and consolidation force. The process parameters studied are shown in Table 1.

The strength of the interface was characterized using the ASTM D5868 lap shear test method as a single interlaminar bond can be tested in isolation. The lap shear test method has been used in similar work (Yang and Pitchumani 2002; Yang and Pitchumani 2003; Schell et al. 2009; Mantell et al. 1992).

3.1 Temperature Measurement

Due to the rapid placement rates and high heat inputs, temperature gradients can exceed 1000 °C/s in laser tape placement. It is therefore important to use thermocouples with a very fast response time/low thermal mass. 25.4 μm fine wire K-type thermocouples were attached to the surface of the substrates using a soldering iron and a minimal amount of PEEK shavings. Temperature was logged during the process at 100 Hz using a National Instruments cDAQ-9213 thermocouple module.

3.2 Pressure Measurements

Pressure was measured with a Tekscan I-Scan system using a type 5051 sensor which consists of a 44 × 44 sensel array with a pitch of 1.27 mm. Calibration was performed by applying pressure to the consolidation roller on top of a certified mass balance. Static pressure measurements were recorded consolidation forces of 150 and 300 N. The pressure values used in the bonding model were taken as the average pressure across the width of the bonding region, that being the pressure in the region between the tape and the substrate. The pressure distribution was converted to the time domain by multiplying the position by the placement rate.

Table 1 Process parameters for each study

Test	Laser power[W]	Placement rate [m/min]	Consolidation force [N]
A	1000	12	300
B	1200	12	300
C	1200	12	150
D	1400	12	300

3.3 Sample Preparation

For each process setting a total of nine lap shear samples were prepared. The gauge length, width and overlap of the samples were 90, 12 and 6 mm respectively. Due to the continuous nature of the tape placement process, it is not feasible to introduce the breaks in the layers necessary to produce a lap shear sample during processing. Instead, strips of 3 mm × 0.0254 mm polyimide tape were attached to the substrate prior to placement, so as to introduce breaks in the bond line precisely isolating a 6 mm long bonded lap region. After placement, breaks were made above the polyimide tapes on opposing sides of the sample using a 1 mm diamond slitting wheel. The result is a lap shear specimen as shown in Fig 2.

Fig. 2 Cuts are made in the *top (above)* and *bottom (below)* sides of the samples down to the polyimide tape so as to produce a lap shear sample

Tensile tests were performed at room temperature on and Instron testing machine at a loading rate of 13 mm/min. The lap shear strength was calculated as the peak load divided by the area of the fracture surface.

4 Results

The measured temperature distributions are shown in Fig 3. Since the laser power and placement rate is the same for tests B and C, the temperature was only logged for test B. While tests A and B are performed at different laser power levels, the measured peak temperatures are almost equal, however the cooling history is very different. A review of the process data revealed that the laser angle was set with a bias towards the substrate for test A, resulting in a higher substrate temperature yet a lower tape temperature prior to the nip point. This also explains the difference in the cooling history.

The pressure distributions for the different consolidation forces are shown in Fig 4. It can be seen that the conformable roller spreads the pressure over a larger area for higher roller forces.

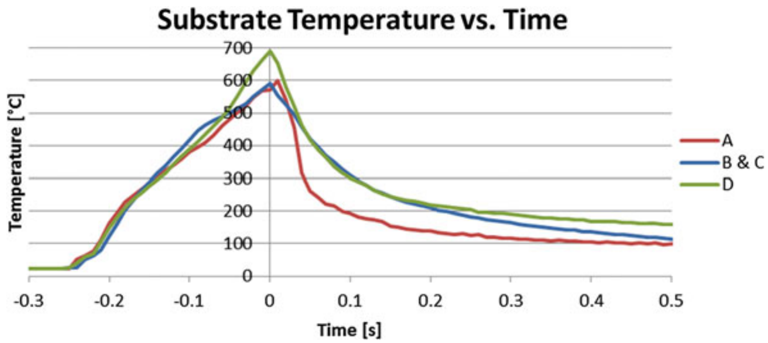


Fig. 3 Substrate temperature versus time relative to the nip point

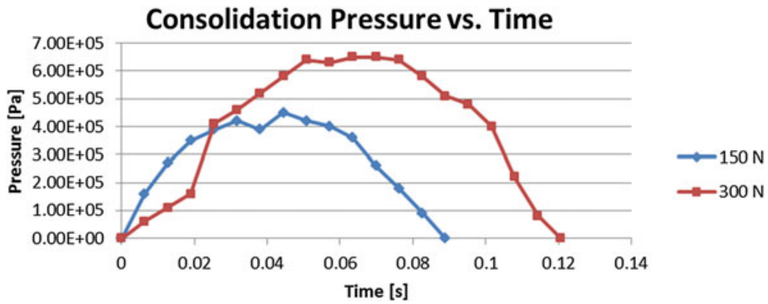


Fig. 4 Consolidation pressure versus time relative to the nip point

The combined temperature and pressure histories were applied to the bonding model. The results in Figs. 5 and 6 show that the degree of healing is high for most areas in intimate contact, thus the overall degree of bonding closely follows the degree of intimate contact. For all of the tests the degree of intimate contact is low (<0.40) and the limiting factor in the bond strength. The effect of laser power can be seen in Fig 5.

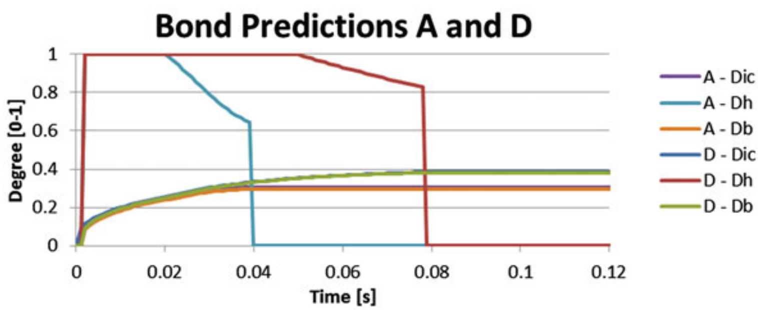


Fig. 5 Bonding model predictions for A and D showing the effect of laser power

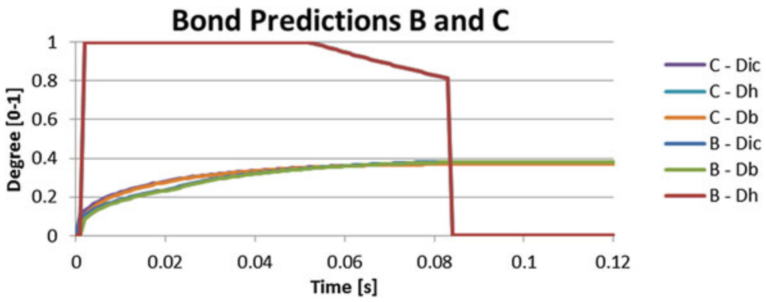


Fig. 6 Bonding model predictions for B and C showing the effect of consolidation force

The longer period at high temperature above the 343 °C melting point leads to increased levels of intimate contact development and a slight increase in the level of healing. Figure 6 shows that the consolidation force was predicted to have little effect on the final level of intimate contact.

The results of the lap shear tests are plotted in Fig 7 with the strength predictions. There is a reasonable amount of scatter in the results, however strength predictions agree well with the data and give a conservative prediction below the mean experimental value with the exception of test C. When low consolidation forces are used on the placement head used for this study, the hysteresis and friction in the pneumatic cylinder become more significant, thus the consolidation force becomes inconsistent. This gives a partial explanation of the lower lap shear strengths seen in test C.

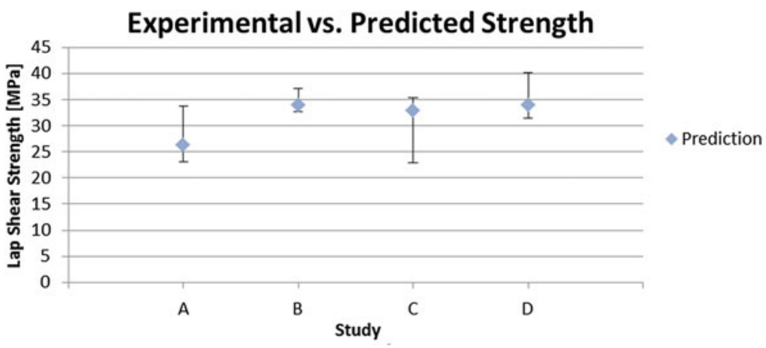


Fig. 7 Experimental versus predicted strengths

5 Conclusions and Future Directions

A laser-assisted tape placement system was instrumented with thermocouples and pressure sensors. A method was developed for fabricating lap shear samples during placement by introducing discreet breaks into the interlaminar bond using polyimide film. A bonding model was formulated and the experimental temperature and pressure data was used in the model to predict the interlaminar bond strength. Predicted bond strengths were found to agree well with lap shear mechanical tests.

The agreement between the modelled bond strengths and the lap shear results indicate the validity of the bonding model. The model predicts that intimate contact development was the limiting factor for the current study with the highest degree of bonding reaching only 0.39. The modelled difference between 150 and 300 N consolidation forces was minimal, suggesting that much higher forces are required to achieve full bond strength. Higher laser power was shown to increase the level of intimate contact by a reasonable level as the interface was above the melting point for a longer period of time.

Acknowledgment The authors gratefully acknowledge funding provided by the Commonwealth of Australia, through the Cooperative Research Centre for Advanced Automotive Technology (AutoCRC) visionary project scheme.

References

Barasinski A., Leygue A., Soccard E., Poitou A (2010) An improvement in thermal modelling of automated tape placement process. In: International Conference on Advances in Materials and Processing Technologies, AMPT2010. pp 185–190, Paris

Grouve WJB, Warnet LL, Rietman B, Akkerman R (2012) On the weld strength of in situ tape placed reinforcements on weave reinforced structures. Compos A 43(9):1530–1536

Khan MA, Mitschang P, Schledjewski R (2010) Identification of some optimal parameters to achieve higher laminate quality through tape placement process. Adv Polym Tech 29(2):98–111

Mantell SC, Springer GS (1992) Manufacturing process models for thermoplastic composites. J Compos Mater 26(16):2348–2377

Mantell SC, Qiuling W, Springer GS (1992) Processing Thermoplastic Composites in a Press and by Tape Laying - Experimental Results. J Compos Mater 26(16):2378–2401

Schell JSU, Guilleminot J, Binetruy C, Krawczak P (2009) Computational and experimental analysis of fusion bonding in thermoplastic composites: Influence of process parameters. J Mater Process Technol 209(11):5211–5219

Schledjewski R, Miaris A (2009) Thermoplastic tape placement by means of diode laser heating. In: SAMPE '09 Spring Symposium Conference Proceedings, Baltimore

Sonmez F, Akbulut M (2007) Process optimization of tape placement for thermoplastic composites. Compos A 38(9):2013–2023

Tierney J (2006) Modeling of in situ strength development for the thermoplastic composite tow placement process. J Compos Mater 40(16):1487–1506

Yang F, Pitchumani R (2002) Healing of thermoplastic polymers at an interface under nonisothermal conditions. Macromolecules 35(8):3213–3224

Yang F, Pitchumani R (2003) Nonisothermal healing and interlaminar bond strength evolution during thermoplastic matrix composites processing. Polym Compos 24(2):263–278

Sustainability in Automotive Pricing

T. Ruhnau and W. M. Bunzel

Abstract This research provides an overview of potential ways how to set prices for certain technologies, features and specifications for passenger cars focusing on the original equipment manufacture's (OEM's) view. After a short introduction, the first part presents a decision model whether a feature can be priced at all. Seven questions guide the OEM to the result if pricing is applicable or not. According to the presented decision model, it is not possible to set prices for features which are not part of the actual car. Furthermore, pricing for options is limited to features that provide a higher benefit than disadvantage. For standard functionalities, a price can be set if there is already a price established within the field of competition. Pricing sustainable features is also possible if the OEM acts as the first mover under the condition that the feature which is intended to be priced is not linked to a matter of legislation. If it is a matter of legislation but giving a pricing signal to competitors is possible, assigning a price to the feature is still feasible. The second part of this research addresses the pricing process. The first step to find the optimum price position for a sustainable feature is to set price boarders. Afterwards, various details need to be taken into account. This research presents a set of suitable ways to reflect the corporate strategy, competition, characteristics of the feature to be priced, market and communication within the pricing process. In addition, it sharpens the view on different ways to offer sustainable features by presenting two examples from practice.

T. Ruhnau (✉) · W. M. Bunzel
BMW Group, Petuelring 130 80809 Munich, Germany
e-mail: thomas.ruhnau@bmw.com

W. M. Bunzel
Institut für Technik und Design, Nördliche Ringstraße 19 85057 Ingolstadt, Germany
e-mail: wilfried.bunzel@bmw.de

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_14,

1 Introduction

In many cases, the increasing need to consider sustainability and environmental responsibility in the corporate strategy of automotive companies is a quite expensive task (IKA 2012). Market and cost pressure as well as various legislation approaches necessitate transferring one time investments, development and production costs to the customer. This research provides an overview which features can be priced as well as ways how to set prices for certain technologies, features and specifications focusing on the original equipment manufacture's (OEM's) view.

2 Price It or Not: A Decision Model

The first question that needs to be answered is whether there is a chance to price a new feature that increases the level of sustainability at all. In the following, a decision support is presented by an easy-to-use set of criteria. In total, seven answers need to be given until it can be decided if it is appropriate to price a feature or not.

Buying a car is—in most cases—not only a rational decision by the customer. Moreover, the customer also expresses his personality, character and status and the value which is delivered by his preferred choice is not only represented by the tangible features (Lauszus 2004). Nevertheless, the implementation of new sustainable technologies in recycling, production or development can just influence the overall brand value or drive certain facets of brand strengths (Homburg and Krohmer 2009). In consequence, the first question in the decision model represents a limitation for concrete features of the car. If an OEM implements more sustainable production technologies, increases the amount of recyclable parts, streamlines the product development or similar topics, the brand value might be positively influenced. Later—if the OEM is able to communicate his achievements in sustainability—this might also lead to the opportunity to establish a price premium versus competitors without the respective technology. But there is no direct measureable link to the customer's willingness to pay. Thus, in this decision model, those technologies are excluded from the presented examination. A concrete price for a technology detached from the actual car cannot be set. Prices can only be defined for a certain specification built into the vehicle.

The following topic focuses the way how sustainability features are offered. Some specifications can be offered either as a standard feature or as an option which can be ordered individually. In general, you can assume that optional features should be priced (Engelke 2004). But especially within the field of features that increase the perception of sustainability, negative effects might correspond.

In consequence, optional features should only be priced if the positive contribution to the overall value of the product exceeds the negative effects which occur complementarily. For example, a special low-emission model offered in addition to the regular engine reduces CO_2 emissions and fuel consumption by 10 % while the maximum power output is 5 % lower at the same time. The OEM needs to assume a value of the reduced emission/fuel consumption versus the maximum power output. Of course, additional strategic targets, such as volume targets, fleet emission targets etc. might influence the pricing decision as well. Those factors are not reflected in this decision rule. If the OEM still sets a price although the value of the sustainability feature is assumed to be lower than the complementary negative effect, the potential price does not represent the additional value of the specification; rather the opportunity to individualize the product is priced.

After taking a look on optional features, standard specification changes need to be analyzed, as well. Within this field, several aspects have to be taken into consideration. Legislation, first mover advantages, competition and signaling influence the pricing possibility. At first, the question is if the specification has to be integrated into the vehicle in order to fulfill certain legislation targets. In general you can assume that customers are not willing to pay for the fulfillment of local regulations. If basic laws to register a car are not held, the product could just not be offered in the appropriate market. Thus, there is no alternative for the OEM but to equip the cars with specification that grant to achieve the appropriate legislation requirement. But this assumption can be canceled if some conditions are given. If the OEM is the first mover within his defined vehicle or market segment, he might be able to give a signal to the competition that pricing of a certain feature is appropriate despite the fact that regulations force the companies to launch the specific technology. For the industry, no disadvantage arises if all OEMs stick to this kind of silent bargain initiated by the first mover (Maschler et al. 2013). The other way round, if the OEM is not the first mover, but one or more competitors already priced the necessary feature, the smartest way is to follow. If no price can be observed within the field of competition, a price increase of the car is not applicable without eroding the existing price position.

The described way of determining the possibility of pricing is not only valid for topics which are enforced by law but also for other aspects of increased sustainability. If an OEM is not the first mover and competitors give an orientation, the most suitable way is to follow accordingly. The widest scope to set prices arises if an OEM holds the status to be the first mover for a new sustainability feature and the topic is and will not be influenced by regulations. In this case, the company can combine the specification integration with a wide range of price setting strategies (Kotler et al. 2008). Figure 1 shows the complete decision model and gives an overview about the criteria that drive the decision whether a feature should be priced or not.

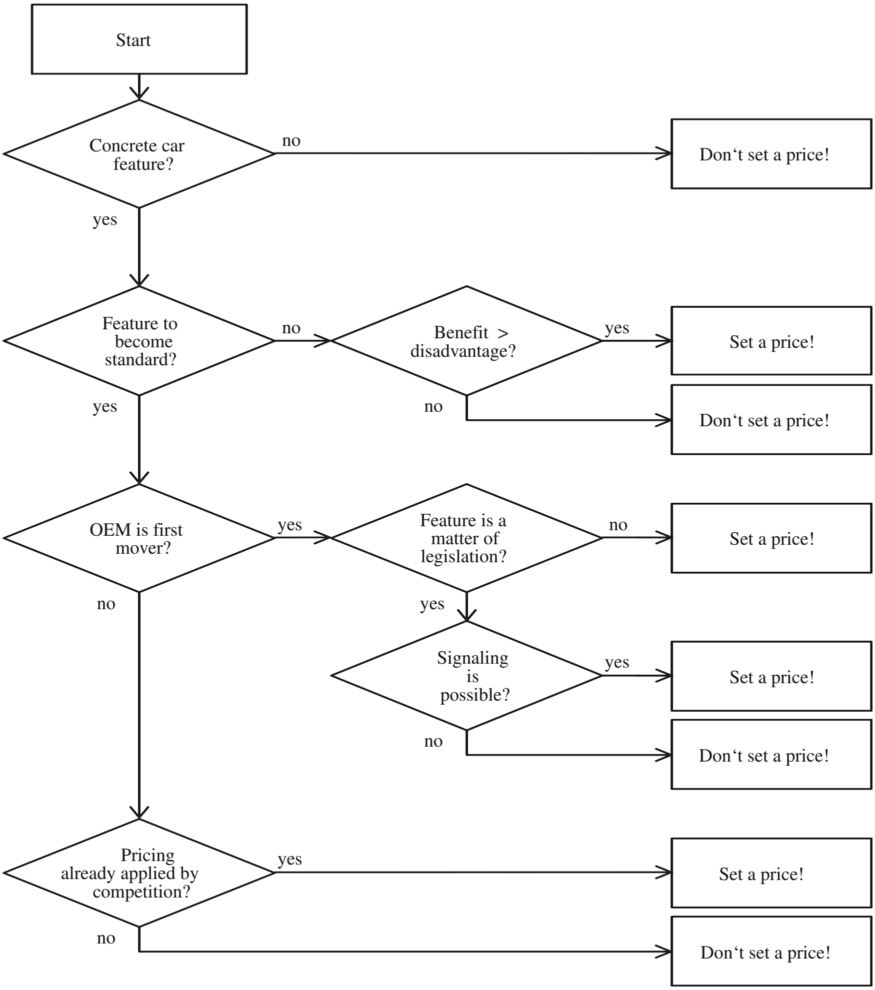


Fig. 1 Pricing decision model

3 How to Determine a Suiting Price Position

There is not one correct price position as prices are always linked with certain purposes. Therefore this section is a guideline showing possible steps in the process of pricing: Setting boarders, evaluating the field in between, deciding strategy, knowing background and competition, considering country and communication. Finally two examples are given.

As it is the global target of companies to maximize profit and create liquidity (Witte 2007), lowest price is influenced by production and purchasing costs. After deduction of taxes, turnover has to equalize expenses at least (Nagle et al. 1998; Smith 2012). Of course there are strategic decisions to be made at this point already. What minimum contribution margin has to be secured by each option or model? If profit neutrality is accepted as base for the lowest price of the discussed feature of sustainability, the next question is whether this target has to be reached including expenses within the sales channel and fixed costs or without.

The highest price position that could be achieved equals the realized customer value (Nagle et al. 1998; Simon and Fassnacht 2009; Smith 2012). Customers will not pay more money than the monetary realized value of the relevant option is. This value depends on each single customer's personal needs. Sustainable features can address functional, conscience or reputation needs. Further drivers of the customer value are reductions of total cost of ownership (Vohra and Krishnamurthi 2012). Basically this should be lower taxes and less fuel consumption, but also reduced maintenance costs could be a possible way—even though some of today's features tend to increase these [e.g. necessity to refill Ad Blue (Audi 2013; BMW 2013a)]. Lower taxes and reduced expenses for fuel are quantifiable positive aspects of a feature. One could deduct a price for that. Given that a car is usually owned for few years, customer is maybe ready to pay the savings from the first year or a certain percentage of his ownership for the feature in advance as long as the customer is still better off in the end (Vohra and Krishnamurthi 2012). In the worst case the customer value is even zero. This is the case for a feature that is generally needed or mandatory e.g. by law. So customers won't pay extra money to get a base driver's seat or a seat belt. The necessity can be direct (e.g. every car needs seat belts) or indirect (e.g. corporate average fuel economy). To find out the one and only value for this position is not possible as it depends on each single customer.

The discussed aspects lead to the inverse demand-function as a way to determine the optimum price position and/or qualify the area between the set boarders (Simon and Fassnacht 2009). This curve shows how many customers are willing to pay which price or—from company's point of view—what volume could be sold at which price at given competitors' average price (see Fig. 2). That enables the price setter to find a profit maximum. Still, some requested premises are not fulfilled in this case (Simon and Fassnacht 2009). Usually, you do not have a complete free market at all. In most cases, a customer decides first what car he is going to buy and decides about options afterwards with given features and price. E.g. a BMW customer cannot buy the headlight washer system from Audi.

Still, there is a comparable formula that more customers tend to buy a feature the cheaper it is (Vohra and Krishnamurthi 2012). In few cases volume might stay stable for a broad range of prices, e.g. if the feature is almost vital like park distance control. Rare cases could be found where really low prices do not lead to high take rates neither because the low price is seen as signal that this feature is not valuable by the customer.

Having found a proper range of prices that might be part of discussions within the pricing process, the OEM has also to make up his mind about several strategic

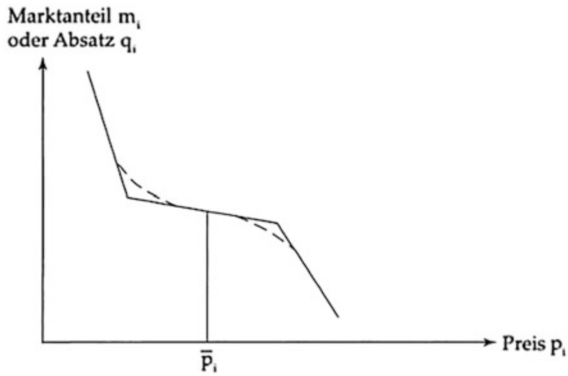


Fig. 2 Inverse demand-function with competitors' average price (figurative) (Simon and Fassnacht 2009)

and general aspects. Is the feature supposed to be offered as standard equipment or as an option? Offered as standard equipment, every customer will have the advantage and driver's experience is continuous regarding the given feature. With regards to pricing, every customer has to pay his share. On the other hand the price is integrated into the car price directly raising the communicated sticker price. Offered as an option, generally higher prices can be set and packaging with other features including granting of discounts is possible. If the OEM makes up his mind about pricing early enough other strategies like target costing/target pricing (Clifton et al. 2004) can be applied.

Price setters have to be aware that overall customer spending is limited in most cases independent from the decision in which way the feature is offered. Furthermore pricing has to be in line with competition (Nagle et al. 1998). That does not mean that pricing has to be equal at direct competitors, but a general strategic price position has to be found (Mohr et al. 2010). A look at the competitors—offer and price wise—gives the base for the decision to follow or not [e.g. Mercedes uses to set higher prices for vehicles and optional features than Audi or BMW, even though changes could be observed recently (Audi 2013; Mercedes 2013)]. Talking about total spending, comparable thoughts need to be spent regarding lease ranges for company customers.

Pricing from OEM's point of view starts with general aspects like production costs, strategic decisions, competition and customer value. The next step takes national aspects into consideration. Different countries have different laws, cultures and—most important—customer needs. That also needs to be reflected in pricing as well as ways of payment (leasing or buying), exchange rates, taxes and budget to spend.

A further aspect that should not be forgotten is marketing and communication. This aspect is not limited to the OEM's own measures. Competition's communication is always directly linked to your company as well. Customers will ask whether a comparable feature is also offered at yours. Besides, as mentioned above, decision and communication of setting a price or not by the first mover influences following OEM's decision. Availability as well as functionality and price have an indirect influence on brand experience and therefore brand value which leads to higher achievable prices and/or volumes. In most cases this effect is not quantifiable. In the best case you can measure brand values at customer surveys but a valid link to pricing is hard to establish. If general standards and communication aspects are in place (e.g. CO_2 emissions and fuel consumption with coloured efficiency class ("B"), s. Fig. 3) customer's awareness is much more likely to follow than in cases where information about technologies is hidden behind a deep link.

Fig. 3 Build your own section shows sustainability aspects prominently (BMW 2013a)

A short look at two samples shows different ways of offer and pricing. First examples are measures to reduce nitrogen oxide at Diesel models. There are catalytic converters (some need refilling of Ad Blue) to reach target values of upcoming EU6 emission guide line. These are offered as standard on some models (Mercedes 2013), as separate model with a price increase and reduction of diesel tank as well as performance (Audi 2013) or as an option (BMW 2013b). BMW's so called EfficientDynamics models represent a second example of how to price sustainability (BMW 2013b). These models sum up several measures (e.g. reduced power, special wheels) to reduce consumption and CO_2 emission. Offered as model, they are priced at the same amount as comparable standard models which have more power.

4 Conclusion/Summary

To find the best price for a specific feature and situation, price setters have to take several aspects into consideration. The decision drivers shown above are generally helpful but especially needed in the case of pricing features that are related to sustainability. These drivers are seldom heading in the same direction, in most cases opposing suggestions have to be matched to find the sweet spot.

References

Audi (2013) Konfigurator Audi A6 Limousine. http://konfigurator.audi.de/entry?mandant=accx-de&vc=a6limo&&next=model-page. Accessed 23 March 2013

BMW (2013a) Konfigurator BMW 3er. http://www.bmw.de/vc/ncc/xhtml/start/startWithConfigUrl.faces;jsessionid=5e19a0bfd930927e78f3cc4a8b7a.2?country=DE&market=DE&productType=1&brand=BM&language=de&name=p4w3a5z4#MODEL_ENGINE. Accessed 23 March 2013

BMW (2013b) Die BMW 3er Limousine. Preisliste. BMW Group, München. http://www.bmw.de/dam/bmw/marketDE/bmw_next/newvehicles/allfacts/pricelist/3_LI_F30_pricelist.pdf.download.1360309991070.pdf. Accessed 23 March 2013

Clifton MB, Bird HMB, Albano RE, Townsend WP (2004) Target costing. Marcel Dekker, New York

Engelke J (2004) Preisgestaltung von Sonderausstattungen. In: Ebel B, Hofer M, Al-Sibai J (eds) Automotive management, Springer, Heidelberg

Homburg C, Krohmer H (2009) In: Marketingmanagement. Gabler, Wiesbaden

IKA (2012) CO_2 Reduzierungspotenziale bei PKW bis 2020, Abschlussbericht: http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/Studien/co2-reduzierungspotenziale-bei-pkw-bis-2020-abschlussbericht,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf. BMWi, Bonn

Kotler P, Keller KL, Bliemel F (2008) Marketing management. Pearson Studium, München

Lauszus D (2004) Bestimmung des Markenpremiums in der Automobilindustrie. In: Ebel B, Hofer M, Al-Sibai J (eds) Automotive management, Springer, Heidelberg

Maschler M, Solan E, Zamir S (2013) Game theory. Cambridge University Press, Cambridge

Mercedes (2013) A-Klasse. Preisliste. Daimler AG, Stuttgart. http://www.mercedes-benz.de/content/media_library/germany/mpc_germany/de/mercedes-benz_deutschland/pkw_emb_nextgen/neufahrzeuge/a-klasse/preislisten_pdf/A-Klasse_W176_Preisliste.object-Single-MEDIA.download.tmp/Preisliste_A-Klasse_130201.pdf. Accessed 23 March 2013

Mohr JJ, Sengupta S, Slater SF (2010) Marketing of high-technology products and innovations. Pearson Education, New Jersey

Nagle TT, Holden RK, Larsen GM (1998) Pricing. Springer, Berlin

Simon H, Fassnacht M (2009) Preismanagement. Gabler, Wiesbaden

Smith TJ (2012) Pricing strategy. Cengage Learning, Mason

Vohra RV, Krishnamurthi L (2012) Principles of pricing. Cambridge University Press, New York

Witte H (2007) Allgemeine Betriebswirtschaftslehre. Oldenbourg Wissenschaftsverlag, München

Conceptual Design Evaluation of Lightweight Load Bearing Structural Assembly for an Automotive Seat Adjuster Mechanism

M. Kajtaz, A. Subic and M. Takla

Abstract An application of a novel methodology in a redesign of the load bearing subassembly of an automotive seat adjuster is presented. This novel methodology efficiently evaluated concept variations at a higher rate than the traditional approach based on FEA and therefore enables a comparison of the objective spaces rather than undesirable point design comparisons. This significant increase in efficiency increased the amount of generated knowledge that was presented to the design engineer in a form of the Pareto front comparisons. The comparisons of the Pareto fronts allowed for a clear identification of Concept #3 as the preferred solution, given the load-bearing and the light weighting criteria only. The results also indicated that Concept #2 could also be promising solution after major enhancements, as it showed potential to outperform the current solution in some cases.

1 Introduction

Due to increased need for fuel efficiency and emissions reduction (EUR-Lex 2011; NHTSA 2012), the automotive industry is investing significant effort into downsizing and light-weighting by implementing alternative design and technology strategies and in particular through substitution of materials. Studies have shown that 10 % reduction of vehicle weight results in 5–8 % increase in fuel efficiency (Brooke and Evans 2009; Gibson 2000). To meet the stringent legislation targets, an ordinary material substitution that is relaying on material performance improvements alone may not be sufficient. Advancements in structural concepts also need to be considered to bridge the gap between the current situation and the desired targets (see Fig. 1). There is a general consensus that currently available

M. Kajtaz (✉) · A. Subic · M. Takla
School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, PO Box 71 Bundoora, Melbourne VIC 3083, Australia
e-mail: mladenko.kajtaz@rmit.edu.au

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_15,

engineering tools may not be efficient or adequate in tackling alternative light-weight structural concepts. Additional research effort needs to be directed towards the development of more appropriate tools. In that regard, the authors have previously developed a novel approach (Kajtaz et al. 2013) capable of achieving significant improvements in efficiency and confidence over a traditional approach while not sacrificing the optimality of the solution. This paper presents an industrial application of the developed approach, which involves redesign of the load bearing subassembly of an automotive seat adjuster. The developed method evaluates a range of concept variations at a higher efficiency rate than the traditional approach based on FEA. The study also demonstrates an extensive knowledge base that is generated when the proposed method is applied in order to facilitate more informed, objective and confident decision-making early in the design process.

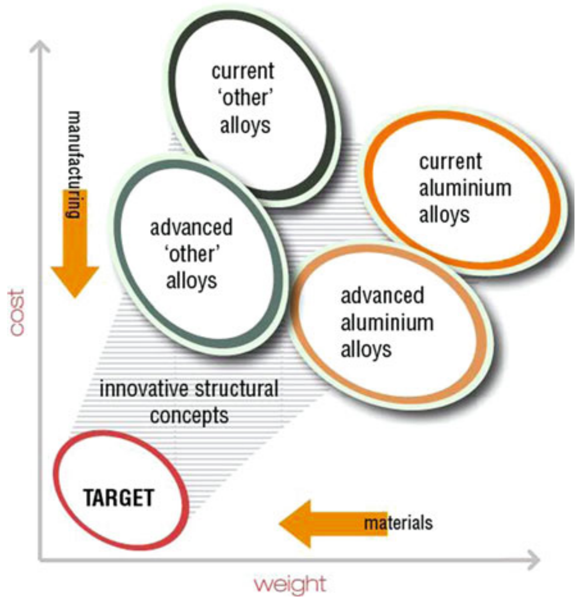
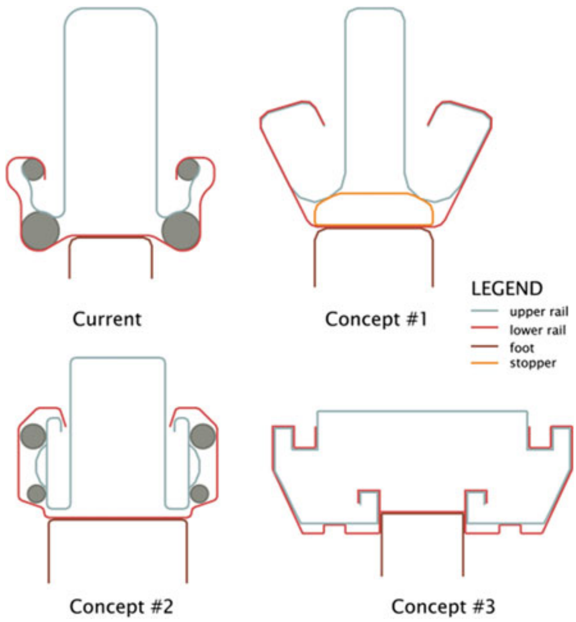


Fig. 1 Down-weighting by material substitution and innovative structural concepts (Kajtaz et al. 2013)

2 Generated Concept Solutions

The desired system functionality was achieved via a range of concept solutions and the preferred solutions are identified for further evaluations with the respect to the load bearing capabilities. The selected solutions tend to achieve the desired system functionality in their specific and innovative way, however, while some of them resemble the current configuration, others tend to be more inventive. The following concepts were evaluated using the novel approach (Fig. 2):

Fig. 2 Current solution and proposed concepts



- **CONCEPT #1**: While the current solution features the ball bearings to facilitate a relative motion between the rails, Concept #1 instead relies on a sliding device, identified as "stopper". Intuitively, the stopper directly influences the overall weight of the solution and it is almost independent with the respect to the crash resistance, which is the second objective. However, the effects of the implied added stiffness are unknown and may be favourable in some load cases. It is therefore critical to evaluate if the presence of the stopper is detrimental to the overall performance and if there exists a particular shape or configuration of the stopper that would provide an efficient and effective overall solution.
- **CONCEPT #2**: This concept is perceivably an incremental improvement of the current solution. From the perspective of the design engineers of the current solution, the performance of this solution may partially be predicted by their experience-based knowledge. However, even for them, there are still ambiguities on effects of the wider foot-print, different heights of the components, increased number of point contacts, etc.
- **CONCEPT #3**: Unlike the other concepts, Concept #3 is a revolutionarily novel design in comparison to the current solution. It reduces the number of components by eliminating the rolling balls and ball cages and by absorbing a sliding device directly into the design of the rails. Furthermore, it features a number of novelties such as different proportionality and topology, surface contacts and a material substitution, whose effects cannot be intuitively predicted.

3 Finite Element Model

The load bearing subassembly, shown in Fig. 3, as a safety critical component of an automotive seat is subject to the specific safety requirements specified in many road safety regulatory standards such as FMVSS 207/210 (NHTSA 1998) or ECE R14 (UNECE 2006). A generic model of the load bearing components usually consists of the front and rear feet, the upper and lower rails and the cross members that link the left and the right hand sides. During a car crash or the most severe simulated crashworthiness test, the observed failure of a seat is a partial separation of the upper and lower rails. The upper and lower rails are usually vertically locked together via "C" shaped sections of the rail lips oppositely bent and a rolling mechanism between them. As the lower rail is fully fixed to the feet and due to a moment applied to the upper rail by the inertia, the "C" shaped sections tend to open causing the separation of the rails (see Fig. 4).

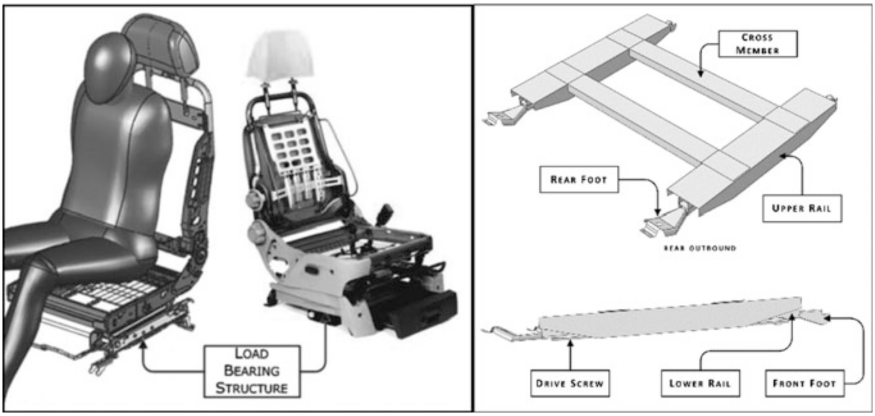


Fig. 3 Load-bearing components

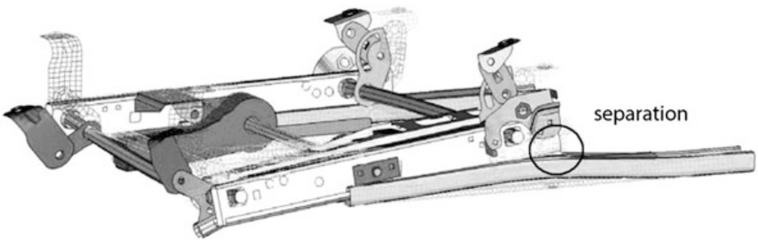


Fig. 4 Deformation of load-bearing components

3.1 Extended Substructures

The approach, outlined in Kajtaz et al. (2013), for a comparative evaluation of engineering design concepts that exhibit non-linear structural behaviour under load is adopted in this study. The preparatory steps for the adaptation of the load bearing components to the approach require definition and implementation of the extended substructures. As the load transfer between the rails and the rails interfaces themselves were of a very high complexity and very non-linear in their nature, utilisation of the traditional substructures would be impractical and very inaccurate for this problem. However, to allow for the benefits of the substructuring to be still applicable, the extended substructures were successfully implemented (see Figs. 5 and 6). In particular, Fig. 6 indicates a large discrepancy in the response of the assembly if the traditional substructure were used. This discrepancy was then gradually reduced as the extended substructures of the components were incrementally introduced by replacing the traditional substructures. The incremental introduction of the extended substructures was not necessary and it was used here for the demonstrative purposes only. The intermediate responses of the assembly are shown in Fig. 7, and Table 1 summarises the recommended values for the parameters used in the extended substructure definition of Concept #3 (see Fig. 5).

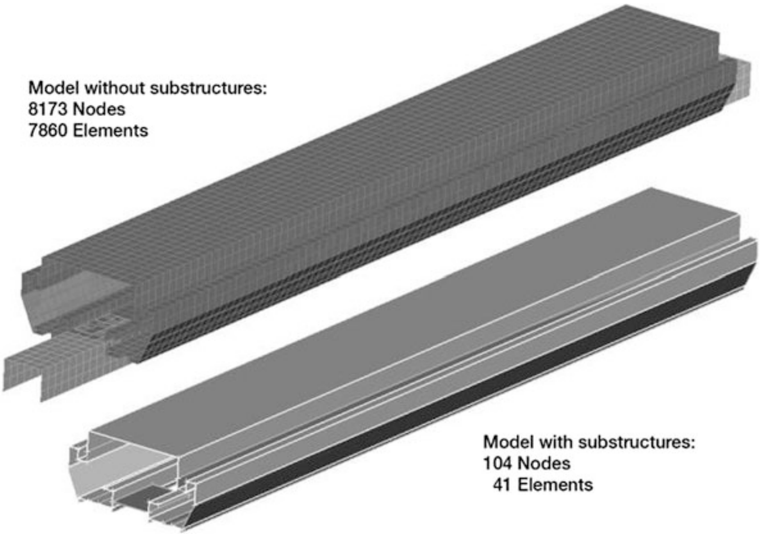


Fig. 5 Concept #3 model size–with and without extended substructures

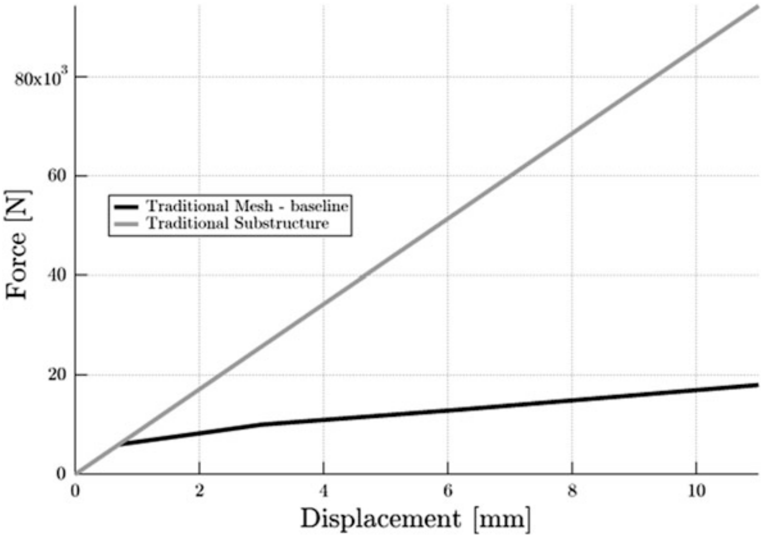


Fig. 6 Extended substructure versus traditional substructure

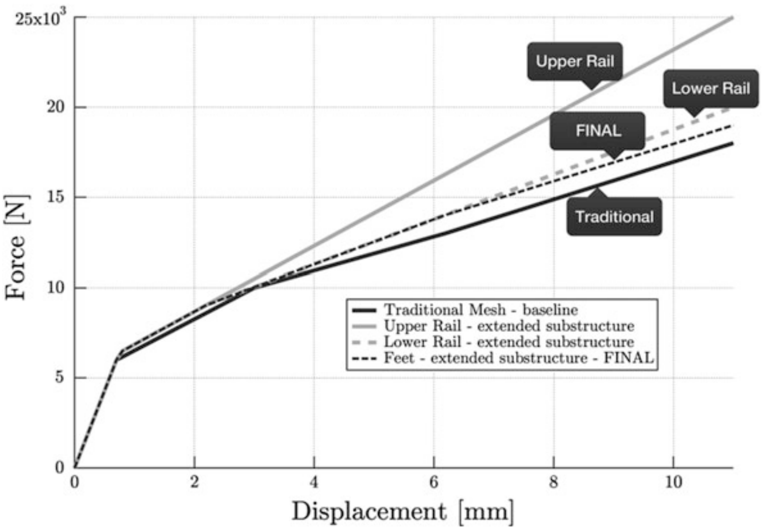


Fig. 7 Extended substructure performance

Table 1 Extended substructure parameters for Concept #3

Upper rail		Lower rail		Front foot		Rear foot	
m	t	m	t	m	t	m	t
0.09	1214.37	0.12	2520.27	0.12	1974.80	0.11	2084.6

The interpolation approach to determining the parameters m and t, as described in Kajtaz et al. (2013), produced final results that are 90 % accurate when compared with the traditional FEA based approach applied to the same class of design problems (Fig. 7). The practical application required a balance between accuracy, time and effort to produce an implementation that was feasible and acceptable, therefore different user preference with respect to these parameters may produce alternative results.

3.2 Optimisation/Search Algorithm

The FEA results produced in the search were assessed by the constraints and rated by the objective functions. The objective of the design search was to find the lightest design that maximises the crash resistance expressed as a reaction force on applied external loading. The input design parameters were carefully defined to effectively produce varieties of the rail configurations. The optimisation algorithm used in this study was Multi-objective Particle Swarm Optimisation (MOPSO) (Kennedy and Eberhart 1995). This algorithm is motivated by the simulation of social behaviour of bird flocking. Unlike the Genetic Algorithm (GA) and many other population-based algorithms mimicking the competitive theory of survival of the fittest, MOPSO promotes a concept of maintaining a population of collaborating individuals. This algorithm requires a user specification of only one parameter called “turbulence operator” (similar to the concept of mutation in GA), which is used to reduce the probability of premature stagnation. A small turbulence increases the robustness of the algorithm and the value used in this study was 0.2.

4 Results

A limited number of design variations of each concept design would have been investigated if the traditional approach based on FEA for evaluation of design concepts was utilised in this study. Since the details of the finite element models are relatively known and complete, the only remaining impediment to the effective utilisation of FEA in the concept evaluation was the prohibitive computational effort. An analysis of a single model variation using the traditional approach lasted in excess of two hours on average (compared to 20 min in the worst case scenario using the adopted approach) which indicated that a comprehensive comparison study may not be possible to complete within the set budget of 24 h. In particular, only 12 variations of each concept were obtained by parallelising the traditional approach, which definitely produced an insufficient amount of information in order to concur objective decisions. This further implies that unless the adopted approach or a similar enhancement is utilised, a point design comparison would virtually be obtained rather than a comparison of objective spaces. The imperilment of the point design comparison is a tendency to compare non-optimal variations of the concepts or in even worse case scenario: an optimal variation of one concept with the non-optimal variation of another. The result of the comparison is thus influenced by the choice of the non-optimal variation whereby the conclusion is expectably favourable to the concept that contributed with its optimal variation only because its counterpart is the non-optimal solution. This can be illustrated by considering Fig. 8 that shows the objective spaces of the selected concepts. For example, if a non-optimal solution of Concept #3 design presented near (3 kg, 10 kN) is compared with an optimal solution of Concept #2 design presented near (3 kg, 35 kN), the preferred option would obviously be the optimal candidate of Concept #2, although Concept #3 is capable of generating equally if not a better solution than Concept #2.

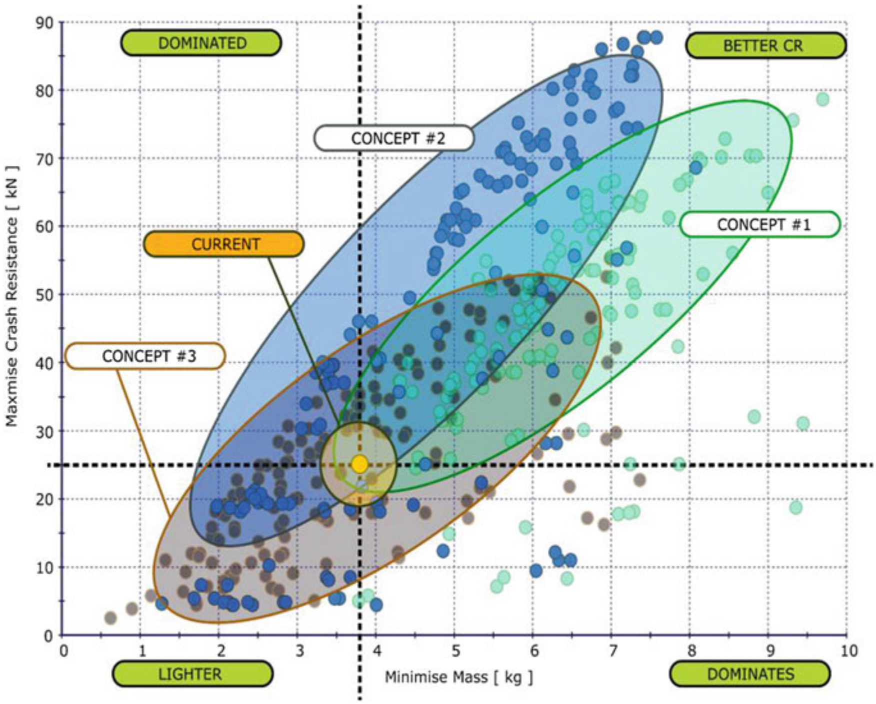


Fig. 8 Comprehensive concept comparison–comparison of objective spaces

By contrast, the adopted approach constraints the comparison to only optimal solutions whereby the Pareto fronts of all selected concept solutions are presented to the design engineer for a further preference selection. For this particular study, Fig. 8 summarises all non-dominated solutions from the perspectives of load-bearing and light-weighting, however the selection of the preferred concept is often greatly influenced by a matrix of other design factors such as manufacturability, cost, comfort etc. Nevertheless, the aim of this study was to evaluate the concept solutions with the respect to load bearing capability and (light)weight, thus from that perspective, the Concept #3 would be preferred and Concept #2 would also be considered after major enhancements as it showed potential to outperform the current solution in some instances. The sliding device implemented in Concept #1 proved to be detrimental to the overall performance of the concept. However, the comprehensive evaluation provided by the adopted approach generated required knowledge to identify disadvantages of this concept, which may be enhanced in the next design iteration in order to improve its candidacy.

5 Conclusions

In an attempt to overcome the demerits of the currently available engineering tools for a successful exploration of the innovative structural concepts, the authors have previously developed a novel approach (Kajtaz et al. 2013) capable of achieving significant improvements in efficiency and confidence, while not sacrificing the optimality of the solution. In this paper, which demonstrates an industrial application of that approach in a redesign of the load bearing subassembly of an automotive seat adjuster, an extensive knowledge base was generated and it was presented to the design engineer in a form of the Pareto front comparisons for a more informed, objective and confident preference selection. The presented evidence suggests that the sliding device implemented in Concept #1 proved to be detrimental to the overall performance of the concept. From the perspective of load-bearing capability and (light) weight, the Concept #3 would be preferred and Concept #2 would also be considered after major enhancements, as it showed potential to outperform the current solution in some instances.

References

Brooke L, Evans H (2009) Lighten up! Automotive engineering international, Society of Automotive Engineers (SAE) International

EUR-Lex (2011) A roadmap for moving to a competitive low carbon economy in 2050. http://eur-lex.europa.eu

Gibson TL (2000) Life cycle assessment of advanced materials for automotive applications. Society of automotive engineers (SAE) 2000-01-1486

Kajtaz M, Subic A, Takla M (2013) Comparative evaluation of engineering design concepts based on non-linear substructuring analysis. Advances in engineering materials, product and systems design. A. Subic. Switzerland, Trans Tech Publications, p 15–35

Kennedy J, Eberhart R (1995) Particle swarm optimization. In: IEEE International Conference on Neural Networks, Perth, Australia

NHTSA Federal Motor Vehicle Safety Standards (FMVSS) (1998) Crashworthiness. http://www.nhtsa.gov/cars/rules/import/fmvss/index.html. FMVSS 207/210, 1998

NHTSA Summary Of Fuel Economy Performance (2012) http://www.nhtsa.gov/cars/rules/cafe/CAFEData.htm

UNECE European Testing and Safety Regulations (2006) Seat Belt Anchorage. http://www.unece.org/trans/main/wp29/wp29regs1-20.html. ECE 14. 2006

Towards Sustainable Individual Mobility: Challenges and Solutions

W.- P. Schmidt and T. J. Wallington

Abstract Individual mobility is a basic human need. However, with the growth of global population, wealth, and technological development this need has led to long-term sustainability challenges with climate change and global gridlock being perhaps the most pressing issues. Solutions are complex and require changes in vehicle technology, infrastructure, driver behaviour, vehicle numbers, business models and inter-modality. While the path to solve the climate change challenge is rather established there is as yet no blueprint for the global gridlock issue. An integrated approach and strong cooperation between stakeholders is required.

1 Introduction

Individual mobility is and has been an important prerequisite and catalyst for economic and personal development allowing citizens to satisfy their needs in terms of labour and leisure, personal independence and flexibility and continues to enable them to "exercise many of their widely accepted human rights" (Coudou 2013). Mobility is a basic human need (Hunecke and Sibum 1997). One of Henry Ford achievements had been to make cars affordable and allow a growing number of citizens to satisfy their mobility needs enabling them a new level of mobility freedom. Economic growth and individual mobility are highly correlated.

The World Business Council of Sustainable Development (WBCSD) defined sustainable mobility as "…mobility that meets the needs of society to move freely,

W.-P. Schmidt
Ford, Henry-Ford Street 1, 50725 Cologne, Germany
e-mail: wschmi18@ford.com

T. J. Wallington (✉)
Ford Motor Company, 2101 Village Road, Dearborn, MI 48121-2053, USA
e-mail: twalling@ford.com

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_16,

gain access, communicate, trade and establish relationships without sacrificing other essential human or ecological requirements today or in the future." (World Business Council Sustainable Development 2004) If individual mobility is targeting sustainability then it has to fit into this concept. This definition though leaves space for different interpretations. The WBCSD definition of sustainable mobility should be seen rather as a guiding principle and caution is required with respect to claims of achieving sustainable mobility. Preferably such rather vague claims should not be used as per ISO 14021 which states that "An environmental claim that is vague or non-specific or which broadly implies that a product is environmentally beneficial or environmentally benign shall not be used. Therefore, environmental claims such as 'environmentally safe', 'environmentally friendly', 'earth friendly', 'non-polluting', 'green', 'nature's friend' and 'ozone friendly'" and one would like to add 'sustainable' "shall not be used" (International Organization for Standardization: ISO 14021 1999). In particular for vehicles detailed work had already concluded that a precise definition of "environmental friendly vehicles" is not possible (Schmidt and Butt 2010)—even more questionable would be terms like "sustainable vehicles" where additional social and economic criteria would be added to the environmental ones. Again, it is more important to the aim towards more sustainable patterns—rather than claiming that a certain pattern or vehicle is already sustainable. Thus tools measuring relative progress rather than absolute status are more helpful.

While on an individual vehicle level there are positive trends towards sustainability (see also for tools and results (Schmidt and Butt 2006)) it is important to note that the WBCSD concluded in their work that there are challenges with respect to the trend of increased emissions of CO_2 and increased congestion associated with growing global vehicle fleet (International Organization for Standardization: ISO 1402 1999). Thus it is important to analyse the challenges of moving towards more sustainable individual mobility.

2 Main Challenges

Vehicle emissions like particulates and nitrogen oxides have been significantly reduced over the last 20 years and ambient air concentration of various VOCs have declined—for example in Los Angeles where VOC concentrations have historically been dominated by vehicle emissions—on a yearly rate of 7.5 % (Warneke et al. 2012). In fact this led to a de-coupling of emissions and transport growth where we see declining emissions and increasing vehicles miles travel, population, GDP, and energy consumption in OECD countries (USEPA 2008). In contrast, vehicles are and will continue to have—at least in the near future—a significant impact on climate with its current share of around 10 % of all man-made CO_2 equivalent emissions.

This share differs from region to region looking more precisely at statistics for the 2010 global carbon emissions of in total 32 Giga tons (U.S. Energy Information

Administration 2013). By region, China emitted the largest share, 26 %, followed by the United States (18 %) and the EU-27 countries (12 %). Looking at the share of emissions produced by various sectors in the United States (U.S. Environmental Protection Agency 1990) and the EU-27 (European Environment Agency 1990) it is apparent that in both regions electricity generation produces the largest share of CO_2 emissions, about 40 %. The transport sector emits 32 % of the CO_2 in the U.S. and 25 % in the EU-27. Furthermore, passenger cars and other light-duty vehicles are responsible for 61 % of the transportation sector CO_2 emissions in the U.S. (U.S. Environmental Protection Agency 1990) and 73 % of the transport CO_2 in the EU-27 (European Environment Agency 1990; Transport and Mobility Leuven 2013). Overall, light-duty vehicles in the U.S. emitted 3.5 % of the global CO_2 in 2010 while LDVs in the EU-27 emitted 2 % of the global CO_2 in 2010.

The increasing vehicle population and mileage led to a continued increase in carbon dioxide emissions. To avoid an increase of the global average temperature beyond 2 °C a large reduction of global carbon dioxide emissions is required. Road transport will need to contribute and companies like Ford Motor Company have used a scientific approach to calculating their fair share of the emissions reductions required to stabilize atmospheric carbon dioxide at 450 ppm (Ford Motor Company 2010). A broad portfolio approach is required to achieve this pledge. Also world-wide regulators are targeting this most important environmental aspect of vehicles after other issues are seen as more or less solved (see above regulated emissions or recycling). However, these standards clearly pose a challenge to global automotive industry (e.g. 2020 targets for EU with only max. 95 g/km for cars, for Japan with min. 20.3 km/l and for US light duty vehicles with 182 g/mile). Note: Given the different test cycles/procedures as well as the differences in affected vehicles a comparison of these regulatory fleet targets is not straightforward.

Another huge challenge for individual mobility is its own success in meeting societal needs combined with population growth in urban areas. It is assumed that todays around 800 million vehicles could increase to around more than 2 billion vehicles by 2050 leading to a "global gridlock" (Ford Jr 2011). This issue is particularly pressing for mega-cities and regions. For example, in 2010 there was a 100 mile traffic jam that could be only cleared after 11 days. Given there will be around 50 Mega-cities with more than 10 million people in the next decades "the mobility model we have today, will not work tomorrow" (Ford Jr 2011). Irrespective of how clean the vehicles are—gridlock is still gridlock.

3 Potential Solutions

3.1 Climate Change

Reducing the climate impact of individual mobility can be achieved by actions in several areas including:

- Technology (vehicle technology, fuel and energy generation);
- Infrastructure improvements including improved urban planning and greater access to intermodal transport options;
- Vehicle numbers and usage.

Lots of improvements have been made and will continue to be made on a vehicle technology level. This is the measure of choice as it enables personal mobility freedom while not sacrificing the environmental requirements. This measure does not rely on behavioural changes while driving and offers the customer the "Power of Choice" in her or his purchasing decision. Currently, consumers can select between advanced gasoline and diesel vehicles, various levels of vehicle electrification (HEVs, PHEVs, BEVs), and various alternative fuel vehicles (biofuels, natural gas, and in future hydrogen, etc.). These technologies have different levels of tailpipe CO_2 emissions that are communicated by automotive manufacturers based on the regulated test cycles and procedures that make these vehicles comparable. However, it is important to resist calls for technology-prescriptive rules by pushing through regulations towards one specific technology. The track-record of regulators picking the right technology is not really promising. In the end technology, affordability, timing and customer acceptance need to match (e.g., see recent EU Commission communications around biofuels).

The non-tailpipe carbon emissions (e.g. from electricity or fuel generation, bio-mass production, material production etc.) are outside of the influence of automotive industry. For example, Battery Electric Ford Focus vehicle (BEV) has from a life cycle perspective lower CO_2 emissions than an advanced diesel Ford Focus (with 88 g tailpipe CO_2/km) only if the electricity carbon footprint of the selected electricity provider is below 400 g CO_2-eq/kWh (not just direct emissions from electricity generation but all life cycle emissions from electricity generation). Only if using electricity from a grid with a high renewable share like in Norway, Sweden, Switzerland, and Austria as well as in California will BEVs have substantially lower CO_2 emissions than vehicles powered by internal combustion engines. For other market BEVs are not necessarily linked to reductions in climate change impacts over their life cycle—at least not until they have further decarbonized their electricity supply. Obviously, the carbon footprint of the electricity grid mix is outside of the influence of automotive manufacturers. The electricity supplier controls the electricity grid mix and in some countries the customer can select low carbon electricity suppliers.

Another example for infrastructure related actions include road infrastructure investments that remove bottlenecks, increasing capacities, roundabouts and green waves that allow the traffic to flow more steadily reducing frequency and length of traffic jams. A Norwegian Study (Knudsen 2007) showed in case studies that road realignments and up-grades reduced CO_2 emissions by 38 % while local pollutants like NOx have been reduced by up to 75 %. The study also concluded that in two of three cases the better roads did not generate new car trips. An infrastructure-vehicle communication where the traffic-flow/congestion information is incorporated into navigation systems including real-time information on road signs can significantly help avoiding bottlenecks and congestion. The centralization of 40,000 signal controls permitted improved traffic flow management in Japan leading to a reduction of around 1 million tonnes of CO_2 emissions and by linking 20,000 automatic sensors measuring the traffic flow with this system helped to reduce emissions by a further 0.5 million tonnes (Stevens 2007). Just closing a 7.1 km gap in the Tokyo inner ring (Metro Express Inner Ring—Oji Section) led to an emission reduction of 20,000–30,000 tonnes of CO_2 while reducing the number of accidents by 30 % (JAMA 2006).

Another example is the driving style affecting the vehicle usage—there are various claims about real-world fuel economy being worse than certified by authorities. On the other hand a comparison of fuel economy before and after an eco-driving training demonstrates that a conscious driver reduces the real world fuel consumption below these certified numbers (in Europe around 20–25 % improvement by eco-driving training, long-term more than 10 % for private drivers). In a broad literature overview values differ from 5–35 % short-term and—3–25 % long-term (Berry 2010) showing that this is really dependent on the individual driver. These numbers indicate that on average very significant improvements are demonstrated by eco-driving (also called greener driving). For good reasons UNEP concludes 'Greener Driving is one important step towards sustainable mobility' (UNEP 2013). Reducing the increase in global vehicle numbers can contribute to a solution if the alternative transport modes are really satisfying the specific mobility needs and result in overall lower emissions than in those of vehicles.

3.2 Global Gridlock

Solutions for global gridlock are more difficult and more work is required to establish those. We are at the beginning of this journey. For a start let's analyse the same three approaches as for climate change:

- Vehicle technology level;
- Infrastructure measures;
- Vehicle usage.

Vehicle technology improvements towards clean vehicles are irrelevant for global gridlock. Indeed an argument could be made that vehicles consuming less expensive energy might be used more (rebound effect) potentially leading to increased gridlock. However, vehicle-to-infrastructure information technology, infrastructure measures reducing emissions by limiting the likelihood of congestion (see above) as well as a more relaxed green driving can improve but not solve the issue if we are approaching a high vehicle density. Nevertheless, in the short- to mid-term and long-term outside of Mega-Cities these approaches are clearly part of the solution. Also reducing the vehicle number can soften the impact—again if the alternative mobility modes are really satisfying the specific mobility need. Of all these measures, the biggest improvements can be expected by improved communication between vehicles and between vehicles and infrastructure. The connected vehicle cloud can provide faster real-time warnings for reduced traffic flows, infrastructure sending information about green traffic lights, free parking lots and roads with lower traffic density can direct vehicles faster to their destination—avoiding that they are part of the problem creating a gridlock. Autonomous driving as well as 'platooning' will maximize the utilization of the existing space on the roads by minimizing the vehicle-to-vehicle and maximizing the traffic flow for a given infrastructure (e.g., see EU co-funded project SARTRE). All this, though, is less a question of missing vehicle technology. The bigger challenge will be the infrastructure investments and the legal questions.

Solutions for global gridlock are difficult and more work is required in this area. We are at the start of this 'journey'. Additional solutions should be considered including:

- Vehicle footprint;
- Logistical concepts;
- New business models and inter-modality.

The vehicle footprint is developing in different directions: Within a vehicle segment the size of the vehicle is typically increasing with the comfort expectations of the customers. For example, the first Ford Fiesta (1976) had a length of 3565 mm and a width of 1567 mm (i.e. around 5.59 m^2) while the current Ford Fiesta increased to a length of 3950 mm and a width of 1722 mm (i.e. around 6.8 m^2) while still offering the space for five passengers. It has to be admitted though that the new Fiesta has with five stars EuroNCAP also the best possible third party safety rating and with down to 87 g CO_2 /km much better fuel consumption—not to speak about the increased comfort and entertainment. But still—from a pure global gridlock perspective this is an increase of more than 20 %. In larger vehicle segments the increase is even more significant leading not only to new parking problems but also a decreased infrastructure capacity. On the other hand smaller "vehicle" segments of the past (see two-seater Messerschmitt KR 175 with only three wheels in the early 1950s and a length of 3000 mm and a width of 1270 mm) might have a revival with new approval systems. For example, Japan's Ministry of Land, Infrastructure and Transport (MLIT) has established an approval system for ultra-compact mobility three- or four-wheeled vehicles being even smaller than the Japan-unique Kei cars, and with a passenger capacity of up to two (including the driver). Also in Europe "car-like" types are allowed in the Directive 2002/24 (Quads and other L7 type vehicles below 400 kg). The Japanese government has relaxed some of Japan's safety requirements for these cars with limited speeds. However, safety-conscious vehicle manufacturers and their customers are less likely to follow this extreme route but rather limit the vehicle size while staying within the given safety standards.

The changing shopping patterns with more virtual shops (either in internet or virtual stores where customers scan with their Smartphones the products and order for home delivery) will change transport flows potentially increasing the risk of the gridlock. To combat that challenge cities and mega-cities will require new logistical concepts for their supply establishing logistic hubs outside the cities, consolidation centers in the city will "sort and dispatch goods intelligently, avoiding the need for multiple trips and thereby reducing congestion and CO_2 levels", urban intermodal hubs connecting different urban transport modes as well as locker boxes and other means will be needed (Frost et al. 2013).

Also new business models are required to increase the acceptance of intermodality. The number of vehicles cannot be simply decreased by regulatory restrictions leaving citizens alone with their individual mobility needs. The acceptability of for example public transportation systems may not increase over time. In contrast, in Asia the number of vehicles sold has increased in Europe and America in the past leaving behind public services that had to reduce their services in a downward spiral with an ever decreasing utilization. To avoid that happening again and to return the trend globally new business models around vehicle ownership will be required. Cooperation between vehicle manufacturers and public service providers can help here. For example, FORD2GO is a cooperation between Ford in Germany, the Ford dealers as well as German Railway company DB Rent GmbH established a car-sharing platform where customers can order with their Smartphone or by internet a car for example to continue their journey from the fast train station to their final destination.

All these activities are evolving and may help to overcome the global gridlock. Global gridlock is not an issue that a single company or a single stakeholder (industry, government, academia, and consumers) can solve. An integrated approach and strong cooperation between all stakeholders is required and invited (Ford Jr 2011).

4 Conclusions

Major progress has been made in reducing vehicle emissions associated with degradation of local air quality. Addressing climate change and global gridlock are the next major challenges in the transition to sustainable individual mobility. These are complex multi-faceted challenges and there is no single technology or stakeholder action that can solve them. Some actions such as improved traffic management and urban planning can address both climate change and global gridlock, but not all actions will address both challenges (gridlock with clean vehicles is still gridlock). An integrated approach involving all stakeholders (vehicle manufacturers, fuel providers, governments, academia, NGOs, and customers) is needed to address these complex issues where no blueprint is established yet.

Acknowledgments We are very thankful for the critical and thorough review of this paper by Andy Taylor, Sustainability Environmental and Safety Engineering Ford of Europe. Special thanks also to Sandy Winkler for preparing the statistics on global carbon emissions.

References

Berry IM (2010) The effects of driving style and vehicle performance on the real-world fuel consumption of U.S. Light-Duty Vehicles. Massachusetts Institute of Technology, U.S., February 2010

Coudou B (2013) Mobility as Human Right. http://www.ifrtd.org/new/issues/human_right.php

European Environment Agency (2012) Annual European Community greenhouse gas inventory 1990–2010 and inventory report 2012. Technical report No 3/2012. Accessed May 2012

Ford Motor Company (2010) Sustainability Report 2010/11. Detroit, US

Ford WC Jr (2011) A future beyond traffic gridlock. TED talk California, USA (March 2011)

Frost and Sullivan (2013) Global mega trends and their implications on urban logistics. London

Hunecke M, Sibum D (1997) Socioeconomic aspects of individual mobility. Secretariat for futures studies report for the institute for prospective technological studies European commission—JRC, Sep 1997

International Organization for Standardization: ISO 14021 (1999) Self-declared environmental claims (Type II environmental labelling)

JAMA (2006) Integrated approach calculations on infrastructure in Japan. Tokyo

Knudsen T (2007) SINTEF. The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology): environmental consequences of better roads—micro simulation used to predict different effects on the environment of improved infrastructure. Norway

Schmidt W-P, Morel S, Ruhland K, Krinke S, Künne B (2010) Feasibility of a globally harmonised environmentally friendly vehicle concept. Int J Veh Des 53(1/2):4–15

Schmidt W-P, Butt F (2006) Life cycle tools within ford of Europe's product sustainability index. Case study Ford S-MAX and Ford Galaxy. Int J LCA 11(5):315–322 (Ecomed Publishers, Landsberg)

Stevens D (2007) Integrated approach calculations on infrastructure in Japan. Brussels

Transport and Mobility Leuven (2013) TREMOVE 3.3.2 pivot tables. http://www.tremove.org. Accessed 28 Feb 2013

USEPA (2010) Our nation's air: status and trends through 2008. EPA-454/R-09-002, 22 Feb 2010

U.S. Energy Information Administration (2013) International energy statistics. http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=90&pid=44&aid=8. Accessed 8 March 2013

U.S. Environmental Protection Agency (2012) Inventory of U.S. greenhouse gas emissions and sinks: 1990–2010

UNEP (2013) Greener driving campaign. http://www.greener-driving.net/site/home.html

Warneke C, de Gouw JA, Holloway JS, Peischl J, Ryerson TB, Atlas E, Blake D, Trainer M, Parrish MM (2012) Multiyear trends in volatile organic compounds in Los Angeles, California: five decades of decreasing emissions. J Geophys Res 117:D00V17. doi: 10.1029/2012JD017899

World Business Council Sustainable Development (2004) Mobility 2030: meeting the challenges to sustainability. Geneva, Switzerland

Part IV
Engines

BARM: Bi-Angular Rotation Machine as an External Combustion Machine

B. Schapiro and S. Dunin

Abstract Schapiro (2011) introduced the BARM as an internal combustion machine, and Schapiro (2012) introduced the BARM as an external combustion machine. This article introduces the thermodynamics of an external combustion BARM in the physical approximation (Chap. 3), designed specifically for exploiting thermosolar energy. The economic and political aspects are discussed in Clause 4.3. A comparison between BARM and Stirling machines is the primary focus of this article. The efficiency of both machines as thermosolar energy exploiters is compared under two scenarios: in the first, the Stirling machine has no heat recuperator and the BARM no heat exchanger. In the second scenario, the Stirling machine is equipped with a heat recuperator and the BARM machine with a heat exchanger. That efficiency is dependent on the power flow through the machine has been taken into consideration. The thermodynamic description, that is the modelling of these processes, is a physical approximation valid not only for BARMs, but for all rotational volume displacement machines in similar application, for instance, in Pyatov (2010) and Pyatov and Schapiro (2010).

1 Precursors

BARM is an abbreviation for: Bi-Angular Rotation Machines. The form of the rotational piston's cross-section as an arc-figure with two corners gives the machine its name. The precursors of the BARM have been well known since the 1920s. To date they have been developed and deployed only as compressors.

B. Schapiro (✉)
BARM—Bi-Angular Rotation Machines UG, Kluckstr. 25 10785 Berlin, Germany
e-mail: bh@schapiro.org

S. Dunin
Physical Department, MPGU, Moscow, 127540 Russia
e-mail: sdounin@gmail.com

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_17,

Like all rotating piston machines, BARMs, too, run smoothly and quietly and have high power density. They have a cylindrical design which simplifies assembly and reduces the time and energy requirements for production. They are capable of diesel operation in a single section because their smallest residual volume can theoretically be zero and the volume and location of the separate combustion chamber required for internal combustion is completely independent of the trochoidal geometry. Thus, one can generate almost any compression ratio desired with BARMs (Fig. 1).

2 BARM as an Internal Combustion Machine: Short Review

BARMs employ a different trochoidal chamber geometry than the classic Wankel engine. Like all rotary piston machines, power takeoff is achieved via eccentric planetary gearing. The key element here is an innovative, pendular sealing element that seals the piston surface-to-surface with the chamber walls rather than line-to-surface, as in the classic Wankel engine, Schapiro (2011, 2012).

The chamber contour here is not circular but rather a trochoid, an algebraic figure of the 4th order. BARMs are volume displacement machines capable of deployment in all relevant areas. We expect their particular advantages to be evident when employed as environmentally friendly, high performance combustion engines, range extenders for electric vehicles, emergency power generators, compressors, thermosolar and geothermal engines and machines for exploiting high and medium temperature exhaust heat of all kinds. As our thermodynamic analysis demonstrates, employing BARMs enables more efficient energy production and use than is possible with the classic Wankel engine, thereby saving energy. Let's take a look at a comparison between reciprocating piston and BARM engines, both in diesel versions (Fig. 2).

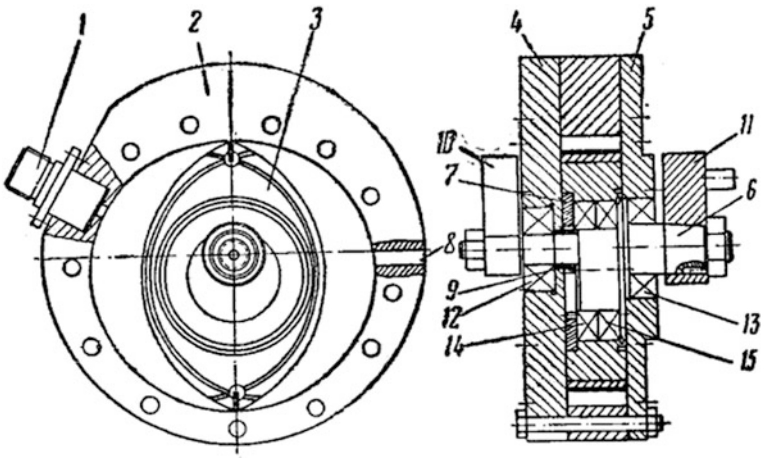


Fig. 1 A compressor developed at N. Zhukovsky State Aerospace University "Kharkiv Aviation Institute" in the 1960s and repeatedly deployed in industry. Cited from Sukhomlinov (1975)

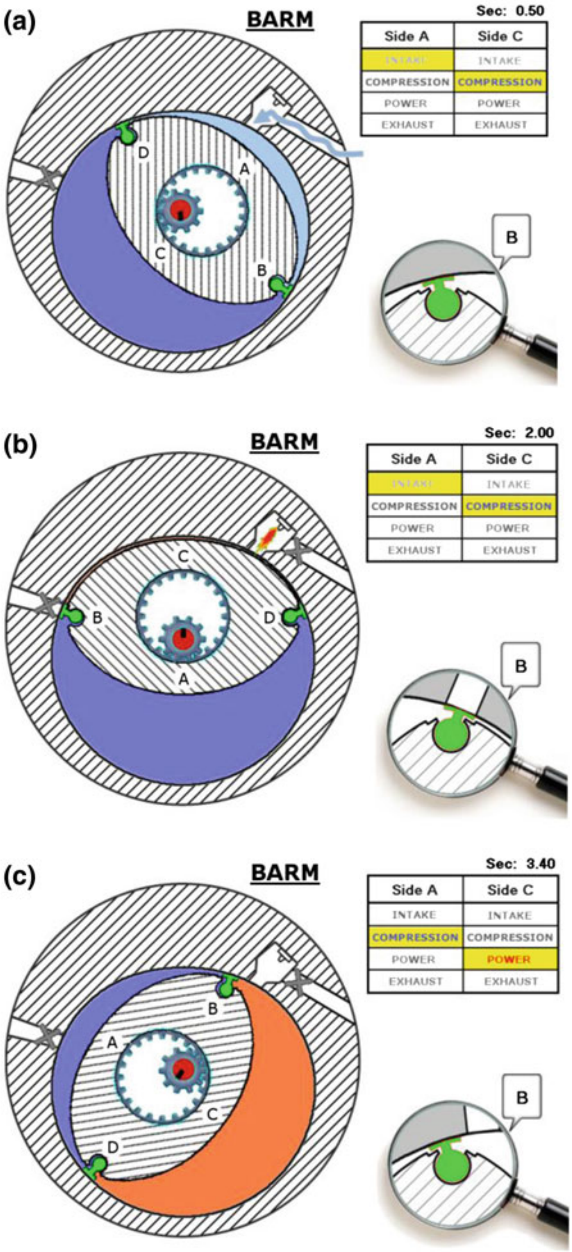


Fig. 2 **a**–**c** Schematic BARM as a 4-cycle engine. Each side of the piston works as an independent piston. Thus a single BARM power unit is equivalent to a two-piston reciprocating piston machine. Shown here are sample piston positions. Constructing a BARM with two pistons powering one drive shaft creates an engine equivalent to a four-cylinder reciprocating piston engine. Every BARM cycle in the two-unit combination is a power cycle, continuously transferring torque to the driveshaft

In this simulation, both the reciprocating piston and BARM machines run a diesel process. They have the same working volume, the same cycle start and end pressures, the same cycle length, “burn” the same amount of fuel per cycle and piston side and, of course, deliver the same energy efficiency under these conditions, namely, 56 %.

Under these conditions, the BARM delivers almost twice as much power per cycle compared to the reciprocating piston engine because both sides of its piston work. It is important to note that—seen kinematically—the BARM piston can turn faster by a factor of almost 4 than can the crankshaft of the reciprocating piston machine under otherwise comparable conditions. If this simulation corresponded to reality, an increase in power density by a factor of 8 ($2 \times 4 = 8$) could be theoretically expected. We think that BARM combustion engines will actually have a three to occasionally five times higher power density than reciprocating piston engines with the same working volume. Thus we expect that a BARM engine can achieve equivalent performance and equal exhaust gas quality as a reciprocating piston engine with but 20–30 % of the latter’s size and weight!

Material for the engines as well as energy for production is also conserved because of the high BARM power density. There exist sufficient heat and pressure resistant materials, such as metaloceramics, silicon carbide and other ceramic materials to withstand the high combustion chamber temperatures (Kriegesmann 2005).

In the state diagram Fig. 3a, the blue point passes the orange point and then the orange passes the blue, so they complete each cycle in the same time. The graphic in Fig. 3b shows the lower portion of the time-dependent function of both volume displacements (orange for BARM and blue for reciprocating piston) from the driveshaft and crankshaft angles of rotation for similar working volumes. The graphic in Fig. 3c shows the comparison of the simulated performance over time, blue for the diesel reciprocating piston and orange for the BARM. Performance is negative at certain points because the machines use energy for moving the pistons and compressing the air. Significantly more energy is won; however, because burning releases the stored chemical energy and both engines convert this energy into usable power driving the driveshaft or crankshaft respectively.

BARM combustion engine CO_2 emissions will be in the same range as that of reciprocating engines and significantly less than the Wankel engine’s due to the higher efficiency of BARMs. The problem with NO_X emissions is the same as it is for reciprocating piston engines.

Competing technologies: Both reciprocating piston engines with their efficiency and classic Wankel engines with their power density compete in this arena. BARM and other rotating piston engines offer the same advantages in the 10 kW to 10 MW power range and thus have a competitive advantage in the technology and industrial markets. BARM does not compete with gas turbines since turbines are usually highly effective in power ranges above 10 MW.

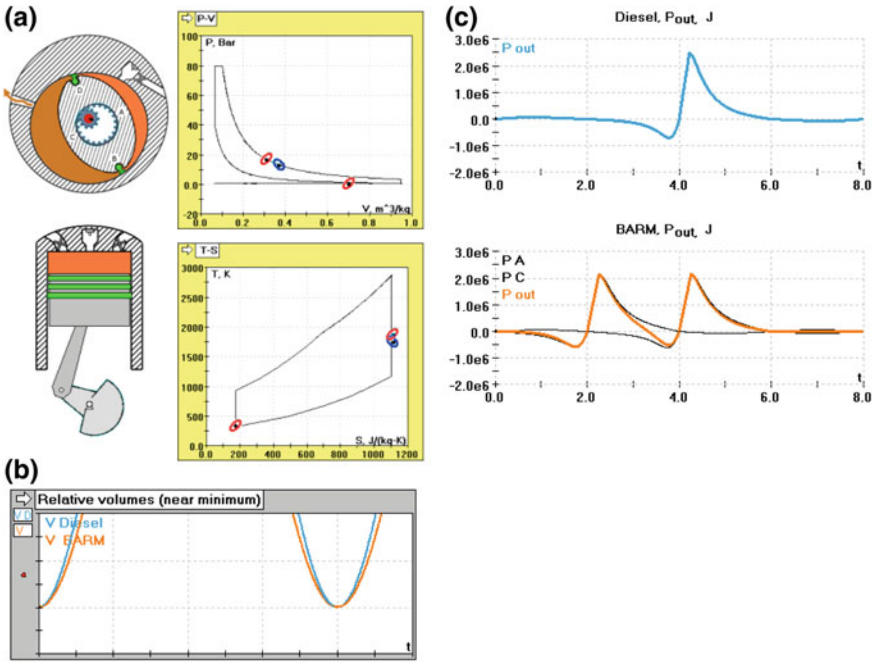


Fig. 3 **a–c** A thermodynamic simulation approximating non-deformable piston and housing as well as a working medium with no viscosity. The *blue point* and *blue curves* corresponds to the reciprocating machine, and the *red* one to the BARM. The work cycle is on side *A* of both the BARM and the reciprocating piston. The points in the *red*, *right-leaning ovals* in the state diagram mark the thermodynamic state on sides *A* and *C* of the BARM piston. The concomitant state is marked by the point in the *left-leaning*, *blue oval* for the reciprocating piston

3 BARM-Utilization as Heat Engines, External Combustion Machine

Heat engines with cyclically regenerative working media, or external combustion machines, do not use chemically stored energy internally to produce mechanical power. They use an externally produced temperature difference, hence, the name external combustion machine. They produce mechanical power by transferring heat from a hot site to a cold site in such a way that part of the heat can produce useful mechanical power. Such machines employ a working medium, usually gaseous, that is cycled back and forth between the heater and the cooler (Fig. 4).

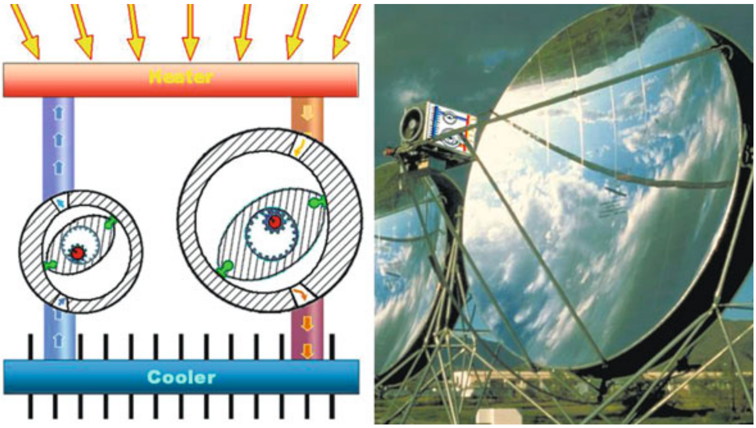


Fig. 4 The larger machine on the sketch's *right* is an expander, that is, a motor. The smaller machine on the *left* is a compressor. The working medium could be helium or another medium. Both machines are laid out such that their power shafts turn at the same speed. Thus both motor and compressor can be mounted on the same shaft which also drives the generator and a cooling fan. With this layout, the machine almost has but a single moving part with a complicated form, namely two pistons, permanently geared to a single power shaft

We wish to use BARMs as heat engines, not only to capture and exploit the waste heat from industry and municipalities but also for power generation using nature's free energy sources, especially thermosolar.

3.1 General Remarks Concerning Heat Utilization

One of the most promising uses of BARM machines is for transforming heat to mechanical power. That is, anywhere there is a heat source available with a working medium between 400 and 1,200 °C of sufficient capacity to deliver between 10 kW and 10 MW of heat energy. This encompasses a wide variety of industrial waste heat sources, such as waste steam and exhaust gases and the burning of flammable waste gases, as well as focused solar heat and thermal output of geothermal sources. Our rough estimate of the total annual potential of all industrial and municipal waste heat is in the range of 1,000,000 GWh, approximately one-fourth of world energy requirements today.

Currently, there exists no technical standard with satisfactory efficiency to utilize the heat available from these sources. The highly efficient turbine technology is advantageous only in the multiple megawatt power range. At present, the best alternative for heat utilization in the low and medium power range is the Stirling engine. Therefore, we wish to compete with the Stirling engine.

3.2 Stirling and Other Ideal Cyclical Processes

It is generally well known that no heat engine can surpass the efficiency of a Carnot machine embodying the ideal Carnot cyclical process. It is less well known that a number of other thermodynamic cyclical processes can exhibit the same coefficient of efficiency η as the Carnot process under ideal conditions. Among these are the Stirling cyclical process especially and, under a few specific conditions, the Rankin process with $\eta_{ideal} = (T_{heater} - T_{cooler})/T_{heater}$. We focus primarily on the Brayton-Joule process. We will show that, as a precursor to our design, it is the best fit to our design for technical and economic reasons. With current technology, the Rankin and Brayton-Joule processes are realized with turbines which exhibit an acceptable efficiency only in the multiple megawatt range. Until now, the Stirling process was the only one employing the principle of volume displacement and implemented with a reciprocating piston engine. The efficiency of an actual Stirling engine depends on how closely the real process can be made to approach the ideal. The same holds true, of course, for the other cyclical processes, this also holds true for our modification of the Brayton-Joule process.

3.3 BARM Versus Stirling Engine

The BARM volume displacement heat engine realizes a new cyclical process we developed together. It is most closely related to the Brayton-Joule cyclical process. Even in an ideal representation, the BARM heat engine does not achieve Carnot ideal efficiency. But since when is our world ideal? Only our beloved wives! So, the future for BARM and for the Stirling engine as heat engines depends entirely on the extent to which technical realization can minimize variance from the ideal. In this respect especially, we consider the BARM competitive with the Stirling engine for the following reasons:

- The BARM has a significantly higher power density that the reciprocating piston Stirling engine. Consequently, its compact architecture.
- With distinctly fewer moving parts, the BARM must be not only smaller, lighter and more economical to produce, but also more reliable than the Stirling engine.
- While we expect very similar friction losses in the working chamber and conduits of both engines, we expect notably less friction losses in the power shaft and bearing mechanics.
- And most importantly—under realistic conditions, that is, with a heat regenerator, BARMs will deliver higher efficiency than Stirling engines.

3.4 The Role of the Regenerator and Heat Exchanger, Respectively

The comparison in Fig. 5 was made without employing a regenerator for either engine. The regenerator idea consists of separating the heat path from the mass of the working medium. With the help of a heat exchanger, one can return a portion of the heat remaining after the power phase to the working medium after the cooling phase. Thus the thermodynamic losses due to irreversible cooling can be minimized.

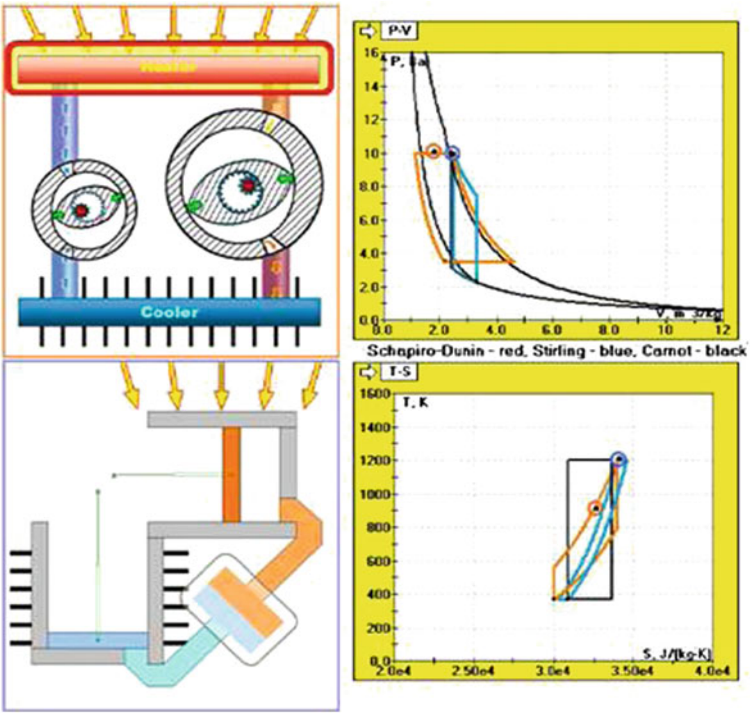


Fig. 5 A thermodynamic comparison between a substantially idealized (although not ideal while without heat regenerator) Stirling engine and an only slightly idealized BARM. The BARM's superior efficiency is obvious. Of course we examined this comparison over the entire relevant power spectrum. The results are not shown here because the comparison really makes sense only when a heat regenerator, that is, a heat exchanger, is incorporated

But the irreversible losses in the Stirling engine seem to be greater than those in the BARM heat engine. That is associated with the typical efficiency of the Stirling engine's heat regenerator, generally in the 60 % range (Fette 2012). The efficiency factor of industrial heat exchangers that can be employed with the BARM is approximately 95 % (Jüttemann 2001). Therefore, we expect that, in reality, BARMs with heat exchangers will outperform today's almost perfected Stirling engines. The relationship of both machines overall efficiency factors will, of course, depend on the output load.

The comparison of overall efficiency is made under thermodynamically equal conditions. The working medium in both engines is He_2 with a mass of 100 g, the maximum volumes of the working chambers are equal, as are the maximum and minimum temperatures, 1,200 and 400 °K respectively. For the simulation, we assumed an exaggerated efficiency factor of 70 % (blue circlets) for the thermal efficiency of the Stirling engine's heat regenerator and 90 % (red squares) for the BARM's heat exchanger. Losses due to mechanical friction and viscosity of the working medium were not incorporated for either engine.

The ends of the curves in Fig. 6 to the right and left of the graph mark the position where thermodynamic utilization is no longer possible. The Stirling engine's efficiency increases monotonically until reaching its maximum value, at which point the working medium can no longer take up heat and thermodynamic function collapses.

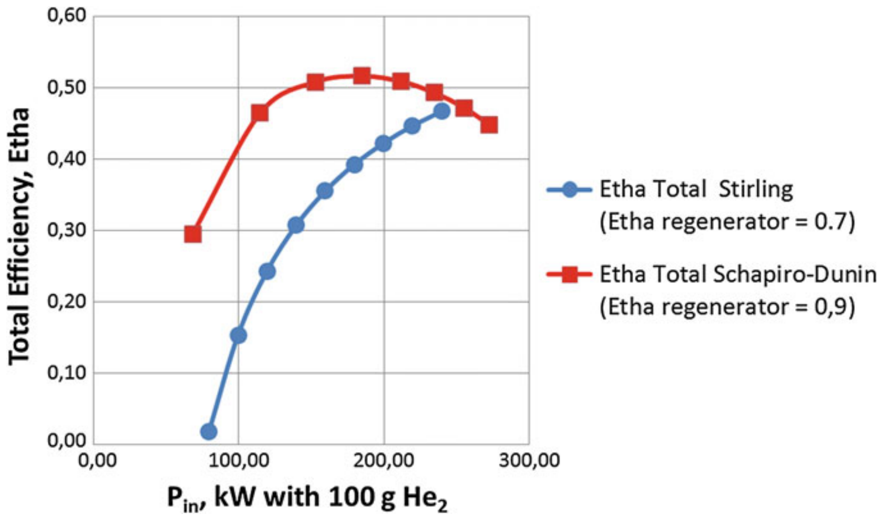


Fig. 6 The computer-simulated total efficiency factor η of the Stirling engine versus BARM, with thermal input $\mathbf{P_{in}}$ in kW, an exaggerated efficiency factor of 70 % for the Stirling engine's heat regenerator (*blue circlets*) and 90 % (*red squares*) for the BARM's heat exchanger, the same 100 g He_2 as working medium for both engines, a maximum temperature of 1,200 °K and a minimum of 400 °K

The overall efficiency factor of the BARM with a 90 % efficient heat exchanger reaches a maximum of 52 % with an energy input of approximately 180 kW. That is around 12 % more than the idealized Stirling engine's overall efficiency and around 18 % better than the overall efficiency of the best Stirling engine currently in use, namely 34 %. Two demonstration models of the BARM exist currently, but no practically tested prototype.

If there is interest in lower power applications, e.g., for decentralized power supply, one can reduce the mass of the working medium. Thus one could achieve approximately the same overall BARM efficiency with but 1 g He_2 and energy input of 1.8 kW, theoretically resulting in 1 kW energy output. Of particular interest is the BARM's equation of state, resulting in a maximum pressure of 10 bar and a minimum pressure of 3.8 bar. That should result in prodigious reliability and extended service life for the engine. The same holds for the Stirling engine, of course. Thanks to the still valid Boyle & Mariotte law, one can minimize the dimensions of both machines inversely proportional to desired pressure.

Competing Technologies: Stirling engines are one of the technologies competing for thermosolar use and heat recapture. The picture in Fig. 4 shows a dish Stirling engine, part of a thermosolar pilot project by the firm SOLO in Spain. We have pasted in a schematic of our BARM to show the potential. Stirling Energy Systems, a US company, achieved a world-record efficiency for Stirling engines of 31.25 % in 2008. Nonetheless, it was forced to declare bankruptcy in 2011.

3.5 Uses as Thermosolar Power Plants and for Heat Recapture

We believe BARMs can be successful in commercial heat utilization in the medium temperature range, such as industrial waste heat recapture and geothermal power plants. Stirling engines are better than BARMs in the low temperature range. However, there is insufficient commercial potential in this range to warrant great effort in this area, except perhaps as a hobby. We expect a clear victory for BARMs in the high temperature range, particular with thermosolar power plants.

4 Conclusion

After intensive and wide-ranging study, our conclusions are:

4.1 External Combustion Machines, e.g. for Thermosolar Energy Production

4.1a. As a trochoidal rotating piston machine, BARM's advantages are higher power density with concomitant smaller dimensions and significantly less weight. BARM's high rotation rate means that its power density is limited only by the rate of temperature increase and the viscosity of the working medium.

4.1b. In contrast to the well-know Wankel engine, trochoidal BARMs will have a very long service life. The reasons for this are described in Sect. 4.2b.

4.1c. BARMs with heat exchangers are particularly interesting in the high temperature range around 1,000 °C, where they can achieve the same efficiency—slightly more than 40 % (optimistic estimate: up to 45 %)—as other volume displacement engines under realistic conditions.

4.1d. The external combustion BARM gains a small efficiency advantage from the fact that, from its starting position, the BARM piston opens the crescent-shaped working volume more slowly than a reciprocating piston (both compared at the point of minimal volume). Compared with other common geometries, this lengthens the isochoric pressure increase phase, thus improving efficiency slightly.

4.1e. A further advantage is the BARM's simple construction which, along with the lighter weight, promises lower production costs and longer service life. The expectation that external combustion BARMs will produce only slightly higher efficiency than other volume displacement machines relates to the fact that theory predicts the efficiency factor's dome-shaped dependence on the pressure relationship with a maximum in the range of P_{max}/P_{min} from 8 to 10 for the more powerful high temperature version. Thus, the real strength of volume displacement engines, namely their ability to create large pressure differentials, cannot contribute to increasing efficiency in thermosolar applications. Nonetheless, BARMs can contribute significantly to increasing power density as well as lowering production costs.

4.2 Internal Combustion Engines for Motorized Energy Production

As internal combustion engines, BARMs can, in principle, actualize every known cyclical process. The Diesel or Atkinson cycles are especially attractive. We believe that internal combustion BARMs offer the most advantageous combination of high power density, good efficiency, low noise level and affordable production costs.

4.2a. High power density is typical of all trochoidal rotating piston engines. High rotation speed is the best known advantage of the Wankel engine with the resulting power density. The same holds true in full measure for BARMs.

4.2b. Long service life. The principle difference from the Wankel engine is the long service life of BARMs. The Wankel engine's short service life is not caused, as many believe, by deterioration through wear of the sealing lips. The sealing lips are expendable parts, easily replaced regularly. The short service life results primarily from damage to the interior of the chamber caused by the unavoidable resonance of the sealing lip oscillation due to the high rotation frequency. The fundamental geometric cause of the sealing lip's impact on the chamber wall is due to the inner contours of the Wankel engine's chamber which has both concave and also convex (or at least not concave) stretches. Strong centrifugal forces act on the sealing lips when they slide off the contour very quickly. These forces change their direction during the transition from a concave to a convex stretch and again from convex to concave. The change of centrifugal force direction, amplified by the resonance, hammers deep grooves into the interior wall of the working chamber. These grooves thus appear as though they had been hacked in with an axe. This damage to the interior chamber wall is the real cause of the Wankel engine's short service life. Mazda's RX Wankel engine set a world record of about 150,000 km equivalents on the test stand. The service life of a good Mercedes or Peugeot reciprocating piston diesel engine exceeds 2,000,000 km in a vehicle. The BARM engine's inner chamber wall is very close to a circle in cross-section, that is, only concave, and the curvature of the chamber changes little by little, only gradually and minimally. Thus, changes of direction or quick changes in the sealing lip's centrifugal force cannot occur and damage to the interior chamber wall à la Wankel is never a problem. Therefore, we expect BARMs to have a long service life, certainly not less than that of the classic reciprocating piston engines.

4.2c. We attribute the BARMs good efficiency as volume displacement, internal combustion engines to the fact that their efficiency's dependence both on the temperature differential $\Delta T/T_{Burn}$ as well as on the pressure ratio P_{max}/P_{min} (and also the compression ratio) always increases monotonically. Thus, volume displacement engines can really take advantage of their strength, namely the ability to develop great pressure differentials, to increase efficiency. At a burn temperature of 2,000 °C, exhaust gas temperature of 550 °C and a compression ratio of 24:1, diesel BARMs could theoretically deliver full load efficiency of about 60 %, without considering potential increases via a turbocharger, for example, or other devices. The expected power to weight ratio would be under 1.0 kg/kW (compare: Otto engines 2–5 kg/kW, diesel engines 5–6 kg/kW).

4.2d. We attribute the low noise level to the design's lack of piston rods and crankshaft which are a major contributing factor to the noise levels produced by reciprocating piston engines. Further, noise producing tensions in the motor can, for the most part, be compensated for by the centrally symmetric disposition of the working units, as shown, Schapiro (2011).

4.2e. We expect affordable production costs due in particular to the increased power density (less material per performance kilowatt) and the resulting power to weight ratio of 0.5–1.0 kg/kW, as well as fewer parts and a production-friendly cylindrical construction, similar to the Wankel engine.

4.2f. Because of all these characteristics, we consider BARMs particularly suited for light aircraft engines, low to medium weight helicopters and drones, among others.

4.3 Economic and Political Aspects

BARM provides the potential for a true energy transition both as an internal combustion engine, providing high power density with the same efficiency as reciprocating piston engines, and as an external combustion machine with higher efficiency and power density than Stirling engines. BARM technology can be deployed anywhere, enabling decentralized and diversified energy production between 10 and 30 kW, tailored to the actual needs and sites where it is in fact utilized. This can be realized with the low weight, inexpensive production and small dimensions of BARM engines. If a BARM engine were working on every building and in every industrial facility, one could truly speak of a sustainable and not only seemingly "cost free" energy transition. The costs of a "sustainable" energy transition in the EEG sense tax even successful and productive economies. The German energy management system is not suited for worldwide utilization in any case. BARM technology would be effective worldwide: using BARM engines rather than outdated diesel generators is resource-saving and sustainable energy production. The political potential of BARM technology:

- Conversion of the energy economy. The difference between the economic and political price of energy displays alarming aberrations. On the bourse, a kilowatt hour costs 3.8 cents today. For us, the small end-user, it costs 28.6 cents.
- Avoid the expected financial costs of the transition to supposedly "cost free" energy that already weigh on our entire economy and each individual. These include the costs for disposing of nuclear wastes, disassembled reactors and the construction of new mega conduits for electricity transport.
- Avoid the political costs to be expected with implementation of the mega conduits over the protests of directly affected local residents with a new distribution philosophy.
- Ease the overall political situation by reducing the fear of the centralized omnipotence of the energy concerns and the political impotence of governmental agencies in the energy sector. Instead, build trust and solidarity in the population by granting localities responsibility for their own energy production.
- Prevent the occurrence of extreme worst cases with individually configured energy production facilities for small user entities.

The introduction of a truly new technology such as the BARM technology can induce, finally, desperately needed innovation in the energy economy. BARM enables the conversion of an overpriced, overly complex and thus unmanageable, failure-prone energy production system to a technically easily managed, simple and economical energy production system.

Acknowledgments First and foremost, the authors would like to thank Karl Sittler, Zurich, Switzerland, for his untiring help and support during the entire last decade. We also thank Prof. Yuri Estrin and Dr. Boris Feldmann, Melbourne, Australia, for the manifold consultations in materials science. We give wholehearted thanks to Dr. Andreas Leson, Dresden, Germany, and Dr. Edgar Voelkl, Austin, Texas, USA, for their many years of staunch support. Prof. Lev Britwin and Dr. Ivan Pyatov, Moscow, Russian Federation, we give great thanks for their continuous support as well as their patient and valuable counsel. Dr. Igor Sedunov, St. Petersburg, Russian Federation, we thank for his continuous attention to our work. To our wives, Hella Schapiro and Galina Dunin, we offer deep and wholehearted thanks that they not only tolerate our work but actively support it as best they can.

References

Fette P (2012) Über den Energieaustausch und die Effektivität des Regenerators in der Stirlingmaschine. http://www.stirling-fette.de/dtatherm.htm

Jüttemann H (2001) Wärme- und Kälterückgewinnung. Werner Verlag, Düsseldorf

Kriegesmann J (Hrsg.) (2005) DKG-Technische Keramische Werkstoffe. HvB-Verlag, Ellerau

Pyatov I (2010) Volume-displacing detanders. In: Presentation on ICSAT 2010, 26.02.2010, 2nd international conference on sustainable automotive technologies, University of Applied Sciences Ingolstadt, Germany, 23–26 Feb 2010

Pyatov I, Schapiro B (2010) Volume-displacing detanders. http://www.rkm-schapiro.org/docs/Pyatov-Schapiro%20Volume-Displacing%20Detanders%20EN%20100218.pdf

Schapiro B (2011) Bi-angular Wankel engine. In: Proceeding of ICSAT 2011, the 3rd international conference on sustainable automotive technologies, CU-ICAR, Clemson University, Greenville, SC, USA, Springer, Heidelberg, 4–6 April 2011

Schapiro B (2012) BARM: Bi-angular rotation machine. In: Proceeding of ICSAT 2012, 4th international conference on sustainable automotive technologies, Melbourne, Australia, Springer, Heidelberg, 21–23 March 2012

Sukhomlinov R (1975) Trochoidal rotor-compressors (Трохоидные роторные компрессоры). Verlag Vishcha Schkola, Kharkov Staatsuniversität, Kharkov

Audi Future Energies: Balancing Business and Environmental Concerns

P. F. Tropschuh and E. Pham

Abstract For Audi, sustainability is an important goal in order to continue functioning economically and competitive, protect the environment and guarantee a liveable future for generations to come. For Audi, corporate responsibility is a long-term strategic orientation that runs like a continuous thread through all processes, products and decisions. The goal is to pave the way for eventual CO_2-neutral mobility with Audi products, to use resources sparingly along the entire value chain, and to demonstrate an enduring sense of responsibility for the workforce and for society as a whole. Anyone planning for future sustainable mobility first needs to adopt a new and broader perspective. For example, Audi no longer just considers the CO_2 emitted while driving, it rather analyses the entire life cycle of a car–from its development and production to the phase of customer use and finally recycling. A central issue in this comprehensive analysis relates to the origins of the types of energy used to drive vehicles. In the case of electrically powered cars, for example, environmental impact is only really improved if the electricity they consume was generated from renewable resources. Following this idea to its logical conclusion, it becomes clear that the focus must shift towards new types of fuels. Therefore, Audi is the world′s first carmaker to become directly involved in the development and production of renewable fuels that do not rely on biomass. Audi is addressing the entire range of drive technologies here, and the future fuels are called Audi e-power, Audi e-hydrogen, Audi e-gas, Audi e-ethanol and Audi e-diesel. The first step is the Audi e-gas project, in which the Ingolstadt

P. F. Tropschuh (✉)
Head of Corporate Responsibility, Government Affairs, Academic Cooperation, AUDI AG, 85045 Ingolstadt, Germany
e-mail: peter-felix.tropschuh@audi.de

E. Pham
Press Spokeswoman Corporate Responsibility, AUDI AG, 85045 Ingolstadt, Germany
e-mail: elise.pham@audi.de

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_18,

company is producing an entire chain of sustainable fuels. With this project, Audi intends to provide tremendous impetus to renewable energies. The German energy industry could also benefit from the conceptual approach of the Audi e-gas project over the mid-term, because it must address the open issue of how to store eco-electricity efficiently and independent of location. The Audi e-gas project starts with wind, water and carbon dioxide sourced from a biogas plant. The end products are renewably generated eco-electricity (Audi e-power), hydrogen (Audi e-hydrogen) and synthetic methane (Audi e-gas). Over the mid-term, Audi also wants to create options for replacing liquid fuels by innovative renewable fuels that are no longer energy crop-based and do not compete directly with food production. Right now, the brand is working with a specialist partner from the USA to produce synthetic ethanol (Audi e-ethanol) and synthetic diesel (Audi e-diesel).

1 Audi e-gas Project: A Chain of Sustainable Energy Sources

In the scope of its corporate responsibility strategy, Audi is pursuing CO_2-neutral mobility. Clean operating energy will play a crucial role in tomorrow's sustainable mobility. Audi is establishing a portfolio of sustainable sources of energy as part of its Audi e-gas project.

A joint project of Audi and plant builder SolarFuel, the Audi e-gas plant in the northern German town of Werlte has begun operations in June 2013. It is the world's first industrial facility to use CO_2 and renewable electricity to generate synthetic natural gas that can be fed into the natural-gas network. It is operated by renewable electricity generated via, for instance, wind or solar energy. The accelerating expansion of renewable energies means that energy sources subject to fluctuations play an increasingly larger role. In short, there is sometimes a surplus of electricity and at other times a shortage. With a rated input of around 6,000 kW, the plant will primarily procure electricity from wind power every time there is oversupply. The e-gas plant will help solve a considerable problem associated with the energy transition.

At the power-to-gas plant in Wertle, renewable electricity is converted via electrolysis to hydrogen, or Audi e-hydrogen (see Fig. 1). This hydrogen could one day power fuel-cell vehicles. Because a widespread hydrogen infrastructure does not yet exist, the hydrogen must then be combined with CO_2 in the methanation facility downstream of the electrolysis plant to produce renewable synthetic methane, or Audi e-gas (see Fig. 2). From there, it is fed into the natural-gas network and stored there.

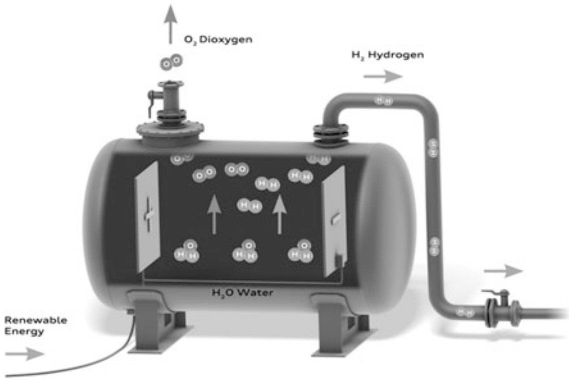


Fig. 1 H_2 Extraction: Electrolysis separates water into dioxygen and hydrogen

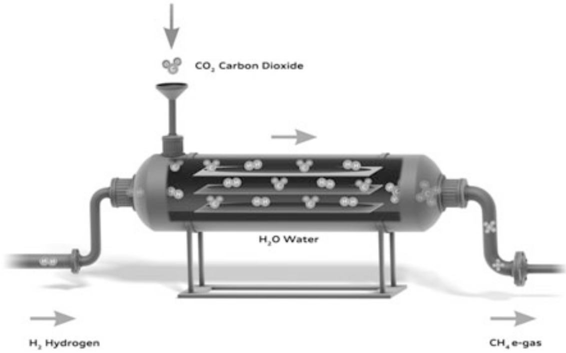


Fig. 2 Generation of e-gas: Methanation joins hydrogen and carbon dioxide into water and e-gas

The CO_2 comes from a stream of waste gas emitted by a nearby biomethane plant operated by EWE, an energy provider. This biomethane plant uses organic waste. The Audi e-gas facility uses the CO_2 as a feedstock for the fuel. Audi e-gas is thus a climate-neutral fuel—when burned in the engine, exactly the same amount of CO_2 is released as was previously bound at the e-gas plant.

Audi e-gas is an energy-rich fuel that is chemically identical to the fossil fuel methane, the primary constituent of natural gas, and it is excellently suited for powering internal combustion engines. Depending on the supply of electricity, the plant in Werlte is expected to produce some 1,000 metric tons of e-gas annually while chemically binding approximately 2,800 metric tons of CO_2. These same 1,000 metric tons of Audi e-gas could power 1,500 Audi A3 Sportback g-tron vehicles for 15,000 km (9,320.57 miles) per year in CO_2-neutral driving.

The A3 g-tron was designed to run on gasoline and natural gas alike. This model is furthermore fully bivalent, i.e. its performance figures are identical in CNG and gasoline modes. The A3 g-tron will operate on one tank of natural gas for about 400 km (248.55 miles)—and, if need be, another 900 km (559.23 miles) thereafter on gasoline. CO_2 tailpipe emissions are less than 95 grams per kilometer (152.89 grams/mile). When the A3 Sportback g-tron is powered by Audi e-gas, no more CO_2 is released than was chemically input in its production beforehand—creating a closed loop (see Fig. 3). Even when one includes in a comprehensive analysis the energy required to build the e-gas facility and wind turbines, CO_2 emissions are still only 20 grams per kilometer (32,18 grams/mile).

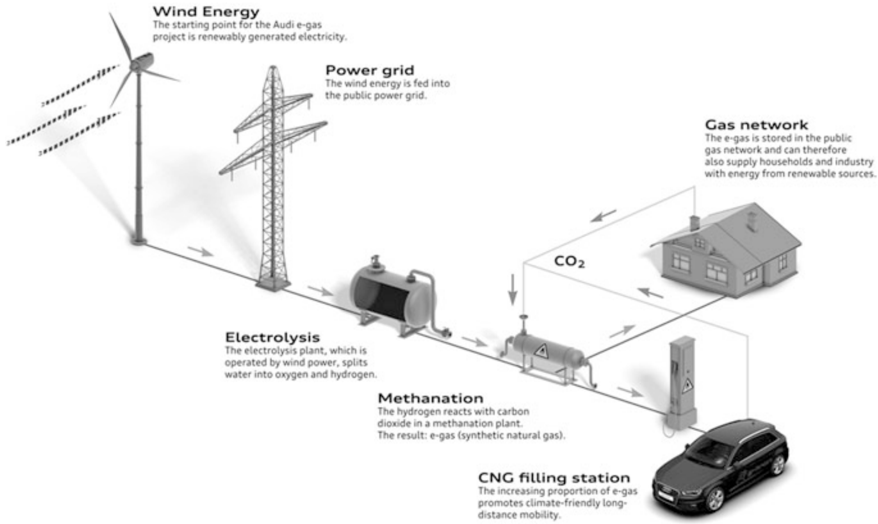


Fig. 3 The Audi e-gas project includes a whole chain of sustainable energy sources

Owners of the Audi A3 Sportback g-tron will buy e-gas at public CNG refueling stations by means of the balanced cycle method, similar to the approach used for customers of green electricity.

The German energy industry could also benefit in the medium term from the concept of the Audi e-gas project, as it provides an answer to the unsolved question of how to store large quantities of green power–efficiently and independently of location.

If winds are strong, excess electricity can be converted to Audi e-gas and stored in the public natural-gas network. With a capacity of 217 terawatt hours, it is easily Germany's largest energy-storage system. If desired, it would be possible to convert the energy from the gas network back into electricity at any time. The potential of electricity-gas cogeneration to store large amounts of wind or even solar energy can provide powerful stimuli for the expansion of renewable energies. The Audi e-gas project can be easily implemented in all countries with existing natural gas networks.

2 Audi e-ethanol and Audi e-diesel: Fuels for Sustainable Mobility

The type of CO_2-neutral mobility that Audi seeks can be achieved only with innovative and sustainable fuels capable of ultimately replacing fossil fuels.

In addition to developing and manufacturing Audi e-gas, Audi is fostering the development of a groundbreaking technology: microorganisms produce diesel or ethanol without using any crops. This technology lies at the core of two projects: Audi e-diesel and Audi e-ethanol.

They will address an old problem in search of a solution. Whenever conventional petroleum-based fuels are combusted, they release carbon dioxide and pollute the atmosphere. Ethanol and diesel from renewable raw materials such as corn and rapeseed generally achieve a better environmental balance, because the plants previously absorbed the CO_2 that is released in combustion. But these fuel sources compete with arable land for growing food. As such, they cannot constitute a long-term solution for our planet's skyrocketing population.

The CO_2-neutral mobility of tomorrow necessitates truly different fuels. Audi is therefore collaborating on just such a solution with Joule, headquartered in Bedford, Massachusetts. In a patented process, Joule manufactures fuels with the aid of special microorganisms in a highly scalable modular system (SolarConverter®).

The process is relatively simple. Solar energy is used to convert CO_2 and either saltwater or brackish water to liquid fuels. Photosynthetically active microorganisms, each just three thousandths of a millimeter in diameter, are the key players in this process (see Fig. 4). Just as plants do, these organisms carry out oxygenic photosynthesis. But instead of using photosynthesis to form new cells, these microorganisms continuously produce fuel. The experts at Joule have modified photosynthesis in such a way that the microorganisms produce ethanol or long-chain alkanes–important components of diesel fuel–directly from the carbon dioxide. In the process, they utilize sunlight, saltwater or wastewater, and CO_2 from, for instance, industrial waste gases. There is no need for farmland or clean drinking water. One of the byproducts of oxygenic photosynthesis is oxygen. The fuel is output by these organisms, and then it is separated from the water and purified.

Fig. 4 Useful microorganisms: single-cell organisms use carbon dioxide and water to make synthetic fuels–Audi e-ethanol and Audi e-diesel

This technology is the basis for Audi e-diesel and Audi e-ethanol. In short, e-ethanol is a product with the same chemical properties as conventional bioethanol. But e-ethanol is far better, as no biomass is used in its production. This e-ethanol can be admixed with fossil-based gasoline (e.g. E10) or constitute the basis for E85 fuel (85 % ethanol, 15 % gasoline).

In addition to the Audi e-ethanol project, Audi is also partnering with Joule to manufacture sustainable diesel fuel. A great advantage to Audi e-diesel will be its purity. In contrast to petroleum-based diesel, a mixture of a great many hydrocarbon compounds, e-diesel is free of sulfur and aromatics. This fuel also offers excellent ignition performance thanks to its high cetane number. Its chemical composition will permit unlimited blending with fossil-fuel diesel. Audi e-diesel will pose neither problems for existing Audi TDI clean diesel systems nor challenges for engine developers.

Audi and Joule jointly built a demonstration facility in Hobbs, New Mexico–an arid region with a lot of sunshine. This facility opened in September 2012 (see Fig. 5). Audi e-ethanol was produced for the first time in transparent plastic tubes in early 2013. Efforts at the demonstration facility alone illustrate the clear superiority over conventional bioethanol. In line with forecasts, the yield of Audi e-ethanol is some 20 times greater! In addition, regions that are unsuitable for agriculture such as deserts could be utilized for energy production.

Audi and Joule have been partnering since 2011. Audi has acquired the exclusive automotive-sector rights to Joule's patented technology. Collaborative work includes technical support as well. Audi engineers apply their extensive know-how regarding fuel and engine testing in helping to develop marketable fuels. Commercial production of the new fuels could begin within the next 5 years.

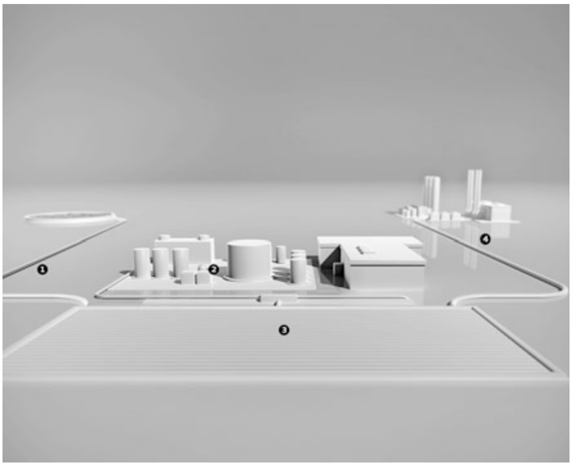


Fig. 5 Production of e-ethanol and e-diesel with (*1*) water supply (*2*) processing plant (*3*) tank for photosynthesis process, and (*4*) CO_2 supply

Efficient Lithium-Ion Battery Pack Electro-Thermal Simulation

L. Kostetzer

Abstract A methodology to derive a computational efficient electro-thermal battery pack model is showed. It is taken the accuracy of 3D modeling from finite element method with an automatic technique of model order reduction. Approximation errors are under 2 % for a solution speed-up of three orders of magnitude for the thermal part. The electrical battery model is implemented and the electro-thermal coupling is done at the system level. This idea is demonstrated with a 10 cells battery pack.

1 Introduction

Battery performance is direct related to operating temperature (Pesaran 2001; Kostetzer 2012) due to its effects on the electrochemical behavior of battery cells, specially for Lithium-ion chemistry. High temperatures can initiate exothermic side reactions that cause self heating. At low temperatures slow, diffusion of Lithium ions can cause saturations at the electrodes and slow chemical reactions that result in the increasing of internal electrical resistances (Smith et al. 2010). Battery life is also affected by temperature. For calendar life (only storage), internal resistances can increase 30 % more if temperatures are raised from 30 to 55 °C (Thomas et al. 2008).

L. Kostetzer (✉)
CADFEM GmbH, Marktplatz 2, Grafing bei München, Germany
e-mail: lkostetzer@cadfem.de

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_19,

Control of the battery pack operation is a task of the battery management system, BMS. It contains electrical protection circuits, current and voltage controllers, state of charge estimators and thermal control. BMS regulates the pack to operate in the desired temperature range for optimum performance/life. Typical task is to reduce uneven temperature distribution in a pack to avoid unbalances in modules/pack and then, avoid reduced performance. Additionally eliminate potential hazards related to uncontrolled temperature (Pesaran 2001).

According to Pesaran (2001) the design of a battery thermal management system (BTMS) should go through the following steps:

- Define goals of the BTMS
- Obtain heat generation and heat capacity of cells
- Prediction of cell behaviour and pack
- Design a preliminary BTMS
- Build a test BTMS
- Refine and optimize BTMS

From those recommendations one can see that the cell behavior must be studied, it means electrical and thermal characterized, second the battery pack. Here an important point is the integration of all cells plus cooling/heating devices and electronic controllers since the overall pack response is direct connected to those equipments.

The control task of BMS has to be designed, and simulation driven approach can bring benefits on that. Here one needs battery pack electro-thermal models to evaluate the battery temperatures for a given electrical load and check whether the cooling devices are properly designed. Load curves from BMS are long transients and modeling all devices in a battery pack is computationally intensive. Here an efficient numerical method is a must, especially if 3D effects are also included.

The objective here is to show how to derive 3D based thermal model for the battery pack and couple it with the electrical cell model at the system level. In Sect. 2 a battery pack 3D thermal model is described and simulated in a simple load case. This 3D model is then transformed into a system level model in Sect. 3. Finally, in Sect. 4 the battery pack system level thermal model is coupled to cell electrical models and the temperature response is calculated with in a drive cycle for an electric vehicle example.

2 Battery Pack 3D Thermal Modeling

Battery pack thermal 3D thermal modeling is a task to be performed with numerical techniques that involve discretization like FEM (Finite Element Method) or CFD (Computational Fluid Dynamics). Here a battery pack with 10 pouch cells is modeled with FEM in the ANSYS software. The pack is water cooled in straight channels made of cooper, see Fig. 1.

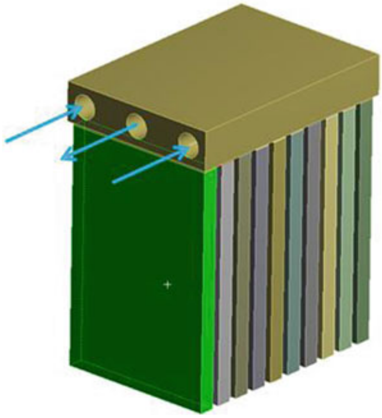


Fig. 1 Battery pack CAD schematic. Here the 10 cells are show with the water flow channels on the *top*. Additionally each cell contains a cover for electrical isolation that in the model is considered with Aluminum material

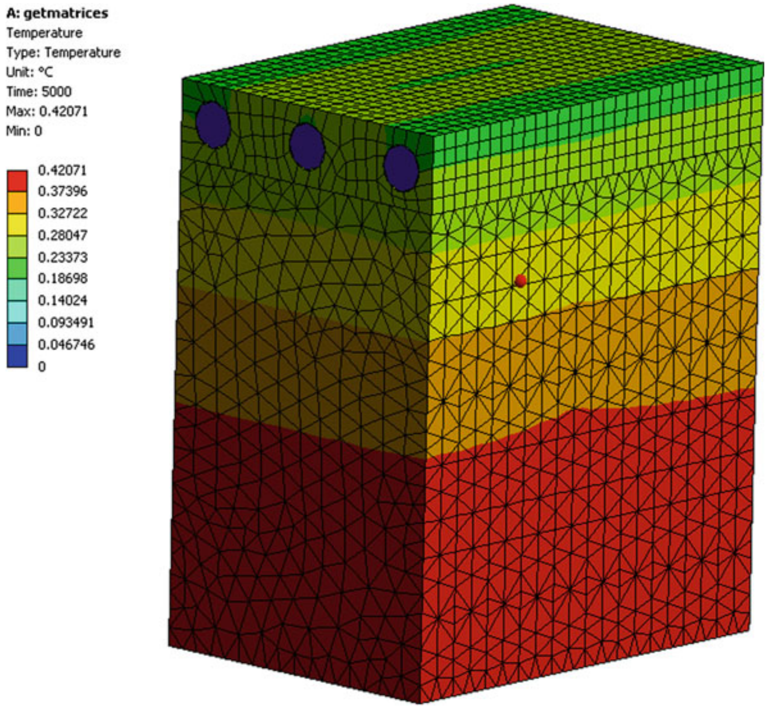


Fig. 2 Temperature field of the 10 cells battery back cooled by water flow channels. Here the temperature differences from water and solid bodies are plotted in a 1 W per cell load at the steady state condition

The FEM model is composed by solid bodies. Each of the cells contains an active material part with orthotropic heat conductivity (smaller values through plane) and in this 3D region the heat load is defined. Externally to the active material is an aluminum cover. Cells are placed side by side with the water channels at the top. The flow is modeled with 1D fluid elements (FLUID116 in ANSYS) and coupled with the solid bodies through convection heat transfer coefficient (Kostetzer 2012), estimated from the Dittus-Boelter correlation. The mass flow in each channel is fixed in 0.1 kg/s with an inlet temperature of 20 °C.

This FEM thermal model is going to be transformed into a system level model in the next step, and here only a simple analysis is performed. A steady state conditions is calculated where each cell generates 1 W. In Fig. 2 the temperature field is plotted with the reference to the cooling water, here the rise is about 0.42 °C is observed. From the computational efforts this model contains 151.10^3 unknowns and one solution takes 31 s in an Intel I7-2.6 GHz. This model is relatively light weight for 3D simulations, but for batteries, difficulties come due to necessary long transient runs like drive cycles (2,000 s). This means at least 1,000 time steps are needed (here one time step took 31 s) what motivates the use of more efficient methods to solve transient thermal problems.

3 Model Order Reduction

After the discretization of a finite element transient thermal model one get a system of ordinary differential equations in the following form:

$$E\dot{\mathbf{x}} + K\mathbf{x} = \mathbf{f} \tag{1}$$

Where E is the heat capacity matrix, K is the heat conductivity matrix, and the state vector $\mathbf{x}$ contains the degrees of freedom DOF, which for thermal problems are the node temperatures and $\mathbf{f}$ is the load vector. In a steady state model the E matrix is not necessary. Here each matrix has the size of the number of DOF's (Kostetzer and Rudnyi 2012).

For model order reduction, MOR, the concept of input/output is introduced. The load vector $\mathbf{f}(t)$is divided in constant vectors $\mathbf{b}_i$ and in time functions u_i. Constant vectors transfer the time functions to specific degrees of freedom.

$$\mathbf{f}(t) = \sum \mathbf{b}_i u_i(t) \tag{2}$$

At the system level there is no need of the complete state vector $\mathbf{x}$ but just a part of that, named $\mathbf{y}$. The relation between them is defined by the output matrix C:

$$\mathbf{y} = C\mathbf{x} \tag{3}$$

The objective of model order reduction here is to **reduce the dimension of the state vector and preserve the dynamical behaviour of the input/output relations**

(Bechtold and Rudnyi 2012). Mathematicians and engineers developed (Bechtold et al. 2007) different techniques for model reduction and some of them use the projection idea:

$$\mathbf{x} = V\mathbf{z} + \varepsilon \tag{4}$$

The projection matrix C approximates the state vector $\mathbf{x}$ with a few of degrees of freedom $\mathbf{z}$ resulting in an unknown error ε. Assuming that error is small the original state vector is described in the sub-space defined by matrix V. The reduced order model is found by projecting the Eq.1 into the lower sub-space:

$$V^T EV\dot{\mathbf{z}} + V^T KV\mathbf{z} = V^T BVu \tag{5}$$

$$\mathbf{y} = CV\mathbf{z} \tag{6}$$

Among existing methods, the present work focus in the moment matching via Krylov subspace. The moment matching means after transforming the dynamic system into Laplace domain, in such that lower-order system have the same first derivatives in the Taylor expansion around expansion points. A particular Krylov subspace finds the projection and the reduced order model matches the first moments automatically. This technology is available in the software MOR4ANSYS and can be applied based on FEM models created in the ANSYS environment.

For the battery pack from Fig. 1 a verification case is presented. The verification is done by comparing the transient FEM solution versus the transient solution with the ROM. The ROM model is configured with 10 inputs, where each cell defines one heat generation input. Outputs are the temperatures at the middle of each cell. To reduce the FE model one first must setup the model in ANSYS with all boundary conditions. Followed by writing all system matrices and load vectors into files. The second step is done in MOR4ANSYS resulting in a system level ROM. The ROM format can be in state space, SML or VHDL-AMS. The dimension of the ROM is chosen to be 100 (size of vector $\mathbf{z}$ in Eq. 5). From experience the dimension 10 per input is a good compromise between CPU effort and accuracy (Kostetzer 2012; Kostetzer and Rudnyi 2012).

A validation load setup is defined by a sinusoidal signal for power loss at cells 1 and 5 Frequency is 0.01 Hz and amplitude of 20 W. All other cells kept without any load. The ROM is solved in Simplorer and the Full model directly in ANSYS, both with fixed time step of 0.1 s and total time of 3,600 s.

Battery cells temperatures from the ROM solution can be seen in Fig. 3. The two highest values are from the cells that received the heat load, cells 1 and 5. Focusing in the cell 1, the Fig. 4 shows the difference between results from ROM and Full solution. Here the error is defined by the absolute difference over the Full value in percentage. The error goes to the order of 2 % and oscillates there, what gives a good accuracy of the ROM compared to the Full solution, further validation of the method is published (Bechtold et al. 2007).

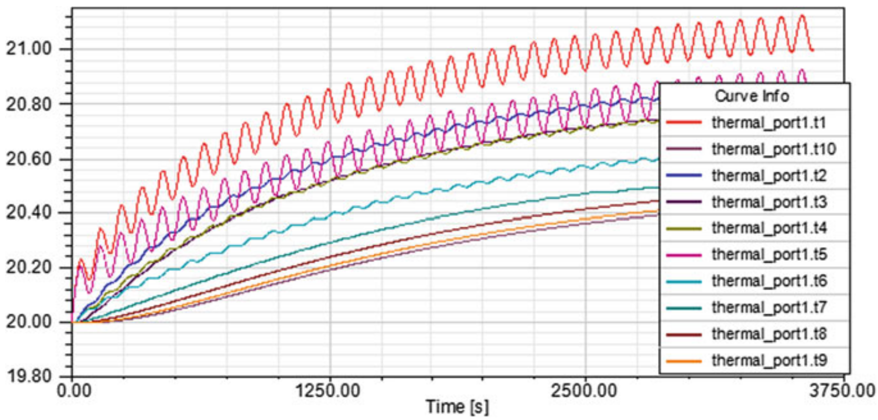


Fig. 3 Reduced order model temperature response for a sinusoidal heat input at the cells 1 and 5. Model solved in ANSYS Simplorer

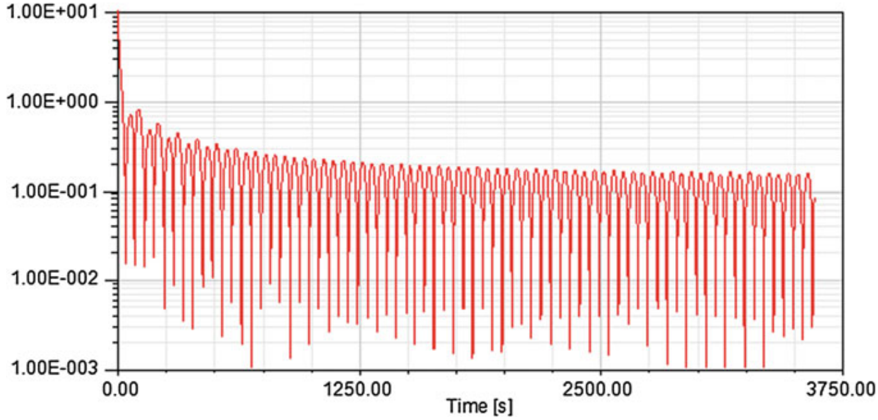


Fig. 4 Relative error for the temperature response of the cell 1. The ROM response is compared with the full FEM solution

From the computational efforts one can see the benefit. Full solution need 47,750 s (13.2 h) and the ROM need 35.9 s for this configuration. The speed-up factor is up to 1,300 for ROM with an error of 2 %. Additionally from the ROM one have to account the only once procedure to get system matrices and to reduce the system itself, here it is about the time to solve one time step in FEM (31 s for this example).

4 Efficient Electro-Thermal Battery Pack Simulation

Having the thermal 3D based battery pack ready at the system level then now the electrical/electrochemical model can be coupled. Battery electrical models need at least to describe the voltage/current relation, its capacity and power losses. For this task there are basically two model types, first is the physical based model where through conservation equations (species, energy, charge) the behavior is described. A famous model is the Newman's group model (Doyle 1995; Newman and Thomas-Alyea 2004; Newman 1998). Physical based models have the advantage of a phenomenological description and the disadvantage is the unknown parameters that are difficult to measure, for example the mass diffusion coefficient of Lithium ions at the electrodes. A more practical and popular approach is the circuit based one, where an equivalent electrical circuit is fitted to experimental data. Here the experiments are well known and results are good for the measured conditions. In this work the circuit based model is used based on results from the funded AiF ZIM project (Stumpp et al. 2012).

A 40 Ah Lithium ion cell is measured (Stumpp et al. 2012) and the respective equivalent circuit is composed by one voltage source for the open circuit voltage, OCV, one series resistor and two sets of one resistor and one capacitor connected in parallel. All the resistors and capacitors have their resistance and capacitance described by 3D tables as a function of temperature, state of charge (SOC) and current. The power loss is described by the joule heat from the three resistors. The circuit based model is implemented here in the software ANSYS Simplorer using circuit components and VHDL-AMS language.

From the battery pack side, each cell is modeled by an independent electrical model with a thermal connection to exchange the temperature/heat flow with the

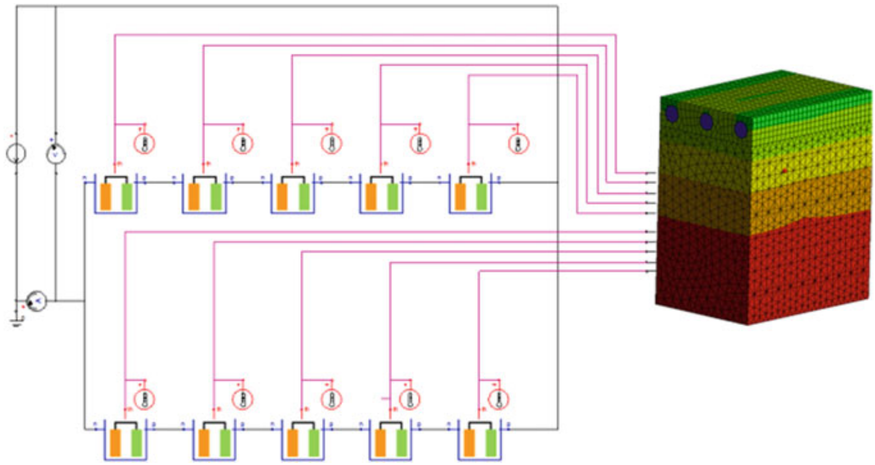


Fig. 5 Battery pack electro-thermal model at the system level

battery pack thermal model. This means an electro-thermal coupling at the system level. The demonstration battery pack with 10 cells is used and the reduced order thermal model from Sect.3 is coupled to the electrical cell models, see Fig. 5. The electrical architecture is with two parallel sets of five cells in series.

A case study is presented based on an electric vehicle (EV), driving in the standard drive cycle FTP75, see Fig. 6. The vehicle is modeled with a power train backward model (Nallabolu et al. 2011) where the simplified mechanical and electrical drive train components calculate the necessary power to follow the velocity profile. The EV weights 1,150 kg and is powered with a 42 kW electric motor. For this study the important load is the current at the battery pack terminals, Fig. 6, where the loads at the cell level are with an average of 120 A (3C-rate) and peak up to 800 A (22C-rate).

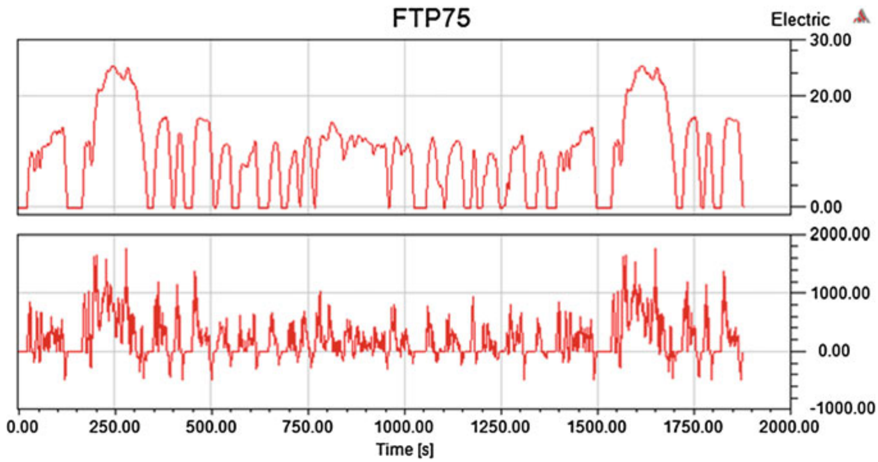


Fig. 6 FTP75 velocity drive cycle and the required current for the battery pack for an electric vehicle

The drive cycle is defined under 1,800 s and an additional parking time is included up to the total of 5,000 s. Parking simulate the cooling without any load. The electro-thermal battery model with the given current load from the EV model is solved for the 5,000 s in 166 s CPU time. From the thermal side each cell contains one temperature value as output from the ROM model see Fig. 7 at the top. The initial temperature is 23 °C and water cooling channels are kept in 23 °C. Cell temperatures rise up to 37.5 °C until the end of the drive cycle (1,700 s). During the parking period all cells are cooled until the thermal equilibrium is reached. Due to the 3D thermal arrangement of the cooling channels and cells, temperature differences between cells are not strong, it stays in the range of 0.2 °C, Fig. 7 at the bottom.

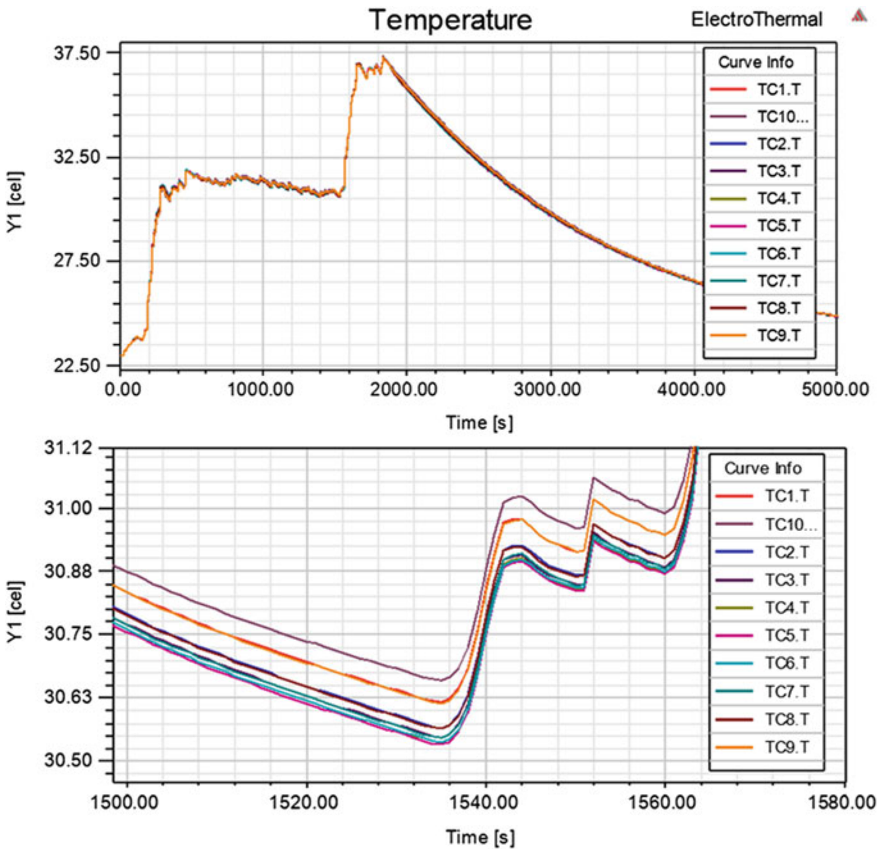


Fig. 7 Battery pack temperature response for the FTP75 drive cycle load. At the *top* the complete cycle plus the parking period from 1,800 s until 5,000 s. At the *bottom* a zoom to show temperature differences between cells

5 Conclusion

It is shown the application of model order reduction technique to automatically reduce the original system of equations of a thermal FEM model into a very CPU efficient model. The approximation errors are under 2 % and the speed up in the order of 1,300. Circuit based electrical models are also implemented and coupled with the ROM battery pack model for a simulation under the FTP75 drive cycle. Simulation results of physical 5,000 s are obtained after 166 s of calculation. Finally with this technique the 3D thermal effects are available for the system engineer to analyze and design the battery pack with in the expected computational costs of system level models.

References

Bechtold T, Rudnyi E (2012) Introduction into model order reduction. CADFEM J Infoplaner N1:53–55

Bechtold T, Korvink J, Rudnyi E (2007) Fast simulation of electro-thermal MEMS: efficient dynamic compact models, Springer, Berlin

Doyle M (1995) Design and simulation of lithium rechargeable batteries. PhD thesis, University of California, Berkeley

Kostetzer L (2012) Battery pack electro-thermal simulation, Master's thesis, University of Applied Sciences of Landshut and University of Applied Sciences of Ingolstadt

Kostetzer L, Rudnyi E (2012) Model order reduction for efficient battery electro-thermal simulation. In: Proceedings SCEE 2012

Newman J, Thomas-Alyea K (eds.) (2004) Electrochemical systems. Electrochemical society series, Wiley-Interscience, Hoboken

Newman J (1998) Dual Foil Software. Online: http://www.cchem.berkeley.edu/jsngrp/fortran.htmlhttp://www.cchem.berkeley.edu/jsngrp/fortran.html

Nallabolu S, Kostetzer L, Rudnyi E (2011) System simulation of hybrid vehicle propulsion with an advanced battery model. In: Antriebssysteme

Pesaran AA (2001) Battery thermal management in EVs and HEVs: issues and solutions. In: Advanced automotive battery conference, Las Vegas

Smith K, Markel T, Kim G-H, Pesaran A (2010) Design of electric drive vehicle batteries for long life and low cost. In: Workshop on accelerated stress testing and reliability

Stumpp S, Kostetzer L, Kellermeyer M, Kuhn R, Rudnyi E (2012) Evaluation of the influence of thermal model details for lithium-ion pouch cells, In: Advanced battery power 2012 symposium for research, development and science

Thomas E, Bloom I, Christophersen J, Battaglia V (2008) Statistical methodology for predicting the life of lithium-ion cells via accelerated degradation testing. J Power Sources 184(1): 312–317

Increasing Sustainability of Road Transport in European Cities and Metropolitan Areas by Facilitating Autonomic Road Transport Systems (ARTS)

J. Schlingensiepen, R. Mehmood, F. C. Nemtanu and M. Niculescu

Abstract The frequent failure of road transportation networks, resulting from traffic incidents, system overloading and lack of optimised support systems is becoming a problem in keeping modern cities functioning, because those incidents affect both, personal mobility and transportation of goods including everyday commodities. Inefficient systems lead to a waste of resources (infrastructure and energy). Therefore not only efficiency of vehicles but efficiency of whole systems needs to be considered to increase sustainability in road transportation. This paper shows the approach using Autonomic Road Transport Systems (ARTS) and gives an overview on upcoming challenge for vehicle manufacturers and scientific society.

1 Need for Action

Transport systems are important components of urban systems or cities and Intelligent Transport Systems are mandatory to transform the city in a smart city (and the transport system in a smart transport system).

J. Schlingensiepen (✉)
Technische Hochschule Ingolstadt, Esplanade 10 85049 Ingolstadt, Germany
e-mail: joern.schlingensiepen@thi.de

R. Mehmood
King Khalid University, Abha, Kingdom of Saudi Arabia
e-mail: R.Mehmood@gmail.com

F. C. Nemtanu
Politehnica University of Bucharest, Splaiul Independentei 313 060042 Bucuresti, Romania
e-mail: fnemtanu@eltrans.pub.ro

M. Niculescu
Intelligent Transport Systems Romania—ITS Romania, 38 Dinicu Golescu (Ministry of Transport), Gate A, 6th Floor, Room 48 010873 Bucharest, Romania
e-mail: mihai.niculescu@its-romania.ro

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_20,

The sustainability of transport systems has four main issues to be addressed: the energy efficiency (for the same transport activity a smaller quantity of energy should be consumed), saving time (the time allocated for transport activity has to be minimized), saving money (the cost of transport is reflected in the price of goods not in the quality of them) and environmental aspects (the transport should protect the environment not to destruct it). The fourth priority area of European ITS Directive (The European parliament and the council of the European union 2010) is focused on linking the vehicles with the infrastructure based, especially, on open in-vehicle platform as well as cooperative systems. That means integration between the vehicles and the infrastructure. Urban ITS is an important domain of ITS applications and ITS and Autonomic Road Transport Systems [ARTS (TUD Cost Action TU1102 2013)] could be tools of solving traffic and mobility problems in cities [Urban ITS Expert Group has already elaborated a set of guidelines oriented on ITS for urban areas—i.e. Guidelines for ITS Deployment in Urban Areas—Multimodal Information (TUD cost action TU1102 2013)].

One of the keys to increase energy efficiency is avoiding traffic jam or other interferences of traffic flow. These also will decrease the amount of CO_2 emitted by traffic as these numbers show: On the one hand in 2007 the CO_2 emissions caused by traffic jams (not including inappropriate periods of traffic lights or additional break usage on heavy loaded roads) in Germany only was 714,000 tonnes (288 million litres of fuel) or approximately 7 % of the CO_2 emissions by passenger cars. On the other hand the recent study “Understanding Road Usage Patterns in Urban Areas” (Urban ITS Expert Group 2013) shows that, even during peak hours 98 % of the road segments are underutilized. Therefore, the approach to better utilize existing infrastructure through better planning of utilization appears promising.

Intelligent transport systems (ITS) can help optimising the overall system. Since mass transportation does not fulfil the demands in individual/personal transport future transport systems will be road transport systems including cars, vans and trucks. Allowing a prospective management of traffic to ensure maximizing the utilisation of infrastructure vehicles need to be integrated in those systems by mobile devices/controllers (on board units). Thus new requirements on vehicles and traffic management systems are emerging. The spreading of incorporated units demands distributed software system architecture. Since several stakeholders are bringing in their devices, which leads to different rates of probability of failure, a fault-tolerant approach is needed. Autonomic Road Transport Systems (ARTS) address these challenges and provide a new approach for establishing transportation networks minimizing the use of energy.

To allow an effective traffic management the current traffic situation and operating grade has to be captured to allow predictions on future situations to hedge decisions made by users and operators. The system shall provide derived recommendations for each individual road users and play back its behaviour to an overall decision support system.

2 Generic Architecture of ARTS

On the basis of existing research approaches, we have developed a general architecture for ITS to derive requirements for future vehicles and to identify issues. ITS backbones basically has to be considered as distributed ICT systems, dealing with all benefits and problems of these systems emerging from heterogeneous user group, heterogeneous devices and the leak of confidence and reliability resulting from the fact everybody can join and leave the system at any time.

2.1 General Structure

Figure 1 shows a general structure of a distributed system. The separation between vehicles as moving parts and infrastructure as the fixed parts is common. On both sites different information like data about the current state (mainly collected by sensors) and plans (input by users and operators) are collected. Based on this information it is possible to derive control factors for the overall system. Therefore, this information must be brought together and evaluated. Therefore a general subdivision of communication in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) is commonly used. The main goal of the overall system is fulfilling the plans of the users (road users and traffic system operators) while using a minimum of resources. Based on the aggregated data both the infrastructure and the vehicle make predictions on the future state of the road and make local or global decisions. Figure 1 gives some examples of modules that interact through the ARTS Backbone. In our generic set-up the number of interactions between components is minimized since interaction shall be done using data integration provided by the backbone. As seen in the figure the plans of infrastructure provider are optimizing the utilisation grade of the infrastructure and allow emergency prioritisation on demand. Therefore a model of the overall system (including vehicle behaviour) and a statistical component using machine learning (Stat-Com) are used to generate a load prediction for all street sections. This prediction engine has learned from the past and is fed by the current state of the overall system provided by the backbone. The load prediction is written back to the backbone and used by the components on the vehicle site to derive local decisions. On vehicle site we have individual plans like reaching a route target, saving fuel and time. Those plans influence local decisions. By providing this plans to the ARTS the prediction of the infrastructure gets more precise. As an example for local decisions on vehicle site the choice of speed, lane and route can be named. Those decisions will be made on the basis of the local prediction of *Lane Limitations* and *Route Limitations*. For example reducing/increasing speed might be reasonable if the best route has limitations that will be gone/arisen sometimes later and an alternative route is not suitable.

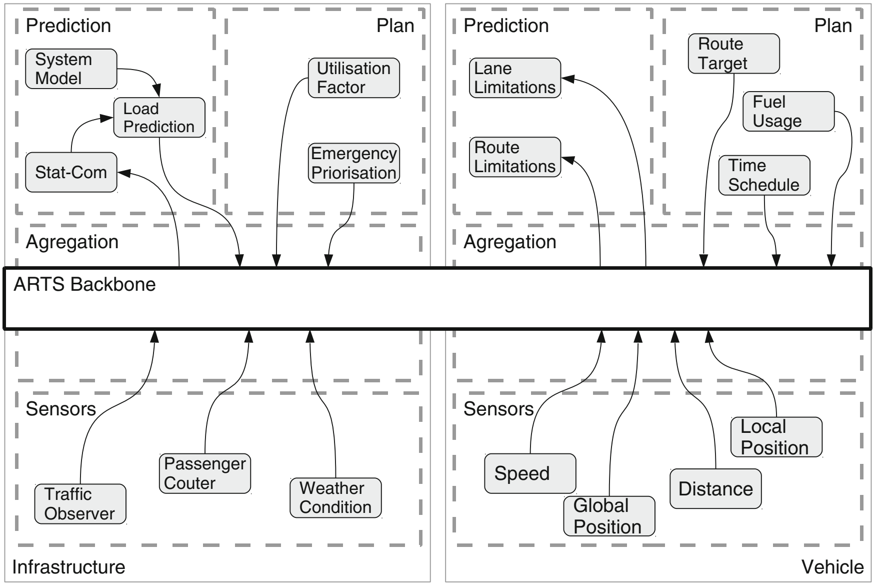


Fig. 1 Skeleton of an ARTS including two sites (infrastructure and vehicle) and a backbone

In order to allow all these predictions, information about the current state has to be collected from the field. On the infrastructure site these information are collected by internal sources like traffic observers but also external sources like weather conditions (including forecast) or passenger counter from public transport systems. On the vehicle site information about the current state like speed and global position and information about environment like local position (lane, direction) and distance to other vehicles are collected to allow having a proper model of current situation, e.g. traffic load.

2.2 Requirements

The first requirement for future systems is apparent at the communication network level. Technologies must be developed and standardized, which allow exchange of traffic information between system components from different suppliers. The architecture will always be some kind of open peer-to-peer (P2P)-system's architecture, where every user can join and leave the network at any time. The components of infrastructure assume different roles than those of vehicles. Such kind of asymmetrical P2P systems are already sufficiently investigated (compare Wang et al. 2012), therefore the challenges to the system design can be easily derived.

Following already known problems from peer-to-peer-systems must be considered in our use case:

- **V2V trust:** In P2P-Systems information is provided by every peer. Therefore the peers need an internal model of evaluating the trustability of the provided information.
- **V2I trust:** Infrastructure provided by local authorities may help solving the problems of trust by providing mechanisms for collecting and verifying information and prognosis.
- **V2V pollution:** A common problem in open P2P-Systems is so called pollution (Schlingensiepen 2008; Costa and Almeida 2007), where malicious peers may send manipulated data to affect the overall system and change its behaviour to earn a benefit or just to create confusion.
- **V2V/V2I anonymity:** In contrast to the requirements on trust the road user requires a level of anonymity that ensures individuals are not tracked by authorities or other parties. Especially in case of transmitting the user's plans to the backbone privacy is a recommended function.

Main problems of trust and pollution within an urban system with dense infrastructure can be solved, at the cost of increased communication latency, by allowing only direct communication between vehicles and infrastructure and establish a pseudo V2V communication via infrastructure covered by state of the art mechanisms from cryptography like local, user and manufacturer certificates and derived signing protocols.

As a result a structured P2P-Overlaynetwork is formed. The problem of anonymity cannot be solved easily in those kinds of networks. In principle confidence in transmitted data respectively information depends on the sender's credibility and therefore an authentication is required or in other words: *If I should trust you, I need to know who you are*. From that follows that motion profiles of vehicles and hence people are possible. Within urban system with high amount of traffic, those problems may be solved by temporary identities and a net of trust. While the information of different road users are matched to get a confident picture but in general all structured P2P Networks are vulnerable to trojan behavior and sybil attacks (Liang et al. 2005). Therefore a deep analysis of the system is strongly recommended before an industrial application.

Further requirements and problems arise while considering the more detailed architecture shown in Fig. 2. Decisions made by road users and operators can be assigned to strategic, tactical and operational level. The decisions refer to different time horizons between long-term planning (strategic), medium-term behavior (tactical) and direct action/reaction (operational).

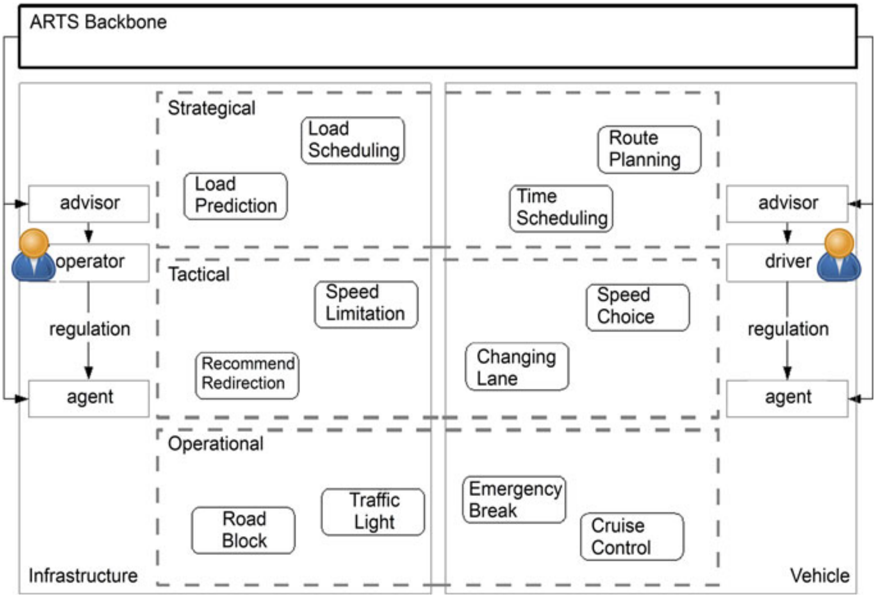


Fig. 2 Allocation of functions and decisions in a distributed ITC system implementing an ARTS

The figure also shows that decisions in the vehicle are made by the on board support systems (agent) or the driver. Today and in the nearer future for legal reasons and reasons of user acceptance all decisions at all levels will be made by the driver, so the information of ITSs are incorporated in the decision-making process as suggestions, provided to the driver by a mobile device called advisor. Studies of University of Twente have shown that the drivers' trust in the advice of the system is an essential requirement and this confidence is often absent (Rowaihy et al. 2005). Drivers make decisions (e.g. choosing lanes, speed adjustment) on the basis of personal experiences. Therefore the effect of not trusting the advice is boosted, because in traffic systems the results of decisions that are inauspicious for the overall system are not hurting the decision maker but other road users. Figure 2 shows some examples for actions respectively decisions made at the different levels:

- **Load Scheduling and Load Prediction** are methods on strategic level allowing the operators to predict the traffic flow and optimize it using scheduling mechanisms.
- **Speed Limitation and Recommend Redirection** are functions on tactical level allowing the operator regulating the behaviour of road users by or defining rules like temporary speed limits or giving advices to selected users to avoid overloads.

- **Block Road and affecting Traffic Lights** are functions on operational level allowing operators to control traffic flow directly. This can be used to ensure emergency privileges or prioritise selected lanes or roads to ensure traffic flow.
- **Time Scheduling and Route Planning** are methods on strategic level allowing road users to find optimal way fulfilling their traffic requirements. Time scheduling describes choosing time slots outboard the rush hour if possible. Route planning describes planning the route to minimize the time or distance. During the ride this is related to the operational level where adaptive route planning may use the recommended redirections to change planned routes.
- **Speed Choice and Changing Lane** are methods on tactical level, where drivers chose an adequate speed to avoid being at known traffic hot spots on the route during rush hour or choose the lane they expect to have less incidents in traffic flow.
- **Emergency Break and Cruise Control** are functions on operational level, that describes reaction on the surrounding traffic. Emergency break is a reaction on suddenly appearing episodes. Cruise control describes adapting suitable speed from other road users respectively their personal speed limit to reach a optimal traffic flow. Today's approaches on this are described by the term Connected Cruise Control (CCC) (Rowaihy et al. 2005).

In longer perspective vehicles will have more autonomous functions and more decisions will be made by the agents. As in every situation all decisions on longer term issues have to be made on the basis of insecure data and a look at the list of functions and decision listed above shows most of them are safety critical. Therefore the main objective of an overall system must be to provide and verify necessary information as early as possible and to provide appropriate methods of prediction on future conditions.

2.3 Autonomification of ITS

At this point it is obvious that reliability of data is essential and the most important requirement to the ITS. Therefore we propose usage of autonomic road transport systems (ARTS). Establishing an autonomic system gives some great advantages in increasing reliability of the overall systems. The term autonomic is a biological metaphor adopted by IBM to describe the desired properties of future complex IT systems, proposed as a highly advanced approach to deal with the problems of the delivery and maintenance of increasingly complex systems. It is hypothesized that systems with autonomic capabilities will help alleviate many of the problems associated with life cycle management of complex systems. Autonomic systems embody self-assessment and self-management abilities that enable the system to assess its own state, then adapt or heal itself in response to that assessment. The interface between system and owner is set at a very high level: the owner sets out goals, policies or service levels that the system must follow, and the system translates these into its system functions resulting in a change of behaviour. IBM defines four areas of autonomic functions: (i) self-configuration through automatic configuration of components; (ii) self-healing through automatic discovery, and correction of faults; (iii) self-optimization through automatic monitoring and control of resources to ensure the optimal functioning with respect to the defined requirements; and (iv) self-protection through proactive identification and protection from arbitrary attacks. We define autonomification as the process of transforming an entity (a service, system, and infrastructure) into an autonomic entity such that the process infuses autonomic properties into an entity causing the entity to become an autonomic entity. In terms of an ITS this influence two aspects of the system: **components design** and **architecture of the p2p-system**. Components needs to be implemented in a way that includes not only posting and consuming data but also self-assessing and giving additional data about own state and the trustability of measured data which can be combined with networks of trust and service levels. The current systems process only measured data with high trustability, in case of harvesting several data from many different measuring entities like it is done in an ARTS processing of unsure data will lead to a more valid picture of current system state.

The architecture of an autonomic ITS has to respect the fact, that the different component in the system are owned, run and configured by different stakeholders with different interest. A suitable approach is to define a peer-to-peer structure, where the different players are net together by using a common backbone like IP. Since current standards in networking in public transport and traffic management are based on IP this will be a good approach to reuse current infrastructure.

On top of this current network infrastructure a p2p-Layer (overlay network) shall be established. Where users can join the network using their personal device, like a smart phone or a satellite navigation system of a car or future personal devices that be carried by the user or will be fixed at a place or vehicle. Beside the personal devices the components of infrastructure like traffic management systems, traffic light systems, trains and the data management systems of service providers like public transport provider, taxi associations and others may enter the overlay network. Since those systems are very heterogeneous the p2p-System will be asymmetric and may follow the approach of corporative IT-Systems (Wang et al. 2012), which allows using the service oriented architecture of a grid on basis of a p2p-overlay-network. Therefore not only service functions and interaction but also a system of trust in service levels, zones and credibility has to be defined.

From today's perspective the network (corporative ITS) will be a hybrid-p2p, where so called super-Peers will have a higher credibility and provide core functionality. We call the network of super-Peers the backbone (backbone peer) and call the other peers members. To define and standardize the architecture of future ARTS the following tasks will be needed: (i) Definition of the overlay network; (ii) Definition of the services in network; (iii) Definition of the quality of service levels; (iv) Definition of the trust in services levels, zones and credibility.

To ensure the resulting system fulfils the given requirement the service location and assessment needs to be enhanced by adding functions to change service providers during runtime to allow self-configuration, self-healing and self-optimization. To allow self-protection mechanisms for detection and exclusion of malicious peers need to be developed.

3 Conclusion

To increase the sustainability of traffic systems minimizing the amount of resources used by this kind of traffic is essential. This can be done by establishing ARTS as a network of stakeholders respectively their devices in a P2P-Architecture. To establish those kinds of networks the following car related technical functions needs to be developed, standardized and implemented:

- Protocols to enter and leave the network, provide and consume data/information that respects privacy.
- On board Units that establish network connectivity and implement the mentioned protocols.
- Definition of a corporated ITC system including definition of services, service levels, zones of trust.
- Integration of on board units with the current assisting systems and definition of a common accepted user interface to advice drivers.

Beside this the functions and interaction mode of current infrastructure need to be enhanced, the prediction systems and their runtime environment needs to be developed and standardized and the legal aspects has to be considered related to the current law and its advancements.

Following this track ARTS can make a contribution in making car traffic more efficient and sustainable and take a step to autonomous traffic that allows even more efficient traffic management, since human irrational decisions do not disturb optimized traffic flow.

Acknowledgment Authors are members of COST ARTS founded by EU commission (www.cost-arts.org).

References

Costa C, Almeida J (2007) Reputation systems for fighting pollution in peer-to-peer file sharing systems. In: Seventh IEEE international conference on peer-to-peer computing (P2P 2007), 2 Sept 2007, pp 53–60

Liang J, Kumar R, Xi Y, Ross K (2005) Pollution in P2P file sharing systems. In: INFOCOM 2005, 24th annual joint conference of the IEEE computer and communications societies. Proceedings IEEE, vol 2. 15 March 2005, pp 1174–1185

Rowaihy H, Enck W, McDaniel P, La Porta T (2005) Limiting sybil attacks in structured P2P networks. Pennsylvania State University, State College, Pennsylvania

Schlingensiepen J (2008) Korporative IT-Systemarchitektur zur Unterstützung unternehmensübergreifender kooperativer Produktentwicklung. Otto-von-Guericke-Universität Magdeburg, Magdeburg

The European Parliament and the Council of the European Union (2010) Directive 2010/40/EU of the European parliament and of the council of 7 July 2010 on the framework for the deployment of intelligent transport systems in the field of road transport and for interfaces with other modes of transport. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32010L0040:EN:NOT. Accessed 12 May 2013

TUD Cost Action TU1102 (2013) Autonomic road transport systems (ARTS). http://www.cost-arts.org. Accessed 26 May 2013

Urban ITS Expert Group (2013) Guidelines for ITS deployment in urban areas—multimodal information. http://ec.europa.eu/transport/themes/its/road/action_plan/doc/2013-urban-its-expert_group-guidelines-on-multimodal-information.pdf. Accessed 12 May 2013

Wang P, Hunter T, Bayen AM, Schechtner K, González MC (2012) Understanding road usage patterns in urban areas. Sci Rep 2:1001 (online version)

Effect of Heat Treatment on Cylinder Block Bore Distortion

S. K. Akkaladevi

Abstract Cylinder block bore distortion has a significant role in the lubricant oil consumption and subsequent block piston assembly failure. The paper discusses the methods to quantify the distortion levels in the cylinder block caused by the heat treatment involved. The optimization of the heat treatment process is discussed in detail with the specimen test, cylinder block individual tests and aggregate vehicle tests. The results show a new philosophy for cylinder block bore distortion-ring conformability.

1 Introduction

Cylinder block piston interface has a vital role in the engine performance. The interface is bounded by thermal, structural and fluid boundary conditions. Each of these affects the functioning and subsequent wear and failure phenomena at the interface (Scheider 1993). Analyzing the failure phenomena in these engine components has been an area of interest since long time.

Among the failures caused in cylinder block piston interface, cylinder block piston ring assembly attribute to a major extent. The ring conformability to the cylinder bore and the cylinder block distortion wear are the two main factors. The later is the topic of interest in this paper and would be discussed in detail.

Analyzing the cylinder block failure for the wear phenomena has been a regular trend. Wear together with distortion effects the interface in the operating conditions (Dunaevsky 1990). Segregating wear from distortion is a difficult task hence

S. K. Akkaladevi (✉)
Ingolstadt University of Applied Sciences, Esplanade 10, 85049 Ingolstadt, Germany
e-mail: ia2287@haw-ingolstadt.de

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_21,

an effort is made to quantify the general trends of distortions which are caused. The surface finish in the cylinder block inner diameter signifies good information of the wear levels in the cylinder block. This helps us to estimate the distortion levels together with the methods mentioned below. The paper discusses the role of heat treatment in the distortion.

2 Method

To quantify the contribution from wear and deformation, the following test is performed on the cylinder block.

The deformation of the cylinder block solely related to the thermal effects is quantified by the application of heat, at an average cylinder block temperature for a specified time (American Foundry Society 2004). The dimensional measurement of the cylinder block is a measure of the deformation of the cylinder block. This deformation should be within the conformability levels of the ring. The measurements at the engine running conditions and the ambient temperature conditions thus obtained are a measure of the deformation caused.

In order to quantity the same, a test was conducted on a standard specimen of aluminum alloy of the cylinder block. Two test specimens are made and used in a separate heating trail. The expansion in the width and height directions is constrained, resulting in a longitudinal distortion of the specimen.

To validate the results of the test specimen, the cylinder blocks with and without heat treatment are tested for distortion. A cylinder block sample made of aluminum alloy with Nikasil coating is used for the test.

The test comprises of heating the samples in a closed furnace at a temperature of 150 °C for a specified time. The cycle is repeated for ten times to finish the required endurance cycle.

Later to validate the results with the actual engine performance, the test is performed on a vehicle. The vehicle is run for a specified kilometer range to check the lubricant oil consumption.

3 Results and Discussion

The results below discuss the tests done for the test specimen and the cylinder block.

Figures 1 and 2 show the distortion levels in the test samples without and with heat treatment. The change in the length of the samples is a measure of the permanent distortion associated.

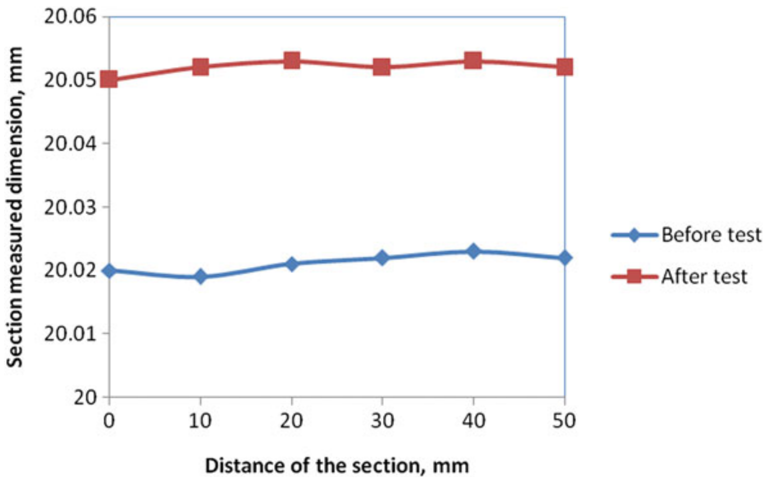


Fig.1 Graph showing the distortion levels in a sample without prior heat treatment

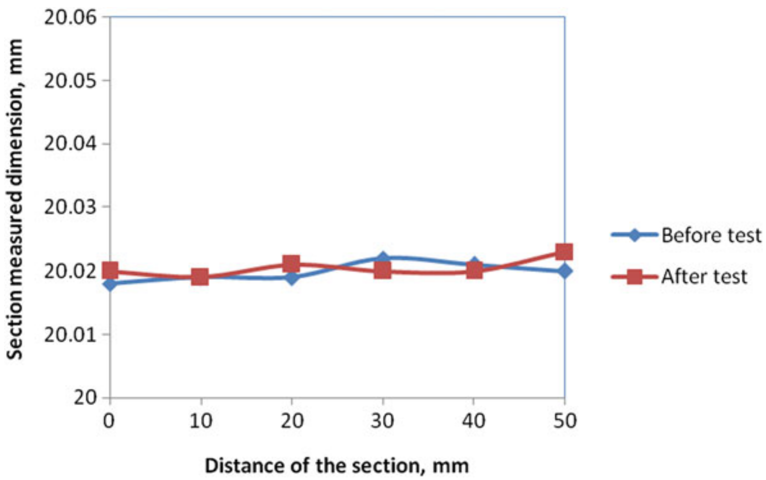


Fig.2 Graph showing the distortion levels in a sample with prior heat treatment

Figures 3 and 4 show the diameter change in the cylinder block with a variation in the heat treatment. The distortion shown has a significant effect on the piston ring assembly and the cylinder block interface. The results here show a distortion of the order of 100 μ. This corresponds to the change in diameter which is represented as zeroth order level of bore distortion. The distortion corresponding to the zeroth order in a cylinder block with the specified heat treatment is negligible. The ring conformability is hence better in the later, which results in a good conformance with the cylinder block. This helps in segregating the amount of distortion caused by thermal effects and the wear caused by boundary lubrication conditions. The comparison is later proved with the oil consumption test with the two types of cylinder blocks on an endurance test. The block with heat treatment showed a consistent and lower lubricant oil consumption than the earlier.

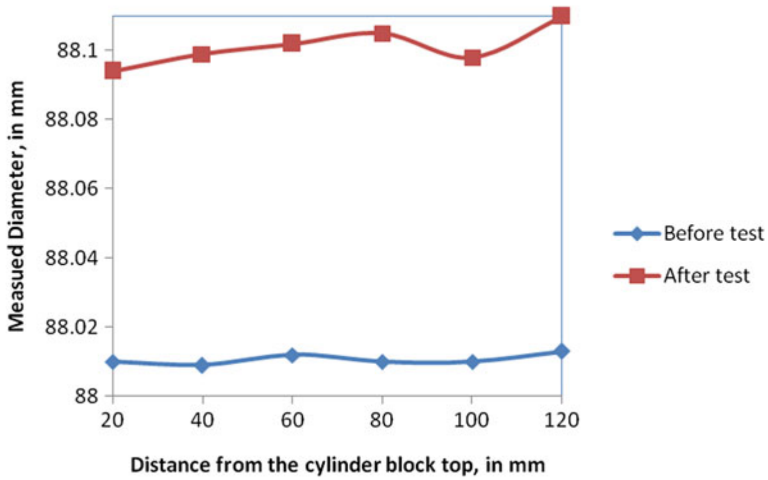


Fig.3 Graph showing the diameter change in the cylinder block without prior heat treatment

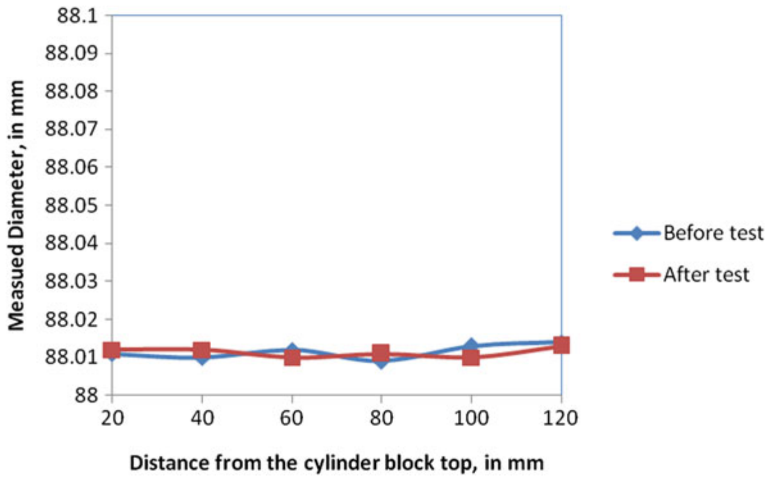


Fig.4 Graph showing the diameter change in the cylinder block with prior heat treatment

4 Conclusion

The role of heat treatment is clearly evident from the results. The comparison of the distortion levels in the samples with and without stress relieving has a major effect on the piston ring and cylinder block interface. A proper optimisation of the heat treatment process with the material chosen is therefore mandatory. Further work may be done by validating the lubricant oil consumption for different configurations of heat treatments for a specified cylinder block material (Kolbenschmidt KS No. 50003804-02). The iterations to control the cylinder block distortion can lead to optimum and stable lubricant oil consumption, which reduced the chances of cylinder block piston failures. The advent of new lightweight materials can be analysed for their feasibility with these tests and improvements can be sorted out.

References

Scheider EW (1993) Effect of cylinder bore out-of-roundness on piston ring rotation and engine oil consumption. Soc Autom Eng 930796:139–160

Dunaevsky VV (1990) Analysis of distortions of cylinder and conformability of piston rings. Tribol Trans 33(1):33–40

American Foundry Society in Cooperation with GM Powertrain Casting Development (2004) Aluminum cylinder block for general motors trucks/SUV engines. Copyright 2004

Kolbenschmidt P (KS No. 50003804-02) Latest machining techniques for aluminum cylinder bores (Alusil® and Lokasil). Press Release Motor Service.

Part V
CO_2 Emission Reduction

CO_2 Emission Reduction: Green Heat Treatment of Engine Components (Cylinder Heads)

M. Belte and D. Dragulin

Abstract The present paper presents practical and theoretical aspects of the solid state heating and heat treatment of aluminium and aluminium alloys. The analysis contains practical results from the development and production activity of BETE AG. The present paper will emphasize the heat transfer through radiation. These technologies become an increasingly importance due to actual environmental restrictive policies. The present paper will focus on the energy reduction during the (pre)heating respectively the cooling phase (see Fig. 1).

1 The (Pre)heating Phase

The support frame elimination through roller passage leads to:

- No investment costs.
- No maintenance costs.
- Significant energy costs reduction (especially during the preheating phase).
- Significant energy "CO_2 print reduction" (especially during the preheating phase).

The use of flat flame gas fired IR burner (Fig. 6) leads to:

- Significant time reduction during the preheating phase: from 80–90 min to 12–20 min (Fig. 2).

The following graphics will present the CO_2 balance in the case of use of support frames made of steel (for the calculation simplification steel = iron); the ratio aluminium/iron varies between 1/3 and 1/0.33 (Figs. 3, 4 and 5).

M. Belte · D. Dragulin (✉)
BELTE AG, Delbrück, Germany
e-mail: d.dragulin@belte-ag.de

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_22,

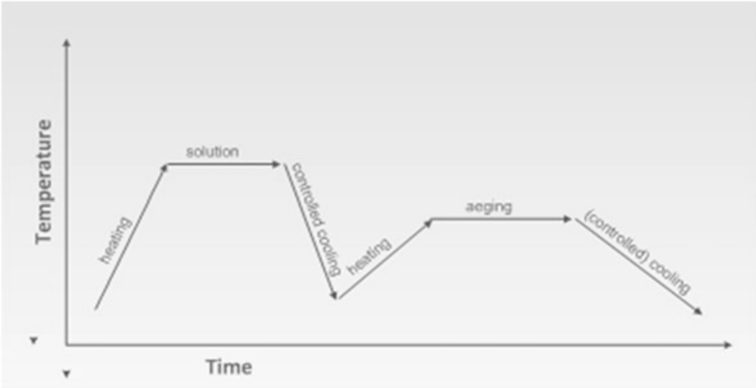


Fig. 1 Heat treatment cycle for aluminium castings

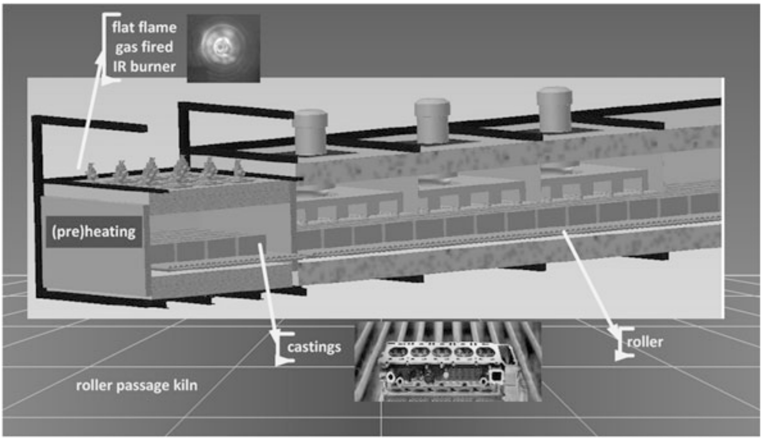


Fig. 2 Roller passage kiln with flat flame gas fired infra red burners—concept BELTE—LOI; Pre-heating and solution heat treatment zones

2 The Cooling Phase

The present study was performed in order to analyze the physical and technological limits of the air cooling in the case of a massive ($\sim$17 kg) aluminium (AlSi10(Cu)) casting (open mould) (Table 1). The experiment was carried out in an aerodynamic tunnel. The mechanical properties were determined using five tensile specimens for each variant. The average values of A and Rp0.2 (see Table 2) were mathematically interpreted using special software. The forced air cooling is a method which shows an increasingly importance in the practice of heat treatment due to the very low level of the residual stress in comparison with the

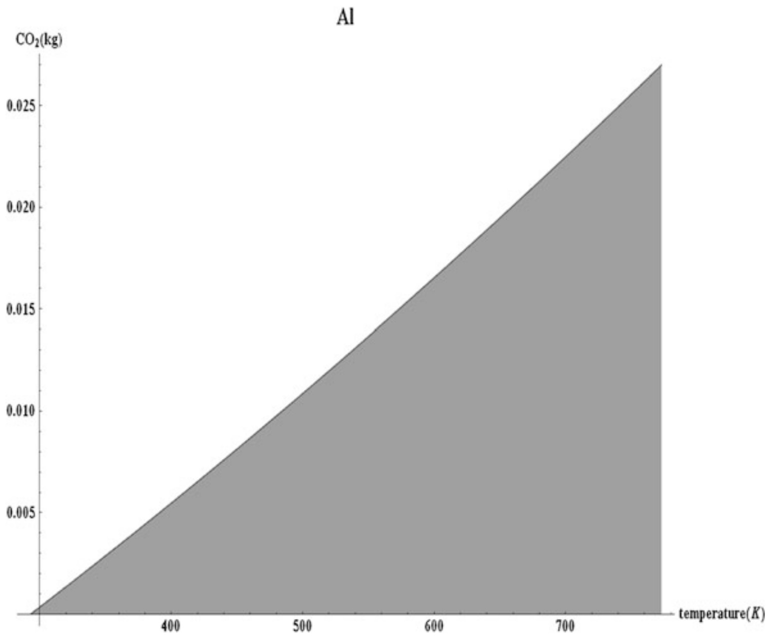


Fig. 3 Theoretic CO_2 print for 1 kg Al between 20 and 500 °C

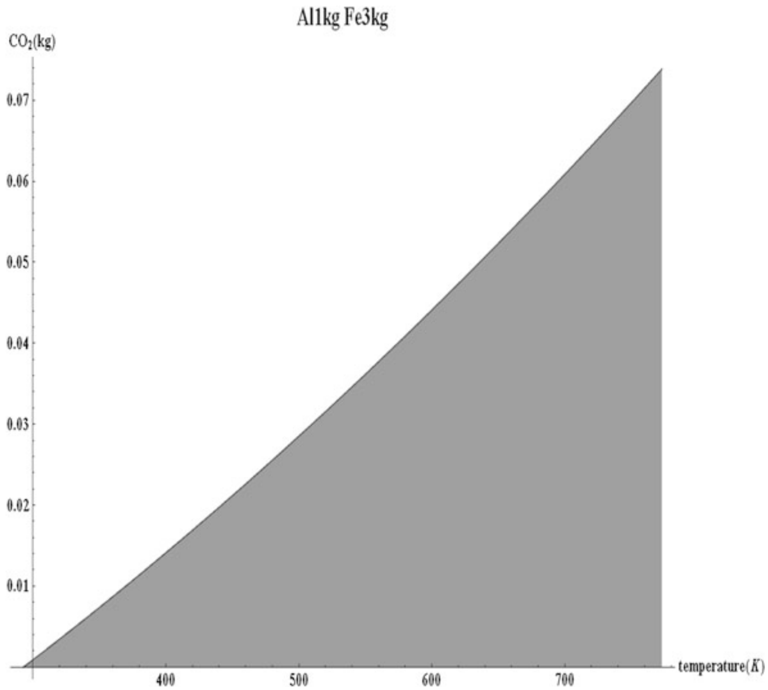


Fig. 4 Theoretic CO_2 print for 1 kg Al–3 kg Fe frame support (worst case) between 20 and 500 °C

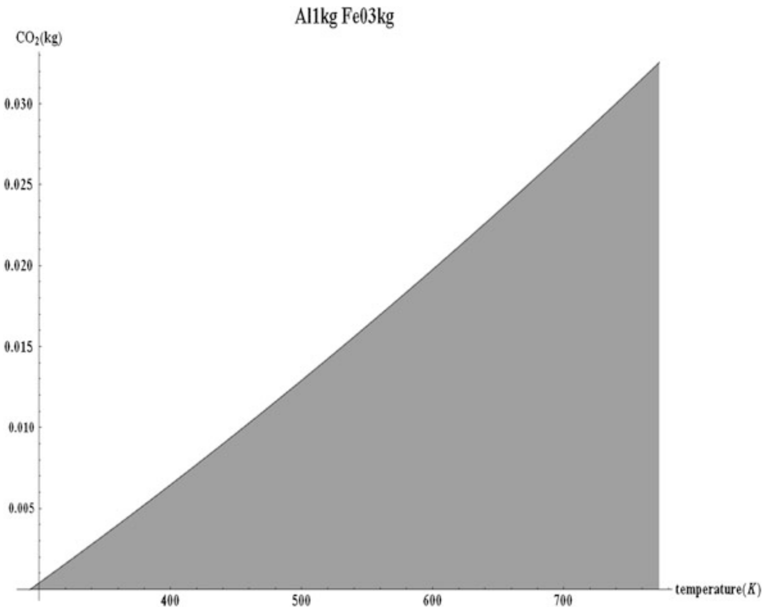


Fig. 5 Theoretic CO_2 print for 1 kg Al–0.333 kg Fe frame support (best case) between 20 and 500 °C

	Gasstrahlungs-brenner	Infrarot-Hochleistungs-strahlungsanlage	Konventioneller Ofen
Durchsatz	2 t/h	2 t/h	2 t/h
Durchlaufzeit	60 min	70 min	240 min
Ofenlänge	10 m	12 m	26 m
Spez. Energiebedarf pro Zylinderkopf	6,88 kWh	15,75 kWh	8,50 kWh
Spez. Energiekosten	3,59 Cent/kWh*	11,55 Cent/kWh*	3,59 Cent/kWh*
Spez. Energiekosten pro Zylinderkopf	24,70 Cent	181,91 Cent	30,52 Cent

Fig. 6 Energy consumption–comparison between flat flame gas IR burner, electric IR "burner" and convection from: "Energieeinsparung durch Schnellerwärmung in der Wärmebehandlung", P.M. Saemann *et.al*. Gaswärme International 01/2012; price level of 2010

Table 1 Massive open mould casting–T6 with air cooling; A–T: various cooling parameters; one part/variant (Fig. 7)

Part	Unit	Temper F	A[a]	B[a]	C	D	E[a]	F[a]	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
Cooling time between 500 and 175 °C [C]	s	–	165	165	185	215	172	172	182	200	154	154	124	162	222	215	324	312	455	357	364	324
Relative Humidity [RH]	%	–	25	25	25	25	25	25	25	25	68	93	68	93	25	82	25	92	25	93	25	25
Suitable for industrial	0 = yes - = no		–	–	–	–	–	–	–	–	–	–	–	–	0-	0-	0	0	0	0	0	0
Rp0,2∅	MPa	107	229	222	222	219	234	227	235	221	214	230	228	222	205	206	192	196	174	183	190	194
Rp0,2 Max	MPa	108	234	231	228	229	242	241	239	230	224	242	237	234	223	218	204	210	184	192	209	205
Rp0,2 Min	MPa	106	219	215	217	210	229	217	225	212	207	222	222	211	194	193	181	186	168	176	177	183
Rm∅	MPa	194	282	294	291	290	291	294	296	292	282	287	294	286	274	276	264	267	249	255	260	262
Rm Max	MPa	196	289	300	298	302	299	300	300	300	294	298	304	291	290	286	275	279	257	285	275	274
Rm Min	MPa	192	277	290	287	281	285	285	291	285	269	278	288	281	264	267	251	260	244	251	253	255
A∅	%	13.7	3.2	6.7	6	6.7	3.4	5	4.7	6.4	6.1	4	6.3	4.9	6.5	7.2	6.8	6.3	8.5	7	6.7	7.1
A Max	%	15.3	6.8	8.3	6.3	7.9	6.8	8.2	6.5	6.9	7.4	6.7	7.1	7.2	7.3	8.1	7.4	8.2	8.8	9.2	7.9	83
A Min	%	12.6	1.9	3.8	5.4	5.9	2.5	3.6	3.6	5.5	3.9	2.5	5.7	3.9	5.6	6	5.4	4.1	8.2	5.4	3.7	45
Hardness ∅	HBW5/250	66	106	106	106	104	107	107	105	104	102	105	108	102	99	99	94	94	88	90	92	92
Hardness Max	HBW5/250	68	109	110	111	109	110	112	109	108	110	109	115	109	107	104	103	98	95	96	102	101
Hardness Min	HBW5/250	63	100	100	103	101	103	101	101	98	98	99	102	92	90	92	90	89	83	82	86	87

[a] repeated experiment

Table 2 Global dependencies

	Rp 0.2(%)	A(%)
CT (cooling time)	73.73	54.82
RH (relative humidity)	26.27	45.18

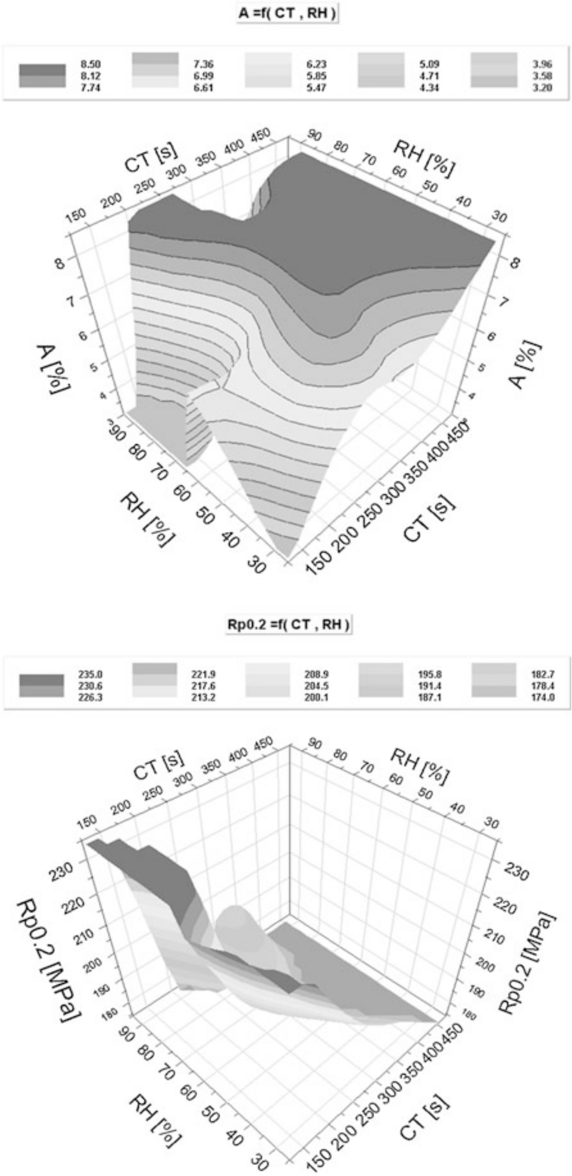


Fig. 7 Elongation & Yield strength as function of cooling time and relative humidity $A = 8, 9153 + 1, 9179 \cdot CT\text{-}0, 8418 \cdot CT^2\text{-}0, 1020 \cdot RH\text{-}2, 1721 \cdot R^2$ $Rp0.2 = 183, 4670\text{-}32, 9740 \cdot CT + 10, 7599 \cdot CT^2\text{-}4, 0508 \cdot RH + 11, 5353 \cdot RH^2$

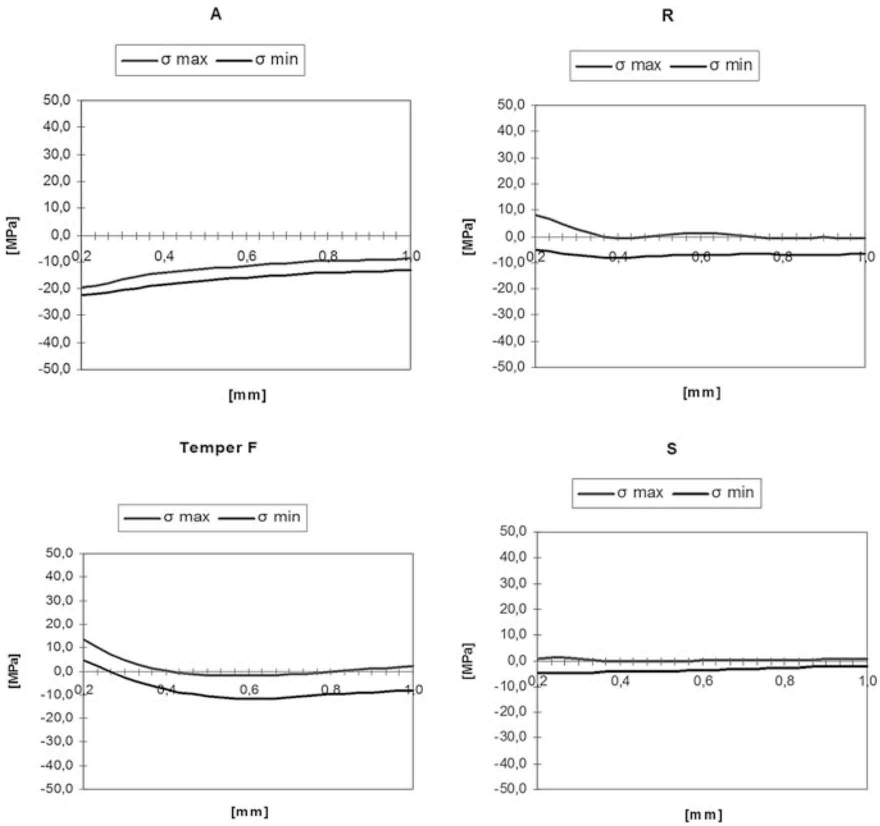


Fig. 8 Residual stress analysis

classic water cooling. The forced air cooling has also a "green" benefit compared with the classic water cooling: elimination of the waste industrial water.

The air cooling produces an extreme smooth (Fig. 7) residual stress profile. The differences observed between the tested parts could be neglected. In the highest cooling rate (part A) produces merely a low level of residual stress (Fig. 8).

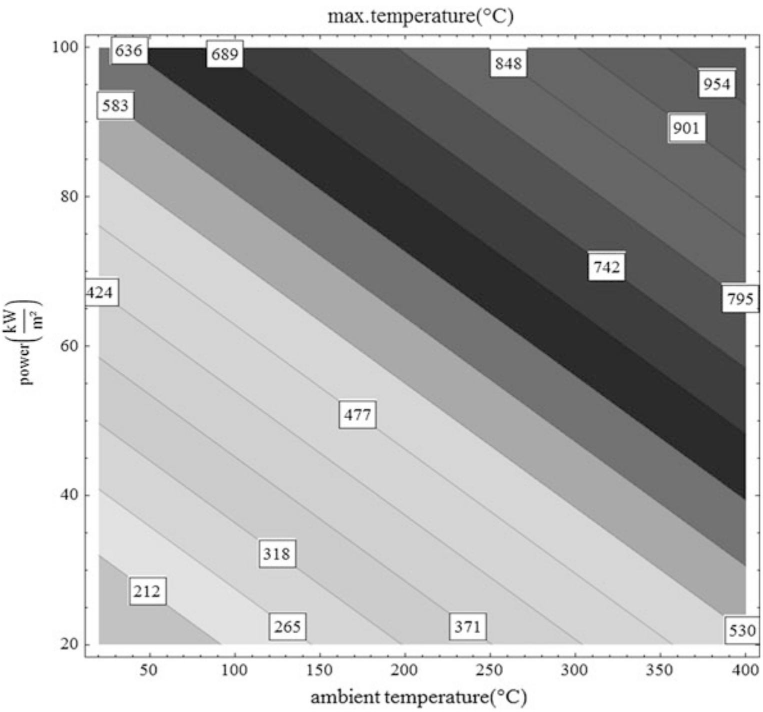


Fig. 9 Maximal temperature = f (power, ambient temperature) (aluminium with polished surface)" [*Source* Dragulin, Belte, Dragulin–Aluminium Heat treatment using Infrared Radiation, Berlin, 2011]

3 Conclusions and Prospects

The meaning of the radiative heat transfer for the aluminium heat treatment is spread far beyond the confined common apprehension. Within the framework of the present work the authors tried to present a series of practical aspects which will underline the benefit of the radiative heat transfer for the aluminium heat treatment in the case of casting alloys. The following figure shows in a concentrate form the potential of the infrared heating (Fig. 9).

Acknowledgment LOI Italimpianti

Holistic Approach to Reducing CO_2 Emissions Along the Energy-Chain (E-Chain)

M. Bornschlegl, M. Drechsel, S. Kreitlein and J. Franke

Abstract Due to the increasing awareness to reduce CO_2 emissions, it is important that car producers (OEM) get transparency about their energy consumption. Especially the production emission is becoming a focus topic in the next years. Hence, it should be started to minimize the energy consumption in a sustainable way. Therefore, this chapter presents a new approach to design a sustainable Energy Chain, which considers all elements beginning from the energy supplier to the end customer. Additionally the energy consumption is assessed, whether it is value-adding or not. This helps to find the levers to reduce energy consumption without reducing the level of quality and quantity. For the implementation of the Energy Chain a suitable software architecture is necessary. This chapter shows possible software modules for energy planning.

1 Introduction

Because of changing political and social views on the use of natural resources, the manufacturing industry is facing new challenges. Dealing with new process technologies, increasing prices of energy carriers and their limited availability,

M. Bornschlegl (✉) · M. Drechsel
Audi Planung GmbH, Maria Göppert Straße 3, 85057 Ingolstadt, Germany
e-mail: martin.bornschlegl@audi-planung.de

M. Drechsel
e-mail: michael.drechsel@audi-planung.de

S. Kreitlein · J. Franke
Institute for Factory Automation and Production Systems (FAPS), Friedrich-Alexander Universität Erlangen-Nürnberg, Egerlandstrasse 7–9, 91058 Erlangen, Germany
e-mail: kreitlein@faps.uni-erlangen.de

J. Franke
e-mail: franke@faps.uni-erlangen.de

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_23,

new political regulations and a rising customer awareness, resource management becomes more and more important (International Energy Agency 2012; Matten and Crane 2005).

In an average car life cycle 70 % of all CO_2 emissions are generated in the use phase (Mock 2010). To set a good example Audi started the "Audi e-gas project" that enables emission free driving by utilizing a power-to-gas technology. Taking this development into account, CO_2 emissions during the production are getting into focus.

In the last years most industries realised that saving energy is economically and ecologically reasonable. A sustainable use of resources leads to competitive advantages (Dao et al. 2011; Thamling et al. 2010). Therefore OEM optimized several single equipment successfully. To reach these objectives, every department optimizes the energy consumption of their own processes. These improvements are evaluated by indicators like saving potential, amortization time, cost or others. The accounting boundary for these calculations is always the department itself. Not taking previous and following processes into account may cause that the sum of single improvements will be less than the result of a holistic optimized chain. This was already postulated by Lovins (1976). Despeisse et al. suggests that quantitative modelling tools should be designed to increase the efficiency within a production plant (Despeisse et al. 2012).

Many OEM set the target to become a CO_2 neutral producer. To reach this goal a new approach containing a superior framework is necessary. This framework should consist of all single measures from the energy generation to consumption till recuperation.

If energy costs and CO_2 emissions are known in different levels, this would help for cost calculation and environmental analyses. It starts from the single process to a whole production site. By analysing the energy input and output of several departments, sustainable concepts can be developed.

2 The Approach of an Energy Chain

Ordinary solutions for energy efficiency mostly try to optimize a small scope to its optimum. But it is unknown how much this field contributes to the total energy consumption. This may lead to huge efforts for small savings. To avoid this, the new approach is oriented towards "Supply Chain Management" (SCM). SCM is the management of material and information flow to provide the highest degree of customer satisfaction at the lowest possible cost over the whole supply chain. Additionally different links are connected as supplier and costumer (Christopher 2005). The methods of SCM in combination with the international standard DIN EN ISO 50001 (Energy management systems 2011) builds the basis for the idea of *Energy Chain Management* (ECM).

The Energy Chain (E-Chain) is a method to analyse the energy contribution from supplier to costumer. All departments are now seen as customer and supplier at the same time (see Fig. 1). For example, inevitable exhaust heat is no longer seen as waste but as an energy source for a follow-up process.

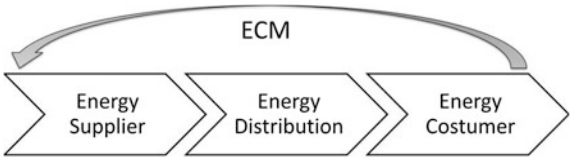


Fig. 1 The E-Chain: every chain element is a supplier and costumer at the same time

ECM can be seen as a new discipline of SCM. To reach a holistic view the E-Chain contains the end consumer by whom the car attributes are determined. For example: The paint shop is the most energy intensive process during the production. If the customer would accept car–wrapping as an alternative, the energy demand in the E-Chain would decrease significantly. This example shows that the E-Chain regards customers' needs as well as production technologies.

For ECM the following steps are necessary: First, the scope and boundary conditions of the E-Chain have to be defined. Then the energy value of chain elements can be rated. Following methods have to be defined and implemented to increase the overall efficiency of the E-Chain. Finally a controlling system has to be implemented.

2.1 Scope of an E-Chain for a Production Plant

For a production plant's energy management it would be too complex to consider every aspect in the first try. Therefore an example OEM E-Chain is described in this subsection which includes representative elements (see Fig. 2). The E-Chain generally starts with energy generation, going to the use of energy and looping up in the possibility of energy recuperation. The main elements are *Source* (e.g. energy supplier), *Transportation* (e.g. current distribution), *Process* (e.g. welding) and *Feedback* (e.g. energy recuperation). The energy sources are energy which comes from an energy supplier and in-plant generated energy (e.g. Trigeneration).

This loop is scalable from a single process to a whole production site. As a consequence there are different layers of the E-Chain like the global level, factory levels, department levels, building levels and process levels. The higher level is an addition of all his subsystems. This system belongs to a greater supersystem out of factory boundaries.

There are two ways to reduce CO_2 emissions in this case: First, the use of renewable energy and the re-use of process energies. Second, decrease of needed energy consumption.

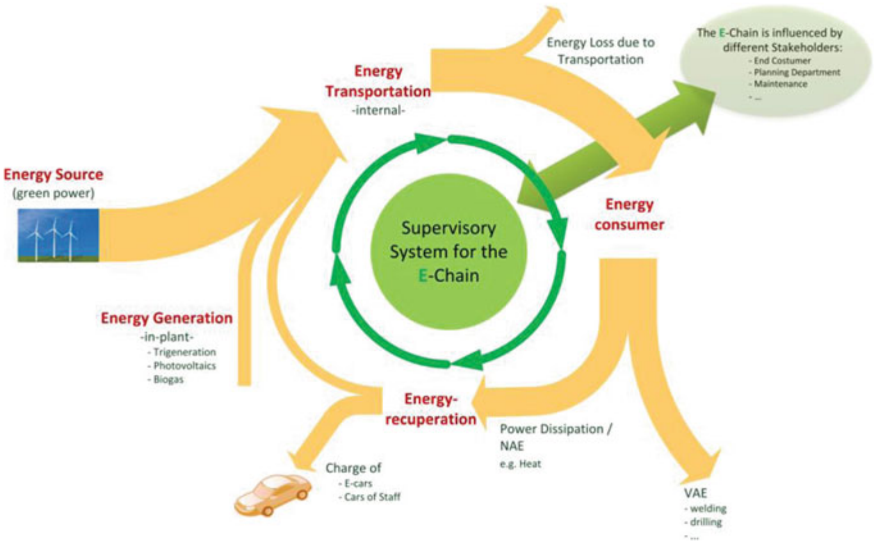


Fig. 2 An example E-Chain at factory level

2.2 Value Added Energy Consumption

After the determination of the E-Chain, the next step is to evaluate the current state of the elements. In analogy to SCM, the E-Chain distinguishes between *value added energy consumption* (VAE) and *non-value added energy consumption* (NAE).

How to rate a chain element is shown with the example of a *resistance spot welding robot cell*. This is a typical cell of an OEM body shop. The first step is the identification of all necessary energy consumers. Not only the welding tong and the robot are taken into consideration, but also necessary support installations like lightning and suction. The next step is to determine the energy consumption of all components, like shown in Fig. 3. Following, the process is classified in VAE and NAE. In the example the biggest electrical energy consumers are supporting processes like robot movement, equipment cabinets, ventilation and lighting. The added value is to combine two or more sheets of metals. This takes place with the sole welding process and results in a VAC of 13 % and a NAE of 87 %.

There are two ways to improve the efficiency of the system (see Fig. 4). Reducing the NAE of the used technology or changing the technology to a more efficient one.

For reducing NAE of the support processes, "*Critical Questioning*" is a possible method: "Why is it necessary that a robot cell is illuminated as long as no worker is inside?" Erlach describes the energy value stream method, to improve the existing process energy efficiency. Based on analysed data, design guidelines for energy efficiency can be used to realise changes (Erlach and Westkämper 2009).

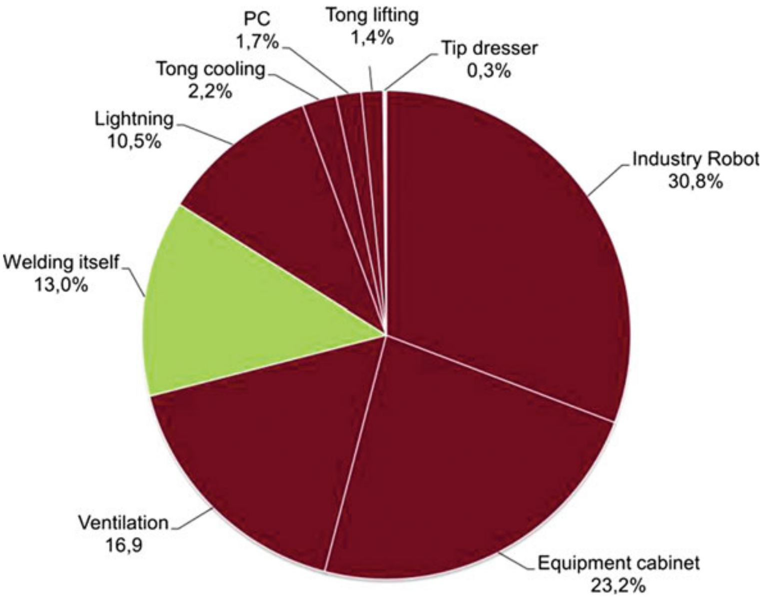


Fig. 3 Energy consumption of a resistance spot welding robot cell

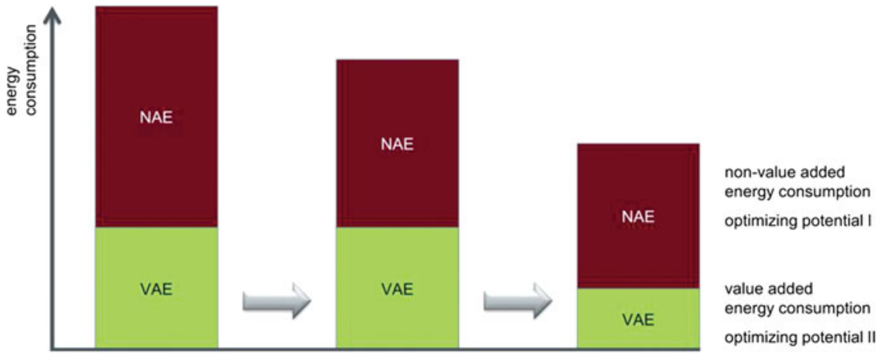


Fig. 4 Energy consumption for a specific process step

A technological change is mostly required to lower VAE. Therefore, the added value process target is to be determined. In this example, the objective is to join two sheets of metal permanently to gain a torsion-resistant car body. If this result can also be achieved by bonding in the same quality, it has to be checked which one is more efficient along the E-Chain.

2.3 Consideration of the Whole Energy Chain

The described improvements have now to be optimized in the whole chain. One possibility is to check, whether waste energy from the resistance spot welding process can be "re-used" for another process. Re-use of energy doesn't improve the current process efficiency, but increases the overall efficiency.

Further, for comparison of technologies, the whole E-Chain has to be considered. For example, if some pneumatic driven equipment is switched to a electric one. Then the energy loss in the pneumatic infrastructure is to distribute at the remaining pneumatic driven equipment, which deteriorated the efficiency factor of those.

By means of continuing networking of the single equipment and production steering, a better forecast for equipment availability will be possible. This enables selective switch off of unneeded consumers and therefore lowers the energy consumption. But of course it has to be ensured that no deterioration in quality and availability occurs.

3 Further Steps for Implementation ECM

Two main factors are necessary for a successful implementation of ECM: support from the management and a suitable software based system. A sustainable energy management requires changes in consisting cooperate and process structures. Without the support of the top management an implementation of ECM is not realizable.

Due to the aspect to save energy and the use of volatile renewable energy sources, an energy flexible production system is required (Reinhart et al. 2012). To handle the complex connections within the E-Chain and to ensure a flexible production a powerful computer aided support system is essential. For the correct interpretation of the E-Chain it is important that all boundary conditions are taken

<table>
<tr><td colspan="2"></td><td>Energy Source</td><td>Energy Transportation</td><td>Energy Consumption</td><td>Energy Recuperation</td></tr>
<tr><td rowspan="4">Energy Chain Planning</td><td>Long-term</td><td colspan="4">Strategic Energy Planning</td></tr>
<tr><td>Mid-term</td><td rowspan="2">Demand Planning</td><td colspan="3">Master Planning</td></tr>
<tr><td rowspan="2">Short-term</td><td rowspan="2">Distribution Planning</td><td>Production Planning</td><td rowspan="2">Demand-driven feed-in</td></tr>
<tr><td>Purchasing Planning</td><td>Scheduling</td></tr>
<tr><td>Energy Chain Execution</td><td>Real-time</td><td colspan="4">Control and Monitoring with a Cyber Physical Energy System</td></tr>
</table>

Fig. 5 Possible software modules for E-Chain planning

into account (Meyer and Bornschlegl 2012). In consideration of these aspects, a modular based software suite is conceivable. Figure 5 shows a schematic example.

The architecture is based on the principles of hierarchical planning. The main focus is on supporting energy through the whole E-Chain from source, transportation, consume and recuperation (x-axis). The planning tasks cover different levels of aggregation and range from long-term strategic planning to real-time steering of production equipment (y-axis). In a future step, a third dimension can be implemented, which represents the process attributes (z-axis). In a holistic view, this dimension also represents the customers' needs.

4 Conclusions

Because of the changes in social values, different stakeholder groups will force OEM to improve energy and resource efficiency. For this reason the implementation of ECM is a useful tool for both management and operational work. The E-Chain creates transparency by analysing energetic input and output. The knowledge gained from this will help to identify fields of low efficiency.

ECM also allows to check, whether a new technology is more efficient or not. Therefore, it enables to develop sustainable concepts to face the challenges of energy optimization.

With the development of further *cyber physical energy systems* (CPES), new situation-related shutdown concepts will be possible. Depending on the product demand in the upcoming hours or days, the system optimizes the cycle time to a minimum of energy consumption. The variables for this modulation can be determined with the E-Chain concept and will be the task for further research work. Additionally, for the calculation of the E-Chains' overall energy efficiency a tool evaluating technology changes is necessary.

References

Christopher M (2005) Logistics and supply chain management—Creating Value-Adding Networks, 3rd edn. Pearson Education, Harlow

Dao V, Langella I, Carbo J (2011) From green to sustainability: Information Technology and an integrated sustainability framework. In. J Strateg Inf Syst 20(1):63–79

Despeisse M, Ball PD, Evans S, Levers A (2012) Industrial ecology at factory level a conceptual model. J Clean Prod 31:30–39

Energy management systems (2011) Requirements with guidance for use (ISO 50001:2011), German version EN ISO 50001:2011, Beuth, Berlin

Erlach K, Westkämper E (2009) Energiewertstrom-Der Weg zur energieeffizienten Fabrik. Fraunhofer Verlag, Stuttgart

International Energy Agency (2012) World energy outlook 2012. OECD, Paris

Lovins AB (1976) Energy strategy: The road not taken? In: Foreign Affairs

Matten D, Crane A (2005) Corporate citizenship: toward an extended theoretical conceptualization. Acad Manag 30(1):166–179

Meyer H, Bornschlegl M (2012) Intelligentes energiemanagement von produktionsanlagen. In SPS Magazin 6:44–46

Mock P (2010) Entwicklung eines szenariomodells zur simulation der zukünftigen marktanteile und CO_2-emissionen von kraftfahrzeugen (VECTOR21). Dissertation, Dt. Zentrum für Luft- und Raumfahrt, Stuttgart

Reinhart G, Reinhardt S, Gral M (2012) Energieflexible produktionssysteme, wt Werkstattstechnik 102(9):622–628

Thamling N, Seefeldt F, Glöckner U (2010) Rolle und bedeutung von energieeffizienz und energiedienstleistungen in KMU, prognos, Berlin

Battery Second Use: Sustainable Life Cycle Design Through the Extension of Tools Used in the Vehicle Development Process

M. Bowler, J. Weber, D. Bodde, J. Taiber and T. R. Kurfess

Abstract Battery second use (B2U) has recently been the subject of attention from not only the automotive and electrical power grid industries, but also governmental institutions, researchers, and the general media. Most observers see Battery second use as an opportunity to maximize the value of the battery throughout an extended lifetime in order to offset the high costs of the battery system in an electric vehicle (EV) application. The viability (or combined economic and technical feasibility) of B2U depends on the battery design, use in the vehicle, reprocessing requirements, integration strategy, the secondary application, and the development of the battery market. Currently the uncertainty integrated along the entire value chain makes it difficult to assess the practicality of a secondary use strategy. We will shown that, with the current state of the market, only the vehicle OEM is capable of facilitating Battery second use strategy through the optimal design and development of the vehicle battery system. This paper will present of a method that extends the tools and information from the vehicle development to enhance the accuracy of current B2U evaluation methods. The method proposed could eventually be used for lifecycle optimization during the early development stages of an electric vehicle. Allowing the OEM to design the battery system and operational processes necessary to maximize the value of the battery system and mitigate the costs and associated with relatively new battery technologies.

M. Bowler (✉) · D. Bodde · J. Taiber
Clemson University International Center for Automotive Research,
5 Research Drive, Greenville, SC 29607, USA
e-mail: mbowler@clemson.edu

M. Bowler · J. Weber
BMW Group, Petuelring 130 80809 Munich, Germany

T. R. Kurfess
Woodruft School of Mechanical Engineering, 813 Ferst Dr 30332-0405,
Atlanta, GA, USA

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_24,

1 Battery Second Use: Potential Despite Changing Market Dynamics

The first study for Battery second use was conducted by Argon National Laboratories for the United States Advanced Battery Consortium in the late 1990s. The goal of the study was to assess if used, de-rated, EV batteries could provide the same performance as lead-acid batteries (the most promising stationary battery technology at the time) in stationary applications (Cready et al. 2003).

More recently other researchers (Narula et al. 2011; Williams and Lipman 2011; Neubauer et al. 2012) have built upon the initial work of Cready et al. 2003 by incorporating more detailed information about market potential and integrating energy storage studies such as (Eyer and Corey 2010) with more detailed assumptions about reprocessing costs and battery aging based on commercially available systems such as the Nissan Leaf and Chevy Volt.

These preliminary analyses show that used batteries are technically capable of being used in stationary storage (Pinsky 1998; Cessna 2012), and there is a market potential for used EV batteries assuming they are competitive with new batteries on a $/kWh basis (Williams and Lipman 2011; Neubauer et al. 2012). Within these analyses a small window of opportunity has been identified, but embody a high level of uncertainty due to coarse approximations of parameters associated with battery system design and aging characteristics. The most important parameters are the state of health of the battery after vehicle use repurposing costs, and second use performance relative to new batteries.

The battery's state of health (SOH) depends upon battery chemistry, thermal and energetic use profile, time, and operational strategy of the battery. For a given battery design the SOH of the battery at the end of vehicle life and can vary significantly vehicle to vehicle depending on the owner's driving profile (Gering et al. 2011; Dubarry et al. 2007).

Repurposing costs are dependent on battery design, how the battery will be integrated into a secondary system, what additional components can be used from the vehicle, and the influence of increasing component failure rate with time. Other influential factors on repurposing include testing requirements which can be reduced through vehicle diagnostics, and the recycling costs of unusable batteries.

The performance of the batteries in a secondary application will depend upon the load profile of the application, battery SOH and the uniformity between battery units. Therefore the performance is highly dependent on the previous two parameters.

By using point estimates, previous studies don't embody variations inherent in problem, nor are they capable of analyzing the tradeoffs and interdependencies between various battery designs, operation strategies, and use scenarios. Therefore these studies show B2U as a potential, but lack the granularity to show what needs to be done in order to capture that potential.

The following proposes a tool that leverages the knowledge created during the vehicle development process in order to better analyze these trade-offs and capture the variation inherent in the problem.

2 Building a Model for the Evaluation of a B2U Strategy

The proposed tool seeks to aggregate the current state of knowledge to decrease uncertainty and determine leverage points. It provides a structure flexible enough to evolve in parallel with methods used in the techno-economic analysis of grid energy storage and the vehicle development process.

The model consists of three main sub-models: (1) End of Life Vehicle Model, (2) Reprocessing Model, (3) Second Use Application Model. A schematic of information flows can be seen in Fig. 1. The model will utilize statistical distributions and Monte Carlo methods which will allow for the variances within the problem to be captured but also allow for decoupling points between the sub-models to allow a large number of scenarios to be analyzed relatively easily.

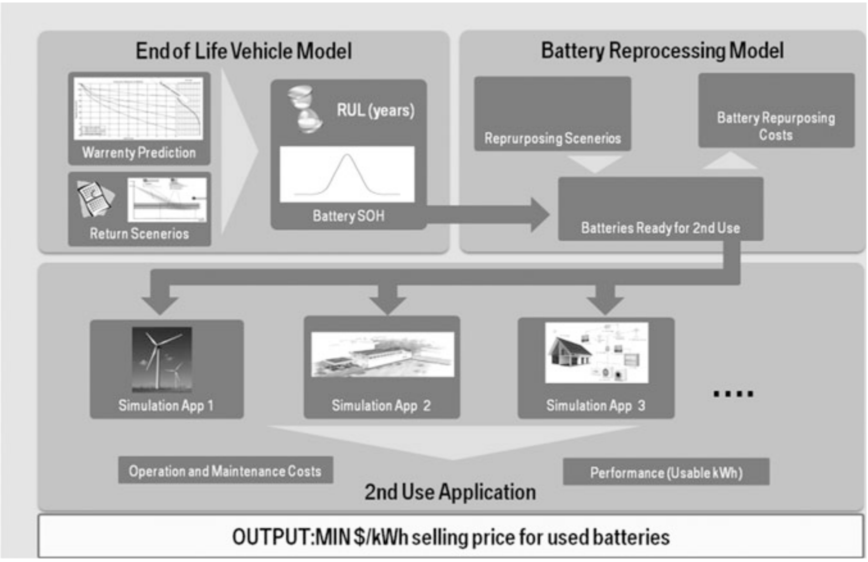


Fig. 1 Schematic of B2U model

The End of Life Vehicle (EOLv) Model uses warranty prediction data and an end of life vehicle criteria to determine the characteristics of a statistically representative batch of batteries. An example of a sample distribution can be seen in Fig. 2. In the given example it is assumed that the remaining capacity of the battery can be modeled as a normal distribution with a mean and standard deviation that change as a function of time. Monte Carlo methods are used to sample the distribution and parameterize battery models that will be used in the later sub models. By parameterizing the battery models based on statistical distribution of properties it is possible to use more complicated conditional models or simple assumptions depending on the level of data available.

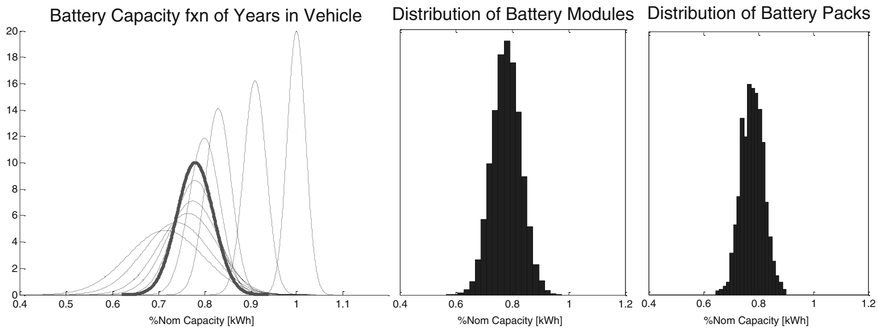
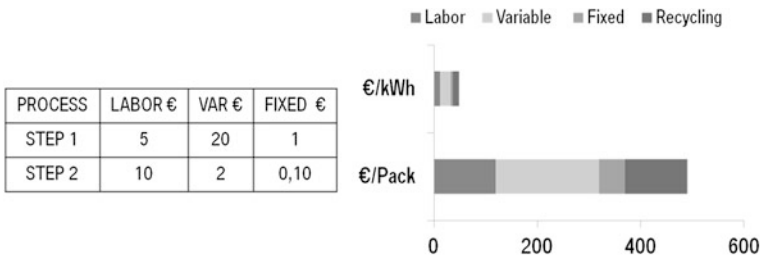


Fig. 2 Example EOLv data

The Reprocessing Model takes a user defined process and associated costs in the form of a process sheet to calculate the costs associated with reprocessing a specific set of batteries from the EOLv model (Fig. 3). Processes include sorting criteria, repair or replacement of components, and disposal of unusable modules. Since each EOLv criteria will yield a batch of batteries with different characteristics (nominal capacity, age, internal resistance, etc.), the costs associated with reprocessing the batteries will also be different dependent on component failure rate and screening criteria.



PROCESS	LABOR €	VAR €	FIXED €
STEP 1	5	20	1
STEP 2	10	2	0,10

Fig. 3 Example data for reprocessing model

The definition of the necessary processes will be dependent on the design of the battery system. Information about how the battery system is put together should be a strong indicator of the requirements to take the battery apart. Therefore the tools and information from the process development can be used to define the data needed for the repurposing model.

Since the reprocessing model is completely independent from the EOLv model, it is possible to run different batches of batteries with different EOLv criteria through the same process and compare results. Or in contrast a single batch of batteries from a given EOLv criteria can be run through different reprocessing scenarios. This would allow the comparison of the influence of reprocessing entire battery packs versus individual modules, having tighter sorting and disposal criteria, or the effects of different battery designs.

The Second Use Application Model consists of two parts. The first is an integration sub-model similar to the reprocessing model which calculates the cost associated with integrating the battery into the system, and total system costs. The second part is a time series model used to calculate battery aging and performance. This sub-model uses the battery characteristics from the EOLv model to parameterize a battery model which will then be subjected to an application specific load profile. The battery parameters are updated yearly based on the aging characteristics and the model is re-run until an end of life criteria is reached. A visual schematic of this sub-model can be seen in Fig. 4.

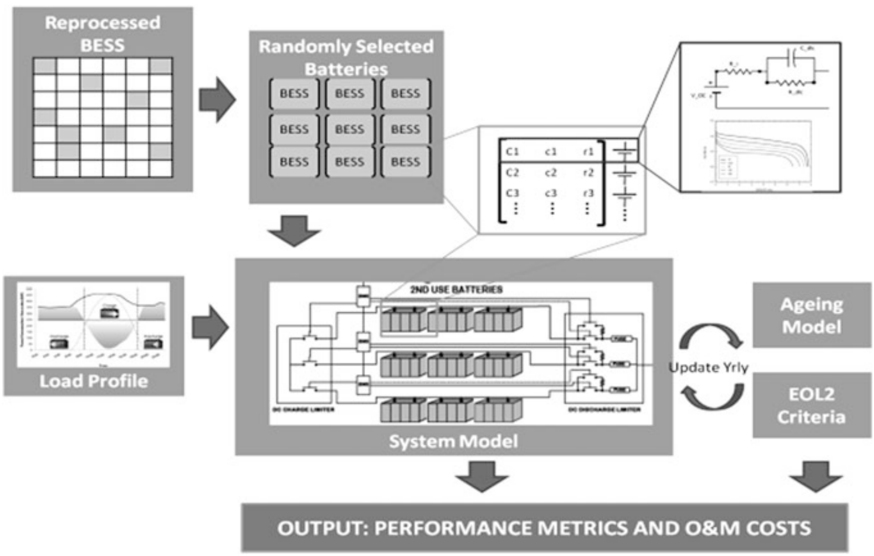


Fig. 4 Schematic of second use application model

This sub-model is capable of analyzing the effects of various architectures for a range of applications from small home energy storage systems to large grid scale systems. Therefore tradeoffs can be analyzed and most the most technically appropriate applications for used batteries can be identified. This information can then be used along with market data to assess the economics of the technically feasible solution.

3 The Importance of Leveraging the Knowledge of the OEM for B2U

Cost drivers for a B2U business include the reprocessing and integration costs, battery life, and relative lifecycle cost of a new system. Reprocessing and integration costs will depend on the design of the EV battery and requirements of a second use system. The life of the battery in the second use will depend on the aging of the battery in the vehicle; which is a function of the number of years the battery is in the vehicle, the user's driving style and average ambient temperature. Lifecycle costs of a new system will be dependent on the price of new batteries and development costs of the system.

Because the automotive OEMs have the most information about the design and aging of the EV system, they are the best equipped to not only evaluate the potentials of B2U opportunities but also influence the outcome. Mainly the OEM must know if the current technology is capable of performing long enough to be practical in a secondary application; and if it is capable, what are the associated reprocessing and integration costs.

The proposed tool will allow OEMs to understand the tradeoffs between the battery design and potential use cases, allowing them to optimize the use of the battery throughout its lifecycle. This would include decisions about battery ownership models (rent vs. lease), battery design, control architecture and battery technology selection. In essence the proposed method will allow the OEM to leverage their current knowledge in order to inform the development of a B2U business strategy.

Acknowledgments The authors of this paper would like to thank the members of the BMW Group for their support of this research.

References

Cready E, Lippert J, Pihl J, Weinstock I, Symons P, Jungst RG (2003) Final report technical and economic feasibility of applying used EV batteries in stationary applications a study for the DOE energy storage systems program. Alburquerque, New Mexico

Narula C, Martinez R, Onar O, Starke M, Andrews G (2011) Final report economic analysis of deploying used batteries in power systems. Oak Ridge National Laboratory, Oak Ridge, TN

Williams B, Lipman T (2011) Analysis of the combined vehicle and post- vehicle use value of propulsion batteries. Berkley, CA

Neubauer JS, Pesaran A, Williams B, Ferry M, Eyer J (2012) A techno-economic analysis of PEV battery second use: repurposed-battery selling price and commercial and industrial end-user value. SAE technical paper

Eyer J, Corey G (2010) Energy storage for the electricity grid: benefits and market potential assessment guide a study for the DOE energy storage systems program. Alburquerque, New Mexico

Pinsky (1998) Electric vehicle battery 2nd use study. Argonne, Illinois

Cessna D (2012) Second life applications of lithium batteries mini e battery pack test report. Monrovia, CA

Gering KL, Sazhin SV, Jamison DK, Michelbacher CJ, Liaw BY, Dubarry M, Cugnet M (2011) Investigation of path dependence in commercial lithium-ion cells chosen for plug-in. J Power Sources, Elsevier, 196(2011):3395–3403

Dubarry M, Vuillaume N, Liaw BY, Quinn T (2007) Vehicle Evaluation,battery modeling, and fleet-testing experiences in hawaii: a roadmap to understanding evaluation data and simulation. J Asian Electr veh 5(2):1033–1042

Novel Latent Heat Storage Devices for Thermal Management of Electric Vehicle Battery Systems

Ch. Huber, A. Jossen and R. Kuhn

Abstract A major aspect for safe and efficient operation of battery electric vehicles (BEV) is the thermal management of their battery systems. As temperature uniformity and level highly affect the system performance and the lifetime, a well-defined thermal management system is substantial for high market penetration of next generation BEVs. A lot of different operation scenarios for BEVs can be conceived, with all of them having in common that at some point there is a maximum peak in heat dissipation. This worst case scenario (e.g. during fast charging) must be covered by the system design. Therefore new innovative solutions for the vehicle thermal management system have to be found, including new materials as well as adapted operation strategies. The effect on overall energy consumption, driving range, curb weight and the flexibility that can be achieved by including latent heat storage elements into the cooling system will be presented.

1 Introduction

Recent studies suggest that there are three main challenges to be overcome, in order to make future BEVs successful in the market. That's first of all the range of the vehicle, the charging time needed to achieve it and of course the total cost of ownership. In order to be successful on a long term perspective, BEVs have to be competitive or even superior to conventional cars in all of these three points (Reiner et al. 2010). Achievement of customer satisfaction requires either long

Ch. Huber (✉) · R. Kuhn
TUM CREATE Ltd, 1 CREATE Way #10-02, Singapore 138602, Singapore
e-mail: christian.huber@tum-create.edu.sg

A. Jossen
Institute for Electrical Energy Storage Technology, Technische Universität München, Karlstraße 45, Munich 80333, Germany

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_25,

ranges and therefore very high capacity batteries or short charging times by high charging currents—Two concepts that demand special focus on the thermal management of the energy storage device (Pesaran 2001).

In both cases phase change materials (PCM) can be considered as supportive measure to mitigate peak loads and guarantee uniform temperature distribution across the whole pack, contributing to a longer lifetime (Karimi and Dehghan 2012). Integration of PCM into the battery pack enables temporarily storing heat during periods of maximum load directly at the place of its release. Cooling components can thus be designed by trend more for the average load level than for the absolute maximum without accelerating aging or cutting back essential safety margins. Hence system layout can be reduced in size and weight. Previous studies already have proven the concept for single modules and have shown that even an entirely passive cooling is feasible under certain ambient conditions (Al-Hallaj et al. 2005).

2 Properties of Phase Change Material

Material properties of common PCM and a Graphite-Paraffin composite are given in Table 1. All values refer to the solid–liquid phase change and properties are given for the corresponding transition temperature.

The nature of most conventional phase change materials brings along several challenges for integration into battery packs. One major drawback of most solid or liquid materials (e.g. Paraffin) is their low thermal conductivity that causes latent heat storage devices to show inertial behavior once the outmost layers have been performing their phase change resulting in limited charge and discharge power (Sharma et al. 2009). That complicates the application in automotive applications, as the cycle-times are short and peak loads have to be reliably mitigated instantaneously at any time. Another essential requirement when used in battery thermal management applications is the actual transition temperature, which has to fall into

Table 1 Material properties of selected phase change materials and the novel composite PCM (Sharma et al. 2009; Bauer et al. 2009)

Material	Transition temperature (K)	Specific latent heat (kJ/kg)	Heat conductivity (W/mK)	Specif. heat capacity (kJ/kgK)	Density (kg/m^3)
Water	273	334	0.55	4.210	999
Paraffin	333	220	0.26	2.094	880
Salts (e.g. $NaNO_3$)	579	175	0.51	1.655	1908
Composite PCM	301	114	3.0	1.886	792

the operating temperature range of the used cell type. Given those premises, common phase change materials in pure form are mostly not suitable for automotive applications—Paraffin due to its limited heat conductivity, water and most salts (e.g. $NaNO_3$) because of their transition temperature levels.

So a new approach has to be taken by combining multiple materials and their properties, achieving considerable figures for both heat conductivity and latent heat storage capacity. In the present study the application of a composite material had been investigated, that consists of microencapsulated Paraffin embedded in a porous graphite matrix, combining the advantages of high heat storage capacity with excellent internal heat transport at a superior low weight.

3 Case Study: Ultra Fast Charging Taxi

For further evaluation of the material's potential in BEV applications, it had been integrated in the design of a high power and high capacity battery pack developed within the TUM CREATE research project. The energy storage is part of an all-electric taxi vehicle concept, which is highly adapted to the regional requirements of tropical megacities and public transportation tasks. Special characteristics of the taxi operation, e.g. the defined pattern of driving periods and pauses, as well as the high demand for cooling make it a promising case study for the utilization of PCM.

3.1 System Layout

To cover the average daily mileage of a conventional taxi, the battery pack features approx. 48 kWh of energy content as well as fast-charging capability with currents of up to 180 A per cell. Principle layout of the cooling system including all main components is shown in Fig. 1. Thermal management of the battery relies on a liquid cooled structure (B) that is linked to the cabin A/C circuit (A) via a chiller and is additionally supported by the novel latent heat storage elements.

3.2 Load Profile

The battery load profile assumed and shown in Fig. 2 includes two driving periods of approx. 200 km (A) divided by one fast-charging break (B) and reflects the typical usage-pattern of a taxi shift in Singapore. Speed and acceleration have been experimentally traced by sensor equipped vehicles and then been converted into the current profile (Agua 2012).

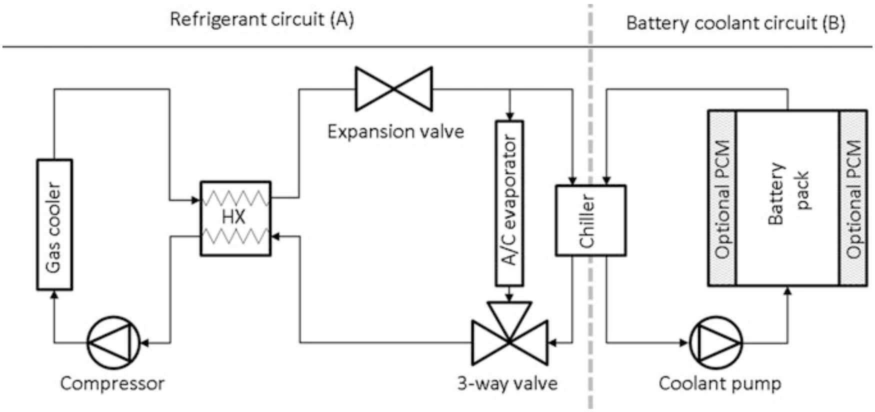


Fig. 1 Overall cooling layout for the electric taxi prototype

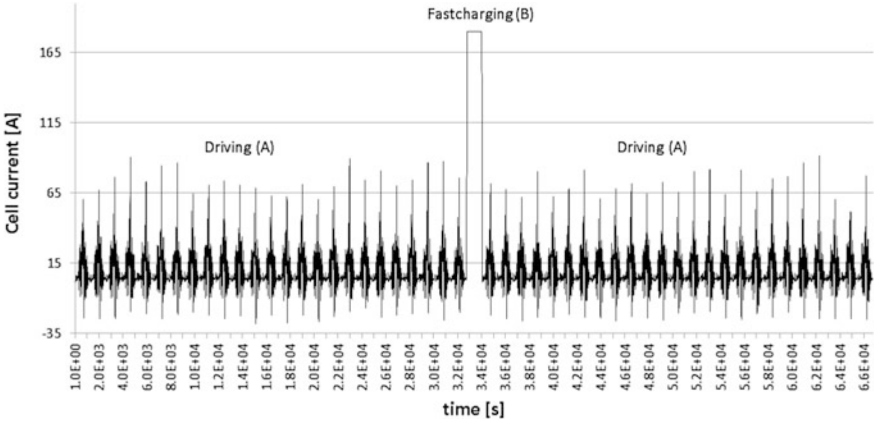


Fig. 2 Current profile of taxi driving cycle

It can clearly be seen that the highest currents of up to 180 A per cell occur during the charging period, while the driving loads average at around 15 A. As any latent heat storage device operates best within significantly differing load levels, this driving pattern suggests itself to be highly adequate to be smoothed by temporarily storing latent heat (Sharma et al. 2009). Another advantage of the investigated profile, facilitating the integration of PCM, is the fact that for the special use-scenario as a taxi, the sequence of different load levels (A and B) is basically predefined and foreseeable. That also applies for the absolute extent of the maximum load as it is given by the fast-charging specifications and will not be exceeded during driving.

3.3 Operational Scenarios

Selection of a certain design and an according operational strategy directly affects most components of the cooling circuit; with the compressor being one of the parts influenced the most. Based on the load profile and the given installation space, amount and position of PCM can be varied. Furthermore also the moment of its utilization has to be specified. In general, heat released from the battery can be stored during the charging period, the driving period or pro-rata at both phases. The setting of this operation mode does not have to be static but should be adapted to actual vehicle or ambient conditions and also be adjusted continuously during the lifecycle of the battery.

For the investigated taxi use case, Fig. 3 demonstrates the thermal compressor power required for safe operation as a function of the selected scenarios. Values are based on a fast charging period of 20 min and cell conditions at end of life.

Compared to the base scenario (1) without any latent heat storage, already the addition of a relatively small amount of PCM reduces the compressor power required by 15 % when utilized during charging and recuperated while driving (2). For the scenario incorporating a significant amount of PCM, compressor size can be reduced almost by half when used as buffer at the charging station (4). Alternately when utilized during driving (5) an almost complete passive cooling can be achieved.

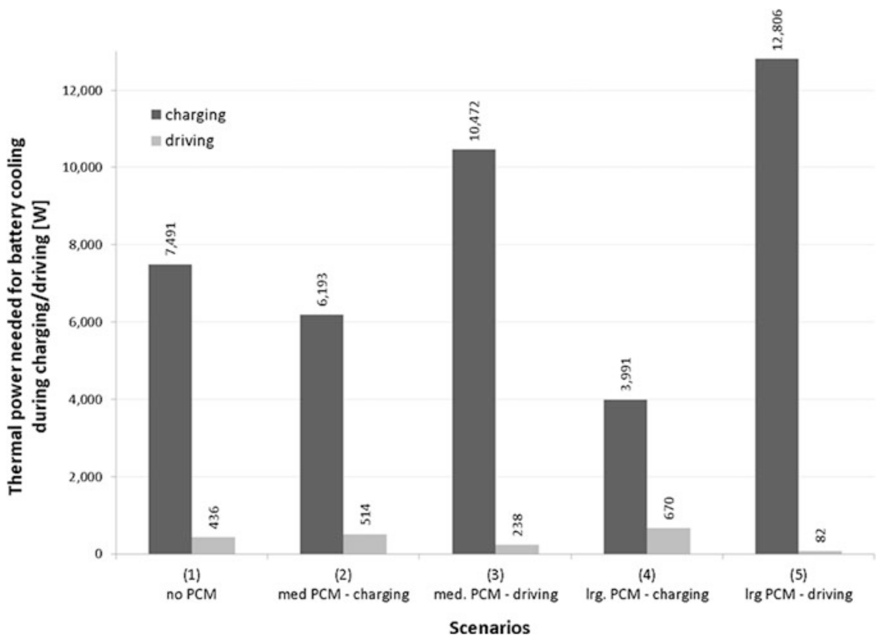


Fig. 3 Compressor power required, as function of PCM scenario

Table 2 Impact of PCM scenarios on weight and driving range

Scenario		1	2	3	4	5
Max compressor power	kW (th.)	7.5	6	10	4	12
Compressor power during charging	kW (th.)	7.5	6.2	10.5	3.9	12.8
Compressor power during driving	kW (th.)	0.45	0.51	0.24	0.67	0.08
Compressor weight	kg	7	5.5	8.5	3	10
PCM weight	kg	0	10	10	30	30
Weight difference to base scenario	kg	0	+7.5	+11	+26	+33
Calculated range	km	206	202	218	193	230

4 Summary

How a decision for one of the scenarios affects the achievable driving range can be derived from the vehicle's overall-energy balance. For the calculations weight of the PCM, the different compressor models and therefore total curb weight had been considered.

Figures shown in Table 2 propose that from a solely range-oriented point of view the addition of phase change material may not necessarily bring an advantage, especially if the PCM has to be recuperated while driving.

Nevertheless in order to enable special use cases as ambitious fast charging or an entirely passive cooled driving-cycle PCM can be very promising. Same is valid, if choice of components is limited and cooling requirements have to be met with a selection of existing parts. Due to its total scalability in terms of heat storage capacity and its flexibility in shape and mounting position the composite PCM material can continuously close the gap between the discrete power levels of other components, enabling choice for the next smaller version. As it furthermore is economically priced and maintenance-free it can be considered to deliver cooling power more cost-effective compared to the scale-up of a conventional system. Extending the lifetime of the battery pack, being non-wearing and recyclable it can hence contribute to a smart and sustainable EV thermal management setup.

References

Agua FM (2012) Electric vehicle modeling and simulation, Bachelor Thesis—Supervised by Tschochner M, TUM CREATE, Singapore

Al-Hallaj S, Kizilel R et al (2005) Passive thermal management using phase change material (PCM) for EV and HEV Li-ion batteries. In: Vehicle power and propulsion conference, Chicago, 2005

Bauer T, Laing D et al (2009) Sodium nitrate for high temperature latent heat storage. In: 11th international conference on thermal energy storage, Stockholm, 2009

Karimi G, Dehghan AR (2012) Thermal management analysis of a Lithium-ion battery pack using flow network approach. J Mech Eng Mechatron 1–2012:88–94

Pesaran AA (2001) Battery thermal management in EVs and HEVs: issues and solutions. In: Advanced automotive battery conference, Las Vegas, 2001
Reiner R, Cartalos O et al (2010) Challenges for a European market for electric vehicles. In: European parliamaent policy department for economic and scientific policy, Brussels, 2010
Sharma A, Tyagi VV, Chen CR, Buddhi D (2009) Review on thermal energy storage with phase change material and applications. Renew Sustain Energy Rev 13:318–345

Total Cost of Ownership and Willingness-to-Pay for Private Mobility in Singapore

R. Kochhan, J. Lim, S. Knackfuß, D. Gleyzes and M. Lienkamp

Abstract This paper gives an overview of the costs for the usage of private conventional versus electric cars in Singapore. The focus is on the composition of the costs of purchasing and using a car in this city state. The purchase price is easily thrice that of a similar car in the European market due to the high Singaporean vehicle taxes. With the high purchase price, the influence of the operating costs on the total cost of ownership is comparatively low, especially for electric vehicles. Additionally, this work shows the results of a survey in which Singaporeans were asked about different mobility attributes. Time savings was found to be the most important attribute when travelling around in Singapore. Based on the important attributes, a second survey has been conducted focusing on the willingness-to-pay for each of these attributes. The initial results showed that the people accept an increased purchase price of electric vehicles if they are offered savings on the operating costs. However, the additional willingness-to-pay is lower than the calculated purchase price difference.

1 Introduction

Does it make sense to focus on private mobility in cities like Singapore? It can be assumed that there will always be a demand for private modes of transportation in megacities. Yet, is it possible that conventional cars can become less attractive, with factors like rising fuel prices, congestions or inner-urban air pollution? Electric vehicles appear to be an ideal replacement for their conventional

R. Kochhan (✉) · J. Lim · S. Knackfuß · D. Gleyzes
TUM CREATE Ltd, 1 CREATE Way #10-02, Singapore 138602, Singapore
e-mail: robert.kochhan@tum-create.edu.sg

M. Lienkamp
Institute of Automotive Technology, Technische Universität München,
Boltzmannstr. 15, D-85748 Garching, Germany

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_26,

counterparts, offering the solution to the aforementioned problems, as they are locally emission free and potentially independent from oil as the primary energy carrier. However, today's electric cars have some disadvantages like high costs and low range which make them less attractive for customers.

Here, two pertinent questions arise, with the first revolving around car costs. What are the Total Cost of Ownership (TCO) of conventional and comparable electric cars, what are the costs of acquisition when buying a car, and what are the operating costs for owning and driving a car in Singapore? Then, there is also the second question that has to be answered: how much people are willing to pay for certain aspects of private mobility.

In order to answer these questions, the TCO for cars from the customers' point of view and the willingness-to-pay (WTP) need to be determined and compared. This paper will give an overview of the TCO of private cars in the unique environment of Singapore where the government has imposed high taxes and strict regulations on car ownership and usage (Energy Smart Communications Incentive 2012). The key cost drivers for a conventional gasoline and a battery electric vehicle will be highlighted using the example of a mid-range car, and the influence of battery costs and varying fuel/electricity prices will be discussed.

The paper will also show results of a consumer survey conducted in Singapore in late 2012. Respondents were asked about the importance of a number of mobility attributes such as time savings and flexibility when travelling around in Singapore.

Finally, the initial results of a second survey about the WTP for electric cars in Singapore are presented. Based on these results, this paper will show the potential of combining the TCO of electric and conventional cars with the customers' WTP in order to make statements about the future success of electric cars in comparison to conventional ones.

2 Total Cost of Ownership

For the estimation of the TCO, the parameters influencing it have been divided into three parts (according to e.g. Contestabile M Offer et al. 2011; NPE 2011): the acquisition, the ownership and the disposal or resale of the vehicle.

In order to give an insight into the special cost structure of vehicles in Singapore, the costs for these three parts have been calculated in detail, using the example of a mid-range private car (electric and gasoline version). The key vehicle specifications are shown in Table 1.

Each of the parts of the TCO, acquisition costs, operating costs and the resale value, will be explained in greater detail in the following three sections. The cost values are based on literature and on experts' assumptions about component prices.

Table 1 Key cost values and assumed vehicles specifications

Vehicle specification	Value	Source
Purchase date	2013	
Usage period	7 years	
Interest rate	3 % p.a.	
Annual mileage	19,000 km	(Singapore Land Transport Authority 2012b)
Efficiencies: [a]	9.1 1/100 km	Assumptions for a mid-range
ICEV Gasoline	16.7 kWh/100 km	Vehicle in Singapore
BEV		
Power ICEV/BEV[a]	81 kW/70 kW	Assumption for a mid-range car
Battery size BEV[a]	22 kWh	Assumption for a mid-range car
OMV of baseline gasoline vehicle[a]	16,000 SGD	Assumption for a mid-range gasoline car
Battery price (2013)	600 EUR/kWh	Estimation based on (Dinger et al. 2011; Element Energy 2011; Hensley et al 2012)

Remarks
OMV open market value: price at which the vehicle is delivered to Singapore from the country of manufacturing (One.Motoring 2013a)
ICEV internal combustion engine vehicle, *BEV* battery-electric vehicle
[a] Technical specifications based on data of the Renault Fluence in Singapore

2.1 Costs of Acquisition

The costs of acquiring a private car in Singapore are one of the highest worldwide. The main reason therefore can be attributed to the high taxes imposed on the purchase price of a vehicle (Singapore Land Transport Authority 2013d). In addition, the vehicle owner needs to buy a Certificate Of Entitlement (COE) when registering his or her car in Singapore (Singapore Land Transport Authority 2013a). The COE is valid for 10 years and can be obtained through a bidding system where the highest bids are successful. There is a monthly quota of COEs, which allows replacement of a certain percentage of the current vehicle population (Singapore Land Transport Authority 2013d, 2013e). The reason for imposing these measures is to limit the number of vehicles on the roads. It is a measure to regulate the urban traffic volume on the limited land surface in Singapore (Energy Smart Communications Incentive 2012).

Table 2 below shows a breakdown of the main components of the purchase price of a new mid-range car in Singapore.

Table 2 Retail price of a gasoline and an electric version of a mid-range car in Singapore (Calculations based on (Edwards et al. 2011; One.Motoring 2013a; Singapore Land Transport Authority 2012a, 2013b, 2013d))

Cost Component		ICEV Gasoline	BEV
Total estimated retail price	[SGD]	122,144	177,227
OMV	[SGD]	16,000	37,876
Customs duty	[SGD]	3,200	7,575
Goods and services tax	[SGD]	1,344	3,182
ARF	[SGD]	16,000	45,026
Registration fee	[SGD]	170	170
CEVS	[SGD]	5,000	−20,000
COE	[SGD]	63,630	63,630
Retailer margin	[SGD]	16,800	39,769

Remarks
ARF additional registration fee: charge to limit congestion, similar purpose as the COE (Energy Smart Communications Incentive 2012)
Registration fee: service fee for registering a vehicle in Singapore (Singapore Land Transport Authority 2013d)
CEVS carbon emission-based vehicle scheme: subsidy on the purchase price for vehicles with low CO2-emissions (Singapore Land Transport Authority 2013d)
COE certificate of entitlement: projection based on average 2012 COE bidding results (Singapore Land Transport Authority 2013b)
Retailer Margin: dealer margins in Singapore are relatively high and vary around 100 % of the OMV depending on the car brand (calculation based on (Singapore Land Transport Authority 2012a))

2.2 *Operating Costs*

Other than the acquisition costs, the running costs of vehicles in Singapore are not subject to a particularly high taxation. However, there are still means of controlling the traffic flow. In particular, the Electronic Road Pricing (ERP) system charges vehicle users who enter certain highly populated areas and expressways, like the Central Business District, during peak hours (Singapore Land Transport Authority 2013c). Parking prices are controlled by the government as well (Singapore Land Transport Authority 2013c).

Table 3 contains the total operating costs for the example mid-range vehicle, including expenses for fuel or electricity, average maintenance and insurance costs, recurring taxes as well as estimated parking fees. The costs for the usage of infrastructure is included for the electric vehicle because charging stations are not yet available and still need to be installed and paid by a service provider who would recover the expenses by charging every usage of the charging stations. The costs would depend on how much electric cars users charge.

Table 3 Total operating costs in a 7-year operation period of a gasoline and an electric version of a mid-range car in Singapore (Calculations based on (EIA 2012; Element Energy 2011; Lokenvitz 2013; Petrolwatch.com.sg 2013; Pierce Transit 2013; SGCarMart.com 2013; Singapore Housing and Development Board 2013; Singapore Land Transport Authority 2013d; Singapore Power 2013; Smartenergy.sg 2012; Windisch and Leurent 2012))

		ICEV gasoline	BEV
Total operating cost	[SGD]	61,530	38,985
Operating costs per month	[SGD/mth]	816	517
Operating costs per kilometre	[SGD/km]	0.46	0.29
Taxes	[SGD]	3,251	4,767
Insurance	[SGD]	8,610	6,888
Maintenance	[SGD]	4,958	4,958
Fuel/electricity	[SGD]	29,599	7,039
Parking	[SGD]	15,112	15,112
Infrastructure	[SGD]	–	220

Table 4 Resale values of a gasoline and an electric version of a mid-range car in Singapore (Calculations based on (SGCarMart.com 2013; Singapore Land Transport Authority 2013d))

		ICEV Gasoline	BEV
Resale Value incl. Tax Refund	[SGD]	33,673	44,417

The ERP costs are not included in this calculation as they are comparative low and need to be estimated based on travel behaviours and time period, which exceeds the scope of this TCO estimation. Typically, ERP charges range between 0.50 and 2.50 SGD per entry (One.Motoring 2013b). Fines for traffic violations and unscheduled maintenance, for example due to accidents, are also not included.

2.3 Resale Value

Usually, a vehicle owner does not have to pay for the disposal of a car as he/she sells it after a given usage period. For this paper, it was assumed that the usage period of 7 years (Table 1) leads to an end-of-life value of 20 % of the initial list price of the car, which is a reasonable value (SGCarMart.com 2013). In addition to that, Singaporean car owners get refunded a certain amount of the taxes which they had to pay at the time of purchase if they sell or deregister the car before the end of 10 years when the COE expires. They get back the unused amount of COE and a certain percentage of the ARF paid (Singapore Land Transport Authority 2013d). For the vehicle specifications assumed in this paper (Table 1), this sums up to the following amounts (Table 4).

Table 5 7-year TCO of two versions of a mid-range car in Singapore

		ICEV Gasoline	BEV
Total estimated retail price	[SGD]	122,144	177,227
Total operating costs	[SGD]	61,530	38,985
Resale value incl. tax refund	[SGD]	−33,673	−44,417
TCO	[SGD]	150,001	171,796
TCO per kilometre	[SGD/km]	1.13	1.31

2.4 Discussion

Table 5 summarises the resulting TCO values for buying, using and reselling the mid-range private car with the specifications in Table 1. The costs are shown as a total sum and as costs per driven kilometre.

Despite governmental incentives in Singapore, battery electric cars remain significantly more expensive than their conventional counterparts. The high purchase price of the electric car cannot be compensated by its low operating costs.[1]

One main reason for the high purchase price of electric vehicles in Singapore is that much of the taxes which a customer has to pay as a part of the purchase price of a car are calculated as a percentage of its OMV (Singapore Land Transport Authority 2013d). Consequently, electric vehicles are disadvantaged because their OMV is usually higher than the one of comparable conventional cars with a similar size and engine power, mainly due to the high battery costs. Some governmental incentives exist to compensate this disadvantage, e.g. the CEVS (Table 2). However, it is not enough to turn the electric vehicle cost-competitive. If the battery can be exempted from taxes, i.e. taxes are calculated based on the OMV without the battery costs, electric cars can become more cost-competitive. In this case, the TCO for the battery electric car drops from 171,796 SGD (Table 5) to 160,010 SGD.

Due to the enormous acquisition costs of private cars in Singapore, the TCO of electric cars is hardly sensitive to changes of parameters that have an influence on the operating costs. For the conventional car, annual fuel costs of 4,200 SGD apply, so that fuel costs sum up to approximately 29,500 SGD or 20 % of the TCO (Table 3). Hence, doubling the fuel price results in a fuel share of the 7-year TCO of almost 33 %. In contrast, the electricity costs for the electric option are about 7,000 SGD or 4 % of the TCO (Table 3). If doubled, the car user has to pay close to 8 % of the TCO more throughout the whole usage period of 7 years.

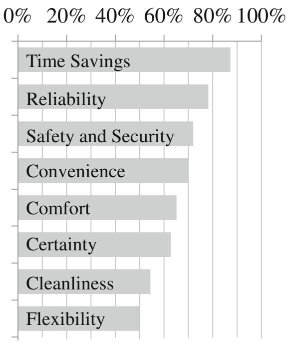
[1] Our calculations revealed that electric cars can be cost-competitive if used as a taxi with a high annual mileage where fuel savings can compensate for the expensive battery.

3 Mobility Attributes

Vehicle costs are certainly one of the parameters that have a significant impact on the purchase decision. However, there are other non-monetary attributes that also influence this decision.

This section summarises selected results of a consumer survey about the mobility behaviour in Singapore. The survey has been conducted in collaboration with the Nanyang Business School, an institute of the Nanyang Technological University in Singapore. In November 2012, responses from 597 Singapore citizens have been collected. The respondents can be considered as representative of the Singaporean population.

In a part of the survey, the respondents were asked about the importance of mobility-relevant attributes which were selected based on (Beirão and Cabral 2007; Ellaway et al 2003; Gardner and Abraham 2007; Mackett 2003; Steg et al. 2001). Each respondent was required to select seven attributes out of a total of 14 which were “more important” to him/her when travelling around in Singapore. Figure 1 shows the attributes which were found to be important for more than 50 % of the respondents.



Description / Example
reducing travel time within Singapore
transport being available whenever needed
e.g. accidents, pick-pocketing
e.g. short working distances, not carrying luggage
e.g. adjustable air-con temperature
guarantee of reaching the destination on time
vehicle or cabin interior
spontaneity, changing travel plans

Fig. 1 Mobility attributes and their importance to Singaporeans (*Source* customer survey)

All of the attributes are to be viewed from the perspective of an owner or user of a private vehicle. The attributes tend to have higher levels of satisfaction when considering a private car in comparison to public buses or urban trains.

The survey results revealed that time savings is most important. For more than 80 % of the respondents, time savings plays an important role when travelling within Singapore. Safety and security are very important attributes as well. Nevertheless, people often take this for granted in Singapore because of the high security standards established and maintained by the government. The attributes which were found to be less important while travelling (i.e. more important to only less than 50 % of the respondents) include being weather independent, feelings of freedom and independence, privacy, driving enjoyment, status signalling as well as personalisation.

Table 6 Three scenarios to estimate the WTP for the important electric mobility attributes

	Scenario 1	Scenario 2	Scenario 3
Comparison	Electric vs. conventional cars *today*	Electric vs. conventional cars with *governmental subsidies for electric cars*	Public transportation vs. electric cars with a *ban of private conventional cars*, for example in order to reduce traffic emissions
Focus	Technical differences	Selected incentives which give an advantage to electric cars	Difference between electric cars and public transportation
Example: Characteristics of the mobility attribute time Savings	Charging time vs. fuelling time	Reducing the travel time by implementing priority lanes for electric cars	Reducing the travel time by using a (electric) car instead of public transportation
Monthly Operating costs	30 %.. 50 % off[a]	40 %.. 60 % off[a]	400.. 500 SGD/mth[b]
Purchase price premium [SGD]	5,000.. 30,000 on top[a]	2,500.. 15,000 on top[a]	30,000.. 110,000 + COE[b]
Percentage of choosing electric version[c]	43.2 %	53.4 %	53.2 %

[a] Relative values for a BEV compared to an ICEV
[b] Total values, estimation based on own calculation results (Table 3); public transportation for 100 SGD/month as an alternative; purchase price depending on the respondent's preferred vehicle size
[c] An electric version was selected in all (eight) choices for the respective scenario

The transportation costs like fares of public transport or costs of private cars were not considered in this survey. However, as mentioned before, it is assumed that the price will have a significant influence on the people's mobility behaviour. Hence, the mobility attributes which are found to be important (Fig. 1) provide the basis for a subsequent survey. In this second survey, the price is taken into consideration in order to determine customers' WTP for the different aspects of private conventional and electric cars.

4 Willingness-to-Pay and Total Cost of Ownership

Regarding the two sections above, the question arises under which circumstances people are willing to pay more for an electric car than for a comparable gasoline car, so that electric cars can be sold despite their high purchase price. People might be willing to pay more if the electric option has certain advantages of which public transportation or private conventional gasoline cars cannot offer.

Therefore, the second survey is based on the eight important mobility attributes presented in Fig. 1. 914 Singaporean car drivers, car users or those who are willing to buy a car were asked about their WTP for electric vehicles in three alternative scenarios. The three scenarios were used to study different characteristics of the mobility attributes (Table 6). In scenario 1 and 2, the electric car is compared to a conventional car, while in scenario 3 to public transportation in Singapore. In each scenario, the WTP for the mobility attributes was investigated by letting the respondents choose between two electric vehicle options with varying price levels in the price range shown in Table 6. Instead, he/she also could choose a conventional car (scenario 1 and 2) or public transportation (scenario 3) as the "non-BEV" alternative.

The initial results showed that people are willing to pay more for the purchase price of electric cars in scenario 1 and 2, given that they can save a certain amount of the monthly running costs compared to conventional cars. In the first scenario (current situation), respondents would be willing to pay about 18,000 SGD on average on top of the purchase price for a conventional car in order to purchase an electric car, if they could save 50 % on the running costs. According to the calculations in Sect. 2, this amount can be covered by the savings on running costs, but it is not enough to justify the higher TCO or purchase price of the electric car (Table 5).

Moreover, around 50 % of all respondents are willing to go for an electric car instead of a conventional car (scenario 1 and 2) or public transportation (scenario 3) under the assumptions in the scenarios (Table 6).

5 Conclusion

In order to estimate the WTP for the mobility attributes (Fig. 1) for the three alternative scenarios, a deeper analysis of the survey results is required. But the preliminary results do reveal that people in Singapore are willing to pay a higher upfront price for their car if they can save money later while using the car. The results also indicate that, under the current battery prices and the vehicle taxation in Singapore, the additional amount that people would be willing to pay upfront is not enough to compensate for the price difference between electric and conventional cars.

Acknowledgments The work presented was financially supported by the Singapore National Research Foundation under its programme "Campus for Research Excellence and Technological Enterprise"(CREATE). The mobility survey (Section 3) was conducted in collaboration with the Nanyang Business School, an institute of the Nanyang Technological University in Singapore.

References

Dinger A et al (2011) Batteries for electric cars. Challenges, opportunities, and the outlook to 2020, The Boston Consulting Group
Beirão G, Cabral S (2007) Understanding attitudes towards public transport and private car: a qualitative study. Transp Policy 14:478–489
Contestabile M, Offer G, Slade R, Jaeger F, Thoenees M (2011) Battery electric vehicles, hydrogen fuel cells and biofuels. Which will be the winner?. Energy Environ Sci 4:3754–3772 (Fig. 2)
Edwards R, Larivé J-F, Beziat J-C (2011) Well-to-wheels analysis of future automotive fuels and power trains in the European context, report version 3c, tank-to-wheels report, appendix 1, vehicle retail price estimation
EIA (2012) Annual energy outlook 2012 with projections to 2035, U.S. energy information administration, Washington DC, USA
Element Energy (2011) Influences on the low carbon car market from 2020–2030, Final report, Cambridge, UK
Ellaway et al (2003) In the driving seat: psychosocial benefits from private motor vehicle transport compared to public transport. Transp Res Part F 6:217–231
Energy Smart Communications Incentive (2012) Ownership pricing (Additional registration fee (ARF) and vehicle quota system (VQS)) in Singapore. http://esci-ksp.org/?project=additional-registration-fee-arf-and-vehicle-quota-system-vqs-in-singapore. Accessed 15 Mar 2013
Gardner B, Abraham C (2007) What drives car use? a grounded theory analysis of commuters' reasons for driving. Transp Res Part F 10:187–200
Hensley et al (2012) Future EV battery costs: building the bottom-up model, McKinsey & Company Inc, New York
Lokenvitz (2013) Expert interview on charging infrastructure, Tom Lokenvitz, smove clean mobility Singapore Pte Ltd, Singapore, 16 April 2013
Mackett R(2003) Why do people use their cars for short trips?, Transportation 30:329–349
NPE (2011) Zweiter Bericht der Nationalen Plattform Elektromobilität, Anhang, Berlin, Germany, Abb. A05
One.Motoring (2013a) Car cost. http://www.onemotoring.com.sg/publish/onemotoring/en/lta_information_guidelines/buy_a_new_vehicle/car_cost.html. Accessed 15 Mar 2013
One.Motoring (2013b) ERP rate table for passenger cars, taxis and light goods vehicles (With Effect from 4 Feb 2013 to5 May 2013)
Petrolwatch.com.sg (2013): Fuel prices at shell stations, Jan 2011–Dec 2012, http://www.petrolwatch.com.sg/price-history. Accessed 20 Jan 2013
Pierce Transit (2013) Your driving costs—maintenance and tires. http://www.piercetransit.org/rideshare/costs.htm. Accessed 29 Apr 2013
SGCarMart.com (2013a) Carpark rates. http://www.sgcarmart.com/news/carpark_index.php?LOC=all&TYP=carpark. Accessed on 29 Apr 2013
SGCarMart.com (2013b) Prices for used cars in Singapore. http://www.sgcarmart.com/used_cars/listing.php?BRSR=20&RPG=20. Accessed 23 Apr 2013
Singapore Housing and Development Board (2013) New season parking. http://www.hdb.gov.sg/fi10/fi10327p.nsf/w/CarPark1NewSP. Accessed 20 Mar 2013
Singapore Land Transport Authority (2012a) Cost (S$) for Cars Registered in August 2012
Singapore Land Transport Authority (2012b) Statistics in Brief 2012
Singapore Land Transport Authority (2013a) Certificate of entitlement (COE). http://www.lta.gov.sg/content/ltaweb/en/roads-and-motoring/owning-a-vehicle/vehicle-quota-system/certificate-of-entitlement-coe.html (Accessed 20 Mar 2013
Singapore Land Transport Authority (2013b) COE Bidding Results 2012

Singapore Land Transport Authority (2013c) Recurring vehicle cost. http://www.lta.gov.sg/content/ltaweb/en/roads-and-motoring/owning-a-vehicle/costs-of-owning-a-vehicle/recurring-vehicle-cost.html. Accessed 20 Mar 2013

Singapore Land Transport Authority (2013d) Tax structure for cars. http://www.lta.gov.sg/content/ltaweb/en/roads-and-motoring/owning-a-vehicle/costs-of-owning-a-vehicle/tax-structure-for-cars.html. Accessed 20 Mar 2013

Singapore Land Transport Authority (2013e) Vehicle quota (COE), quota allocation from April 2010 onwards

Singapore Power (2013) Historical electricity tariff, 2006–2012

Smartenergy.sg (2012) Singapore CNG pump prices. http://www.smartenergy.sg/SMART_Energy/Welcome.html. Accessed 20 Mar 2013

Steg L, Vlek C, Slotegraaf G (2001) Instrumental-reasoned and symbolic-affective motives for using a motor car, Transp Res Part F 4:151–169

Windisch E, Leurent F (2012) L'acceptabilité potentielle des voitures électriques : Quelle profitabilité financière pour l'usager privé en Ile-de-France?, paper presented on the international congress ATEC-ITS 2012, France 2012

Performance Evaluation of Two-Speed Electric Vehicles

P. D. Walker, H. M. Roser and N. Zhang

Abstract This paper presents the findings of a theoretical analysis of a two-speed Dual-Clutch Transmission (DCT) for electric vehicle applications. Electric drives incorporating DCTs can offer improved driving economy, range, acceleration and climbing gradeability, with potentially smaller electric motors (EMs). Through simulation, this paper studies the influence of road grade on EV performance and how motor downsizing impacts on vehicle range and acceleration performance. Particular attention focused on how such vehicles perform using a variety of different drive cycles. Results show that as expected range is heavily influenced by driving cycle. However, for a reduction in motor peak power there is minimal variation in vehicle range. Vehicle performance is also demonstrated to be reasonable through significant reduction in motor size.

1 Introduction

Electric vehicles (EV) are considered one of the long term trends in the development of alternatively powered drivetrain technologies. These vehicles have a number of advantages of conventional internal combustion engine powertrains, with peak torque from zero speed and high operating efficiency across a wide range of operating speeds. Nevertheless, there are limitations to the capabilities of current EV technologies, considering particularly the demands for vehicle driving range and typical performance specifications such as top speed and acceleration.

P. D. Walker (✉) · H. M. Roser · N. Zhang
University of Technology, Ultimo, Sydney NSW 2007, Australia
e-mail: Paul.Walker@uts.edu.au

H. M. Roser
e-mail: Holger.Roser@uts.edu.au

N. Zhang
e-mail: Nong.Zhang@uts.edu.au

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_27,

The major considerations here are motor size, including peak torque and rated speed, and gear ratio selection. The selection of these parameters will define the driving capabilities and limitations of the vehicle; range however is ultimately limited by battery size.

EV powertrain designs are generally comprised of an electrical machine which is directly coupled to a fixed ratio drivetrain in its simplest configuration (Kamachi et al. 2010). Although inherently robust and simple, single speed drivetrains exhibit a range of design and performance limitations (Jinrui et al. 2006). Hence, this research investigates potential performance improvements of two-speed electric powertrains.

The following presents the findings of a study into the performance of single and two-speed electric vehicles to evaluate the design robustness of a two-speed EV to variation in driving cycle and road grade. The results are then extended to evaluate the possibilities for reducing motor size in comparing single and two-speed EVs. As such the remainder of this paper is devoted to the discussion of results achieved from previously implemented EV models. This next section briefly reviews the two and one-speed EV powertrains and respective models. This is followed by a summary of different driving cycles. Results are then presented for simulations of the impact of different cycles on the range and motor efficiency of the two-vehicles, including under different grade. Finally, acceleration, grade climbing and vehicle acceleration are re-evaluated for reduction in motor peak power to investigate the design benefits of moving to a two-speed EV.

2 EV Powertrains and Modeling

Powertrain system modeling of a two-speed EV was developed in the Matlab/Simiulink environment. This work is briefly summarized in Walker et al. (2012), and an initial comparison of single and two-speed EVs conducted in Zhou et al. (2012). Vehicle design parameters are listed in (Table 1).

2.1 Vehicle Dynamics Model

For the purpose of this research it is important to consider the impact of gear ratio, motor torque, powertrain efficiency and driving loads on the two vehicles under consideration. These variables are related in the vehicle mathematical model; this calculates vehicle acceleration and, via numerical integration, determines vehicle speed. Inputs are supplied motor torque, TEM, brake torque, TB, and vehicle resistance torque, TV, and the output is vehicle acceleration.

Equation of motion for the vehicle is:

$$m_V r_t^2 \alpha = \eta_{PT} \gamma T_{EM} - T_V - T_B.$$

The vehicle resistance torque is the combination of rolling resistance force, incline load and air drag. It is defined as:

$$T_v = \left(C_R m_V g \cos\phi + m_V g \sin\phi + 0.5 C_D \rho A_V \omega_V^2 r_r^2\right)$$

3 Drive Cycles

European and US drive cycles are both evaluated for this paper considering both city and highway style driving, each of the considered cycles is characterized by range, average speed, and stopping events in Table 2. Additionally, constant speed tests are also used as an alternative means for evaluation, vehicle speeds include 40, 60, 80, 100, and 120 km/h, each starting from rest.

4 Vehicle Range and Performance Evaluation

To further investigate the application of two-speed transmissions for EVs, a series of simulations are conducted to investigate the impact on driving range and performance for the choice of driving cycle simulations presented above. The

Table 1 Vehicle parameters

Parameter			Parameter	
Mass	m_V	1760 kg	Battery layout	1P120S
Wheel radius	r_t	0.317 m	Battery voltage	384 V
Frontal area	A_V	2.2 m^2	Battery capacity	66 Ah
Drag coefficient	C_D	0.28	Motor torque	
Rolling resistance	C_R	0.016	T_{EM} peak 255 Nm @ 3000 RPM	
Gear ratios	γ	11:1, 6:1	T_{EM} cont. 127 Nm @ 9000 RPM	

Table 2 Summarized drive cycle characteristics for a single iteration

Drive cycle	Duration (s)	Average speed (km/h)	Top speed (km/h)	Single cycle range (km)	Stopping events
US06	600	77	129	12.9	6
HWFET	765	78	96	16.5	1
FTP75	1874	34	91	17.8	23
NEDC	1185	33	120	10.9	13
ECE	195	18	50	1	3
EUDC	400	62	120	7	1

perceived benefits of using such a transmission is the capability to withstand a variety of driving conditions, including variation in drive cycles, speeds, and road grade.

The vehicle study considers two major impacts on driving range performance. First, what is the influence of road grade on driving range? It is well understood that varying grade is a non-recoverable energy loss to vehicular powertrains, driving downhill does not recover the same energy as expended driving uphill. Results in Fig. 1 show an inconsistency in variation of results, low speed simulations show a much higher reduction in range than at higher speeds. Additionally, drive cycle based simulations present a reasonably consistent influence on range, with similar levels of reduced range. Indicating the EV is not significantly influenced by different drive cycles.

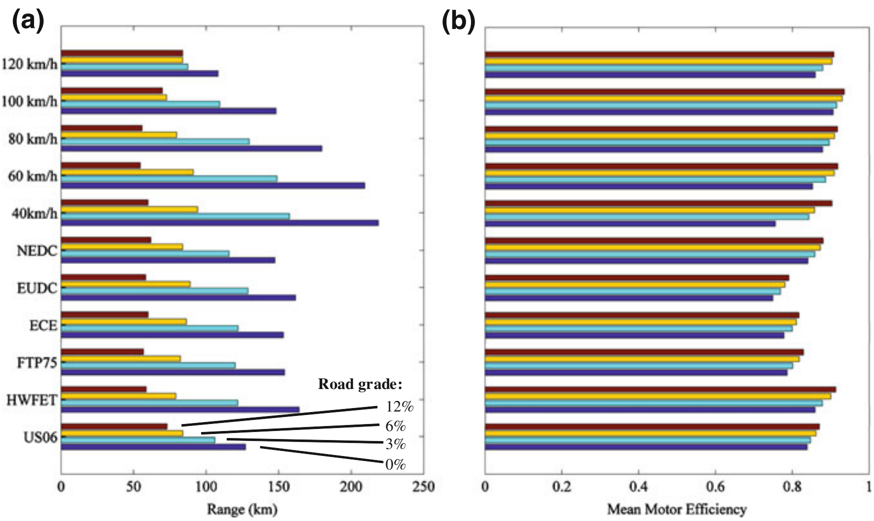


Fig. 1 Simulation results for various drive cycles with increasing road grade; **a** range and **b** motor efficiency

Second, how will reducing the motor size impact on range? The other key benefit of the use of multispeed transmissions for EVs is the reduction in peak motor torque. It is well established that vehicles require high torque at low speed for a range of purposes, including grade climbing and normal acceleration. Results in Fig. 2 demonstrates how significant reductions in peak motor torque, up to 30 %, do not significantly influence vehicle range for a wide range of drive cycles. Through the application of two gear ratios, the powertrain can provide high torque at low speeds whilst maintaining driving requirements under most conditions.

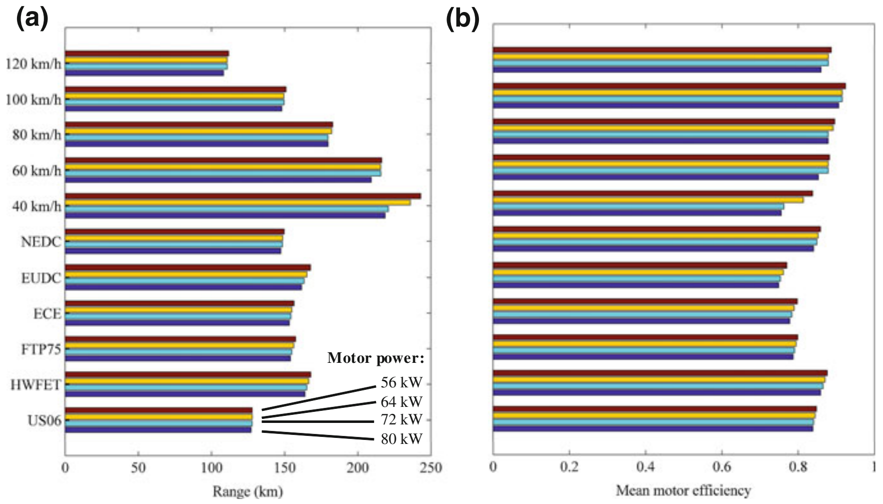


Fig. 2 Simulation results for various drive cycles with decreasing motor power; **a** range and **b** motor efficiency

Table 3 Two-speed acceleration performance

Motor power (kW)	80	72	64	56
Torque (Nm)	255	230	205	180
2-Speed 0–60 km/h (s)	4.68	5.23	5.93	6.86
2-Speed 0–100 km/h (s)	11.87	13.39	15.36	18.01
2-Speed 50–80 km/h (s)	4.12	4.64	5.31	6.20
Single-Speed comparison 0–60 km/h (s)	5.90	6.61	7.50	8.67

In opposition to vehicle range and efficiency, performance characteristics must be considered. Acceleration from rest and overtaking acceleration are compared by conducting simulations of vehicle accelerations with variation of motor peak torque, investigating the impact on acceleration, with results summarized in Table 3. These results are characteristic of what would be expected. As the peak torque reduces acceleration time increases. However, even at a peak power of 64 kW, performance results are not too dissimilar from many commercially available passenger vehicles. The difference between the 60 and 100 km/h is obviously influenced by gear shift to a lower gear ratio; this is particularly influential at lowest peak power results of 56 kW.

Besides a potential reduction in motor power, the benefits of two-speed configurations are more compelling with regard to top speed and road grade climbing capability, as gear ratios can be selected for optimum performance and efficiency during various driving conditions. In essence, the two-speed transmission has the capacity to meet higher torque demands at low speed in first gear, whilst fulfilling higher speed demands in second gear.

5 Conclusion

This paper studies the suitability of two-speed transmissions to EV applications. Vehicle range and performance evaluations using a variety of different drive cycles indicate that improved driving economy, range, acceleration and climbing gradeability are achievable with potentially smaller electric motors. Whilst range is heavily influenced by driving cycle, the simulation results show that for a reduction in motor peak power there is minimal increase in vehicle range. Vehicle performance is also demonstrated to be reasonable through significant reduction in motor size.

Despite a potential increase of drivetrain complexity, compared to single speed configurations, an optimized two-speed DCT in combination with a suitably sized electric motor offers vehicle designers more flexibility with regard to achieving superior acceleration, grade climbing and high speed performance. Furthermore, two-speed drives lend a greater potential of energy recuperation during deceleration.

Acknowledgments This project is supported by the Beijing Electric Vehicle Company and Ministry of Science and Technology, China.

References

Jinrui N, Zhifu W, Qinglian R (2006) Simulation and analysis of performance of a pure electric vehicle with a super-capacitor. In: Vehicle power and propulsion conference, pp 1–6

Kamachi M, Miyomoto H, Sano Y (2010) Development of power management system for electric vehicle 'iMIEV''. In: 2010 international power electronics conference, pp 2949–2955

Walker PD, Abdul Rahman S, Zhang N, Zhan W, Lin Y, Zhu B (2012) Modelling and simulation of a two-speed electric vehicle. In: Sustainable automotive technologies 2012. Springer, Heidelberg, pp 193–198

Zhou XX, Walker PD, Zhang N, Zhu B (2012) The influence of transmission ratios selection on electric vehicle motor performance. In: ASME 2012 international mechanical engineering congress and exposition, IMECE2012-85906, Houston, Texas, USA

The Project: Sustainability Racing—The Vision: Mobility of the Future

H.-J. Endres and C. Habermann

Abstract The advantages of glass and carbon fiber-reinforced plastics (GRP/CRP) have so far been valued and utilized mainly for design layout. But other criteria such as weight, cost, ecological compatibility or disposability of a material are also becoming increasingly important. In terms of these aspects, the potential of natural fiber reinforced plastics becomes evident in the "Bioconcept Car" project.

1 Green Alternative?

The development of sustainable materials for making new products is a necessary step toward a ready-for-the-future mobility. This is the main incentive for IfBB (Institute for Bioplastics and Biocomposites, University of Hanover, Germany) to engage in a cooperation with the race driver Smudo (a well-known celebrity in Germany as a singer of the German hip-hop group "Die Fantastischen Vier") and the Four Motors Racing Team. Funded by the Agency for Renewable Resources (FNR Fachagentur Nachwachsende Rohstoffe e.V.) on behalf of the German Federal Ministry of Food, Agriculture and Consumer Protection, this joint endeavour is focused on the development of bio-based materials and sustainable parts for the automotive industry. Bioplastics and biocomposites in this context are defined as fully or partially bio-based materials or as composites with bio-based reinforcement fibers and/or bio-based matrices.

With increasing use of bio-based components in its construction, the Bioconcept Car is well equipped to stand the strain of competitive long-distance races

H.-J. Endres (✉)
Institute for Bioplastics and Biocomposites, Hanover University of Applied Sciences and Arts, Heisterbergallee 12, 30453 Hanover, Germany
e-mail: info@ifbb-hannover.de

C. Habermann
Hanover University of Applied Sciences and Arts, Heisterbergallee 12, 30453 Hanover, Germany

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*, Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_28,

such as the VLN Endurance Championship or the ADAC 24 h races on the famous Nürburgring circuit. So the Bioconcept-Car sets out a path for a change toward sustainable materials not only in racing but also in normal traffic. There is growing evidence that bio-based materials can well be applied in modern technical constructions which are exposed to heavy strains like automotive parts.

2 Materials and Methods

An increasing number of components for the Bioconcept Car are made of resource-saving bio-based materials, which are extremely light-weight and therefore minimize the vehicle's fuel, or energy, consumption. To achieve the best possible result, different materials and material combinations are tested. On the one hand, thermoplastics which may be bio-based or petro-based (in this case thermoplastics combined with natural fibers to obtain a bio-composite) are used, either reinforced with different fibers or modified without fiber reinforcement; on the other hand, bio-based or petro-based thermosetting materials are combined with various fibers. In any case, the developed materials are fully or partly bio-based—either the fiber and/or the resin. For the light-weight car body resins are used which are reinforced with natural fibers.

Different natural and non-natural fabrics with variable weight and variable weave were produced and tested to achieve the necessary quality/character in terms of stability or processing properties (see Table 1) and to ensure the desired results in combination with the resin. In order to attain the properties of the natural fibers in the composites, they are laminated with a well-known resin ("Epoxidharz L" with "Epoxidhärter GL2" by "R&G Faserverbundwerkstoffe GmbH", see Table 2).

The used test samples (Type "1B"l: 115.0 ± 0.2 mm, b: 10.0 ± 0.2 mm h: according to quantity layer) are milled from the composites. They are produced by means of a vacuum bag process on a steel plate (370 × 370 mm) which was coated with a priming wax and a form release agent. The different layers are laminated by hand before they are cured at 70 °C for 24 h under vacuum. The mechanical parameters are determined after DIN EN ISO 527_2 by means of a universal testing machine Zwick/Roell type "Zmart.Pro".

Table 1 Fabrics overview (based on manufacturer's data)

Textile	Weave	Grammage (g/m2)
Glassfiber-fabric 1	Plain weave	280
Glassfiber-fabric 2	Plain weave	163
Glassfiber-fabric 3	Twill weave	163 ca.
Carbonfiber-fabric 1	Twill weave	285
Carbonfiber-fabric 2	Twill weave	200 ca.
Viscosefiber-fabric	Satin weave	190
Flaxfiber-fabrice 1	Twill weave	197
Flaxfiber-fabric 2	Basket weave	195
Flaxfiber-fabric 3	Twill weave	238

Table 2 Comparison of potential lightweight materials

	Glass fiber (E-glass)	Carbon fiber (HT—high tensity)	Synthetic fiber (viscose, rayon)	Wood fiber (soft wood)	Bast fiber (flax)	Epoxy-resin
Reported in literature						
Density (kg/m^3)	2560 (Baillie 2004)	1750 (Baillie 2004)–1800 (Kohler and Wedler 1996)	1520 (Mohanty et al. 2005)	1500 (;Mohanty et al. 2005) Belgacem and Gandini 2008	1480 (Kohler and Wedler 1996)	1151 (Manufacturer's data R&G Faserverbundwerkstoffe GmbH)
Tensile strength (MPa)	2000 (Baillie 2004)	3400 (Baillie 2004)	593 (Belgacem and Gandini 2008)	1000 (;Mohanty et al. 2005) Belgacem and Gandini 2008	380 (Kohler and Wedler 1996)	74,8 (Manufacturer's data R&G Faserverbundwerkstoffe GmbH)
Young's modulus (GPa)	76 (Baillie 2004)	230 (Baillie 2004)	11 (Belgacem and Gandini 2008)	40 (;Mohanty et al. 2005) Belgacem and Gandini 2008	19 (Accessed 26 Apr 2013)–38 (Kohler and Wedler 1996)	3,1 (Manufacturer's data R&G Faserverbundwerkstoffe GmbH)
Failure strain (%)	2,6 (Baillie 2004)	3,4 (Baillie 2004)	11,4 (Belgacem and Gandini 2008)	–	2,7–3,2 (Mohanty et al. 2005)	4,5 (Manufacturer's data R&G Faserverbundwerkstoffe GmbH)
Material costs (average) (€/kg)	3	35	3,50	2,5	2,50	6
Calculated values						
Spec. tensile strength (MPa*m^3/kg)	0,8	1,9	0,4	0,7	0,3	0,1

(continued)

Table 2 (continued)

	Glass fiber (E-glass)	Carbon fiber (HT—high tensity)	Synthetic fiber (viscose, rayon)	Wood fiber (soft wood)	Bast fiber (flax)	Epoxy-resin
Spec. young's modulus (MPa*m^3/kg)	30	128	7	27	26	3
Density (kg/m^3)	2560 (Baillie 2004)	1750 (Baillie 2004)–1800 (Kohler and Wedler 1996)	1520 (Mohanty et al. 2005)	1500 (;Mohanty et al. 2005) Belgacem and Gandini 2008	1480 (Kohler and Wedler 1996)	1151 (Manufacturer's data R&G Faserverbundwerkstoffe GmbH)

3 Results of Experiments

A comparison of potential lightweight materials reveals the advantages and disadvantages of the different fibers (see Table 2 and Figs. 1 and 2). On the x-axis the Figs. 1 and 2 show the density and on the y-axis the E-Modulus, or tensile strength, in [MPa], the table gives an overview of the main characteristics of the compared materials for design layout.

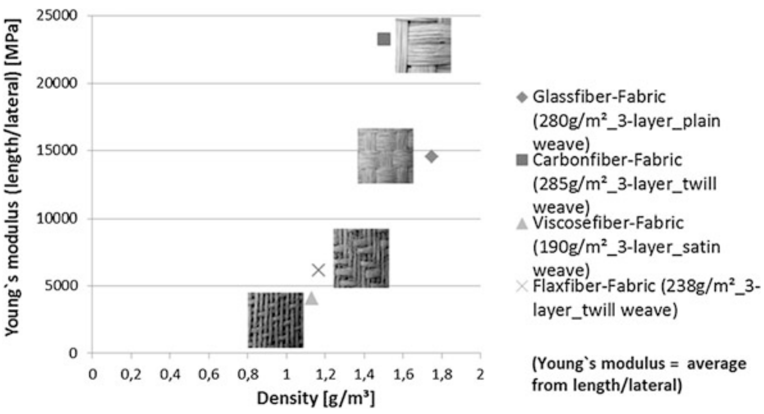


Fig. 1 Composite density versus young modulus

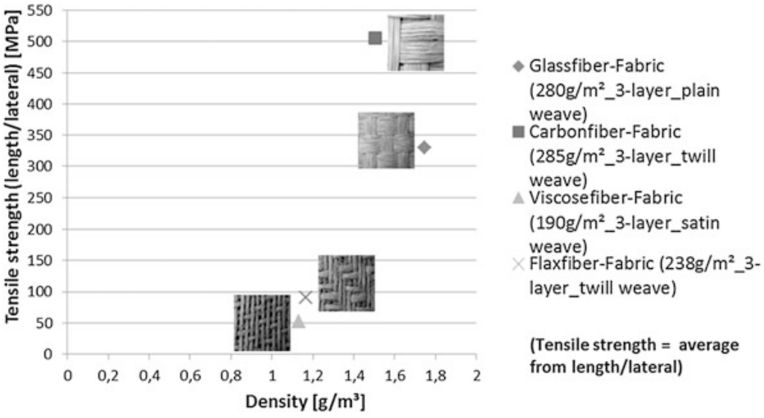
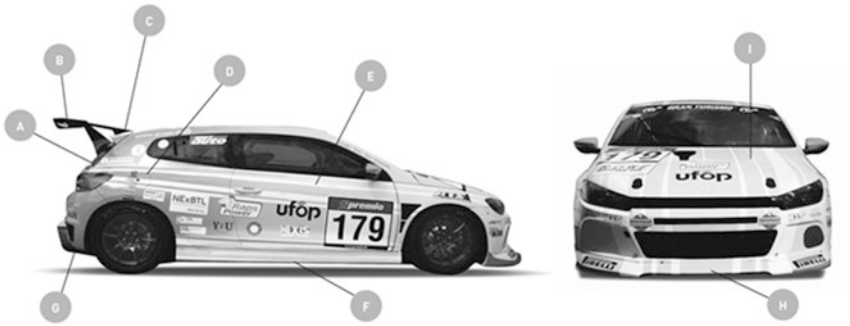


Fig. 2 Composite density versus tensile strength

The advantage of carbon fibers lies in their construction performance, however, this comes at a price—both economically and environmentally. Glass fibers are certainly less costly but more heavy-weight and have some ecological disadvantages similar to those of carbon fibers. Viscose fibers have advantages because of their light weight and better ecological and acoustic properties, but they lack the higher mechanical performance of carbon or glass fibers. Even flax fibers do not reach these levels but come out well in terms of weight, splitting behavior, cost, ecology and acoustics. Considering their very low weight (and price), it is in fact a viable and cost-saving option to increase their use for those parts where they already meet the requirements regarding mechanical performance.

3.1 Next Steps Toward More Sustainability

To increase the proportion of renewable raw materials in the vehicle (see Fig. 3), bio-based resin instead of petro-based resin is used for the components of the Bioconcept car. The raw materials for a bio-based epoxy resin can be different vegetable oils which are suited to achieve the necessary properties, e.g. hardness, viscosity, a quick curing time, or the ability to combine well with natural fibers. A new bio-based resin is currently being used in the tailgate of the Bioconcept Car.



		Now:	Before:
A	Tailgate:	Bio-based plastic (epoxy resin) with flax fabric	Sheet steel
B	Rear spoiler:	Bio-based plastic (epoxy resin) with flax fabric	Petroleum-based plastic (epoxy resin) with carbon fiber
C	Roof spoiler:	Bio-based plastic (epoxy resin) with flax fabric	Petroleum-based plastic
D	Fuel filler flap:	Bio-based plastic (polyamide) filled with talc	Petroleum-based plastic
E	Door:	Petroleum-based plastic (epoxy resin) with flax fabric	Sheet steel
F	Closed underbody:	Bio-based plastic (epoxy resin) with flax fabric	Petroleum-based plastic (epoxy resin) with carbon fiber
G	Diffuser:	Bio-based plastic (epoxy resin) with flax fabric	Petroleum-based plastic (epoxy resin) with carbon fiber
H	Front splitter:	Bio-based plastic (epoxy resin) with flax fabric	Petroleum-based plastics
I	Bonnet:	Bio-based plastic (epoxy resin) with flax fabric.	Sheet steel

Fig. 3 Renewable raw materials BCC (Based on: four motors GmbH)

Furthermore, other parts with more complex shapes—for example components under the hood and the interior part of a car—are designed with injection-moulded bio-based plastics or bio-composites. Different materials, i.e. material components and their configuration, are preselected according to the requirements of the application and the part that is to be realized. The next step is a laboratory-confirmed specific development and optimization of different material concepts of biobased materials. For example, the new fuel filler flap of the Bioconcept Car was produced in a comparable quality on a large-scale production injection-moulding machine with the standard mould.

Especially for this application a commercially available bio-based Polyamid 6.10 from DuPont was modified with talc and different additives.

4 Conclusion/Summary

The Bioconcept Car paves the way for a future sustainable mobility. The project clearly shows the advantages of natural fibers and makes them applicable for future series production in the automobile industry. Using natural fibers as reinforcements for thermoset resins is a sustainable option for light-weight car bodies and is even successful under extreme stress situations during racing. Even though alternative parts are currently being developed specifically for motor sports, these parts are well suited to be included in the series production of standard cars as well.

References

Baillie C (2004) Green composites – Polymer composites and the enviroment. Woodhead Publishing, Cambrige, p 245

Based on: four motors GmbH four motors GmbH Schulstraße 18 72764 Reutlingen Deutschland. http://www.fourmotors.com/5_media/2_pressebilder/

Belgacem MN, Gandini A (2008) Monomers, polymers and composites from renewable resources. Elsevier, Amsterdam, p 405

Kohler & Wedler 1996 and Kennwerte von Faserwerkstoffen nach Bobeth. Link in: http://www.inaro.de/Deutsch/ROHSTOFF/industrie/FASER/mechkenn.htm. Accessed 26 Apr 2013

Manufacturer's data R&G Faserverbundwerkstoffe GmbH. Technical data sheet, available: http://www.r-g.de/wiki/Datei:Broschuere_Epoxysystem_GL_englisch.pdf

Mohanty AK, Misra M, Drzal LT (2005) Natural fibers, biopolymers, and biocomposites. Taylor & Francis, Boca Raton, p 39

N-fibre-database: http://www.n-nibrebase.net/nfibrebase_faser/matdb/matdb.php?sLg=de. Accessed 26 Apr 2013

The Innotruck Case Study on A Holistic Approach to Electric Mobility

L. Mercep, C. Buitkamp, H. Stähle, G. Spiegelberg, A. Knoll and M. Lienkamp

Abstract We present an interdisciplinary approach to electric mobility based on three main research areas: Energy Management, System Architecture and Human–Machine Interface. A flexible energy management model is developed to suit the needs of arbitrary aggregated configurations in different hybrid vehicles. Our modular and data-centric vehicle ICT architecture reduces communication overhead, while addressing component plug-and-play and automotive safety. The classical human–machine interface is extended with a highly integrated HMI module which analyzes the interaction context. A drive-by-wire hybrid vehicle prototype has been constructed, the Innotruck, which serves as both testing ground for the developed concepts and a presentation area for communicating the results to public. Emphasis is placed on the societal importance of our work, impact and dissemination of results. More than 20 industry and research partners contribute directly to the project and the further development of the prototype vehicle.

1 Introduction

The presented work is the summarized result of the project Diesel Reloaded, organized by the Institute for Advanced Study (IAS) and the International Graduate School of Science and Engineering (IGSSE) of the Technische Universität München,

L. Mercep (✉) · H. Stähle · A. Knoll
Fakultät für Informatik, Lehrstuhl für Robotik und Eingebettete Systeme, Technische Universität München, Garching bei München, Germany
e-mail: ljubo.mercep@tum.de

C. Buitkamp · M. Lienkamp
Fakultät für Maschinenwesen, Lehrstuhl für Fahrzeugtechnik, Technische Universität München, Garching bei München, Germany

G. Spiegelberg
Institute for Advanced Study, Technische Universität München/Siemens AG, Garching bei München, Germany

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*, Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_29,

together with the industry partner Siemens AG. The project started in 2011 and is led by Prof. Dr.-Ing. Gernot Spiegelberg, a Rudolf Diesel Senior Industry Fellow at the IAS and the head of concept development for electric mobility at Siemens Corporate Technology. The principal investigators are Prof. Dr.-Ing. habil. Alois Knoll from the Chair for Robotics and Embedded Systems and Prof. Dr.-Ing. Markus Lienkamp, from the Chair for Automotive Engineering. Three doctoral candidates are active in three research areas. Dipl.-Ing. Claudia Buitkamp is responsible for the vehicle's energy management. Ljubo Mercep, M.Sc. is working in the field of human–machine interfaces. Dipl.-Ing. Hauke Stähle is developing the system architecture. The interdisciplinary approach is focused on three different aspects of electric mobility: business models, enabling technologies and communication of science to public.

2 The Innotruck

The Innotruck is our scientific prototype and the project demonstrator at the same time. It is a hybrid diesel-electric drive-by-wire truck with a bionic design from Prof. Luigi Colani. Observing it from the outside, three basic segments can be identified: The self-contained drivetrain, the large semitrailer and the trailer. The semitrailer is internally composed out of three functional segments: Driver's workplace, business lounge and presentation area. The driver's workplace features a highly integrated human–machine interface consisting of a driver's seat with two spherical sidesticks and a central console with the virtual dashboard. The business lounge is outfitted with ambient lighting control and presentation displays. The presentation area is equipped with four large interactive presentation displays (Fig. 1).

Fig. 1 The innotruck at the Hannover Messe 2012

3 Energy Management

Within the Innotruck there are many different electric sinks and sources. Sinks are defined as components that use electrical energy to fulfill their functionality, whereas sources are components which convert power of another form into electrical power. Every component has an energy interface to the electrical intermediate circuit. Furthermore there are components, like the battery, which can be both, a sink and a source. The following table gives an overview of the main sources, sinks, and source/sinks.

Sources	Sinks	Source/sinks
Range extender	Compressor	Li-Ione battery
Solar panels	Steering pump	Electric motor
Wind power	Air conditioning	Eight electrical cars
	Lights, navigation…	External power net

3.1 Necessity of an Energy Management

Depending on the driver wish, the electrical motor is a sink, while driving, and a source while braking and recuperating. Because of the series hybrid configuration, the electrical motor can use the electrical power of two different possible sources, the battery and the range extender with a diesel engine and a generator. Therefore the state of the battery (charging or discharging) and the range extender do not depend on the driver wish and have to be defined by the electrical energy management. Additionally solar panels on the roof provide electrical power and sinks like the air compressor, the steering pump and the air conditioning have to be supplied.

While standing still, the Innotruck can be considered as a smart grid. In this mode, wind power can also be harnessed. Furthermore, up to eight electric cars can be charged by the truck or they can charge the truck's battery and supply its auxiliaries. The truck is also connected to the external power net, to gain power of it or to feed in power.

As shown, depending on the mode of the truck (driving/standing still) different sources provide power and different sinks have to gain it. The electrical energy management is therefore needed to determine the state of each component, i.e. determine the amount of energy each source has to provide and each sink will gain. It has to assure that safety critical sinks are supplied with sufficient power at all times and all sources can be activated by a start-up process. For instance, if the engine-generator unit was turned off in a series hybrid vehicle, the battery should always be sufficiently charged to restart it. Furthermore operating limits of the components should never be exceeded.

3.2 Flexible Energy Management

During the project a flexible energy management, which allows adding and removing different numbers and characteristics of sources and sinks, has been developed (Buitkamp 2013). It is built on a market based approach, where sources and sinks trade electrical energy within the energy management unit. Every energy component tells the energy management, via a cost-power function, its operating costs for electrical power in case of a source, or its priority to be supplied in case of a sink. Components, which can be source and sink, provide two cost-power functions. Every cost-power function takes the operating limits into account. These functions are used by the energy management to calculate the market price and determine the amount of energy each component has to supply or to gain. Thereby the electrical energy management ensures the energy balance, i.e. the same amount of electrical power is provided as it is consumed.

3.2.1 Advantages for the Vehicle Manufacturer

By using autonomous cost-power functions (the function of each component does only depend on its own characteristic and state data), the energy management does not have to be redeveloped and tested for every series hybrid or electric vehicle variant. This allows vehicle manufacturers to reduce development, application, and commissioning costs.

3.2.2 Advantages for the Vehicle Operator

Additionally, every component has to assure the economical operating point for every amount of electric power. For example, the range extender can control the torque and speed of the diesel engine in the most fuel efficient mode for every possible power provided. As the energy management only determines the sources to provide electrical power, which have the lowest operating costs in total, the vehicle operator benefits from minimal operating costs. These do not only include minimal fuel costs, but a minimum of all operating costs in total, including battery aging costs or maintenance costs.

4 System Architecture

A modern vehicle is built with multiple electronic control units (ECU's) from different vendors, which are connected with heterogeneous networks. Each ECU is dedicated to a limited number of tasks and comes as a black box, meaning that only the communication protocols and the functionality are known.

The task of the cars' original equipment manufacturer (OEM) includes the specification and integration of the ECU's while the development and production is outsourced. During this process, the different signals of the ECU's are matched and a solution for the interconnection, timing and safety requirements has to be found.

As the demand for functionality increases the interconnection complexity and whole system complexity increases as well. It is said, that the functional amount increments with linear magnitude, while the interconnection demand increases quadratic, and the integration effort grows with cubic magnitude.

Consequently, this leads to significantly increasing costs if the classic architecture is kept while extending a vehicle's functionality. High-end functions like autonomous driving or driver assistance systems are likely to have even higher requirements for data throughput and quality (Fortiss Technical Report 2011).

4.1 Centralized Architecture

One possible solution to the increasing integration efforts is the implementation of a centralized architecture, which pushes the functionality into the software level based on a run-time environment that offers various system services. The development process should be data-flow based instead of component based.

4.1.1 Principle of Smart Sensors and Actuators

The system architecture for the centralized approach is divided into the centralized processing units and smart sensors and actuators that are interconnected via a homogeneous network.

The sensors and actuators should preprocess the data in order to reduce the data throughput demand. Furthermore, the actuators can run local feedback loops to reduce the response time of control tasks.

All smart actuators and sensors have in common that they propagate their information to the centralized unit and are controlled by abstract commands.

4.1.2 The 5-Module Concept

The 5-module concept was developed by Prof. Spiegelberg to reduce the communication demand between the individual domains in a car by using a data-flow oriented functional distribution. This does not only reduce the costs of wire harness but also the development costs. Less physical communication between the components also means that the resource-intensive developing of interface definitions is reduced to a minimum.

The 5-module concept is divided into a strategy and an execution level. The strategy level consists of the human–machine interface and an optional virtual co-driver. An arbitration unit is in charge to determine if the information of the human–machine interface or the virtual co-driver should be forwarded to the execution level. The virtual co-driver is a software component that interprets environmental information gathered by various sensors in order to calculate a safe vector for the vehicle to move. In contrast, the execution level consists of the drive-train unit and comfort systems units. The drive-train unit controls the individual actuators and stabilizes the vehicle. A communication and management module completes the setup.

4.1.3 Run-Time Environment

As the software components should be able to deterministically interact with each other, a sophisticated run-time environment is necessary to abstract the hardware and communication complexity as well as to ensure the semi or full-automatic enforcement of non-functional requirements. Non-functional requirements include end-to-end latencies, security considerations and safety demands. Further, the run-time system should offer system management, plug and play abilities, component encapsulation, mixed criticality and a set of automotive standard services like sensor-fusion (Buckl 2012).

In contrast to existing systems, the environment should be aware of the requirements of the individual components to be able to offer a reconfiguration service.

4.1.4 Communication Paradigm

For the communication between the software components, we propose the usage of the data-centric paradigm. In the data-centric paradigm, the sender and receiver of data are de-coupled from a developer's point of view. Instead, the requirements for the data transfers are defined for each data receiver and the supported properties are specified for each sender. The runtime environment and the tooling are responsible to match the different requirements.

4.2 Impact of a Centralized System Architecture

The implementation of a centralized system architecture is a challenging task but manufacturers as well as vehicle owners will benefit from it on the long run.

4.2.1 Advantages for Manufacturers

A centralized architecture enables the optimized addition of further functions. This eventually leads to reduced development costs and a shorter development cycle. A standardized and modular system will also open the market for small and medium manufactures.

4.2.2 Advantages for the Vehicle Owner

The safety of a car can be increased by the usage of pre-certified components. Due to the dynamic platform management, the end-user will experience a higher flexibility in system configuration with the possibility of functional extensions. As software implementations from different vendors will compete, it is expected to have a wide variety of different implementations available with free market pricing.

5 Human–Machine Interface

This section can be broken down into answering two main questions:

- How can the intelligent vehicle augment the driver's capabilities?
- How can the HMI affect the business models regarding electric mobility?

5.1 Augmenting the Driver

The Human–Machine Interface (HMI) is currently understood as the part of the technical system which interacts with the user. During such interaction, two intermediate translation steps can be observed.

The first one happens at the user's side, while he translates his ideas to the movements of body parts and interprets the machine's feedback.

The other happens at the machine's side, while it is interpreting the physical input being received through what is currently called a HMI and preparing the feedback through various HMI modalities.

Throughout these steps, a man–machine interaction has been performed and an understanding has been reached.

The interaction was executed with a certain level of mental and physical effort on the user's side and processing and power effort on the machine's side and the interaction had a specific quality in regards to the overall human performance in the task. In the ideal case, the machine would possess artificial intelligence which processes the entire interaction context and it would interact with the user using complete situation awareness. The translation of the original driver wish would be faster and less physically intensive. The feedback would only add to the existing user perceptive abilities and not overlap or overload the user.

The development of such future HMI can be further optimized by leveraging solutions from adjacent domains and defining intermediate steps from the current automotive HMI to the long-term vision (Mercep 2013a).

5.1.1 Context Processing

The first building block is therefore well-designed and well-performing context processing, which enables situation awareness. The user-vehicle-world construct, together with its inherent uncertainties, can be represented with Bayesian networks. Their exact description, through the rules of conditional probability and associated probability distributions, provides predictability and enables formal testing. We focused on exact inference for the same reasons. Four specific areas for improvement in the HMI domain were identified:

- Inference complexity on embedded hardware.
- Separation of conditional dependencies between sensor modalities.
- Dynamic addition and removal of data sources.
- Time constraints for safety relevant functionality.

The extension of the Junction Tree algorithm, called the Probabilistic Application Layer (PAL), has been developed to improve all the four areas (Mercep 2013c). It has been implemented on an Intel Atom-based embedded computer as a part of a combined HMI—Driver Assistance module inside the 5-Module architecture.

5.1.2 Integrated Interfaces

The second building block is composed of physical HMI solutions which minimize the physical effort during the interaction and provide a consistent feedback. Two aspects were considered: Control of the vehicle dynamics and the control of all other vehicle functions. For the primary vehicle control, a spherical sidestick solution from a project partner was integrated as-is. For the control of all other vehicle functions, a centralized touchscreen-based dashboard was constructed (Mercep 2013d). Furthermore, two HTML-based apps for the dashboard were developed: An energy management and a parking and maneuver assistance application (Stoeck 2012). In addition to the HTML apps, a control panel for the electric vehicles' charging stations is provided in the native dashboard software platform.

5.1.3 New Interface Modalities

While new interface types, such as side sticks and brain-computer interfaces, can already be used for vehicle control, we focused on the additional data which they capture by design and which is not related to the primary driving task. We refer to this additional data as "added value" of a specific interface and we attempt to mine it in order to determine the driver state. We focused on the electroencephalography-based brain-computer interfaces and have developed a method for robust detection of driver vigilance, which classifies the drivers into two states based on the spectral analysis of the significant independent signal components (Mercep 2013b, 2013e).

5.2 HMI-Based Business Models

This section deals with the HMI as an enabling technology for different business concepts in the scope of electric mobility. The first step was developing presentational versions of every technical interface, in order to communicate the benefits of specific technology solutions to public (Mercep 2013f). For the second step, an assumption was made that combined traffic solutions and car sharing will be one method of introducing electric vehicles on the larger scale.

5.2.1 Interface Personalization

The concept of personal mobility provided as a service can be a starting platform for customer binding over the HMI. The customer retains his own styles and preferences, together with the infotainment content, from the previous vehicle type or instance. One requirement is a standardized description of such user profiles and standardized software interfaces. Our prototype uses a generic markup language profile description for dashboard elements visualized by vector graphics, which can be extended to describe arbitrary user preferences.

5.2.2 Assistive Applications

Stored user profiles can also contain the description of the driver's skill level, in order to consistently deliver the preferred level of assistance. This level can stay unchanged throughout different vehicle types. In this way, new users or elder population can be gradually integrated into semiautonomous or autonomous vehicles. It is advisable to continuously present the next system step or system state, to attain user's trust. Our maneuver and parking assistant, which comes with an offline training mode, is one of such assistive systems.

6 Summary and Future Work

We have shown how research and engineering in three complementary disciplines can shape and affect the concepts of electric mobility and mobility in general, while addressing the relevant megatrends. For our studies, we have used the Innotruck, a driving simulator with a full chassis mockup and an ENUBA[1] transport truck. The future work includes refinement of current prototypical components into automotive grade systems, which can be integrated into different types of electric vehicles. In the area of HMI, a more complete framework for HMI and driver assistance applications will be developed, in order to strongly separate the developers from the context processing models.[2]

References

Buckl C, Camek A, Kainz G, Simon C, Mercep Lj, Staehle H, Knoll A (2012) The software car: building ICT architectures for future electric vehicles. In: Electric vehicle conference (IEVC), IEEE international, Greenville, 2012

Buitkamp C, Spiegelberg G, Lienkamp M (2013) Reducing costs during development and operation of hybrid commercial vehicles through a market-based electrical energy management. In: Electric & electronic systems in hybrid and electric vehicles and electrical energy management conference (EEHE), Bamberg, 2013

Fortiss GmbH (2011) The software car: information and communication technology (ict) as an engine for the electromobility of the future. Technical Report, Munich

Mercep Lj, Spiegelberg G, Knoll A (2013a) A case study on implementing future human-machine interfaces. In: The 2013 IEEE intelligent vehicles symposium, Gold Coast, 2013

Mercep Lj, Spiegelberg G, Knoll A (2013b) Reducing the impact of vibration artifacts in a brain-computer interface using gyroscope data. In: IEEE Eurocon 2013, Zagreb, 2013

Mercep Lj, Spiegelberg G, Knoll A (2013c) Context processing for human-machine interface. In: Science and information conference 2013, London. In Review, 2013

Mercep Lj, Spiegelberg G, Knoll A (2013d) Die Entwicklung einer zentralisierten MMS im Rahmen des Projekts Innotruck. In: Automotive meets Electronics, VDE/VDI/GMM, Dortmund, 2013

[1] Project ENUBA (ger. *Elektromobilität bei schweren Nutzfahrzeugen zur Umweltentlastung von Ballungsräumen)* attempts to reduce the CO_2 footprint of transport trucks through hybrid drive trains and catenary lines.

[2] This is work in progress together with fortiss Institut der Technischen Universität München.

Mercep Lj, Spiegelberg G, Knoll A (2013e) A robust driver assessment method for the brain-computer interface. In: IADIS interfaces and human computer interaction 2013, Prague. In Review, 2013

Mercep Lj, Spiegelberg G, Knoll A, Stoeck J (2013f) Interface concepts for communicating green cyber-physical systems to public. In: Smartgreens 2nd international conference on smart grids and green IT systems, Aachen, 2013

Stoeck J, Mercep Lj, Spiegelberg G, Knoll A (2012) Platform-independent interface for the management of sensor-generated power and data flows in an automotive data-centric architecture. In: 6. VDI/VDE Fachtagung USEWARE 2012 – Mensch-Maschine-Interaktion, Deutsches Forschungszentrum für Künstliche Intelligenz DFKI Kaiserslautern, pp 33–36

A Literature Review in Dynamic Wireless Power Transfer for Electric Vehicles: Technology and Infrastructure Integration Challenges

A. Gil and J. Taiber

Abstract Dynamic wireless charging refers to the ability to charge a vehicle while it is in motion using resonant inductive power transfer. This is achieved by embedding source coils in the road and including a pickup coil inside the vehicle, these coils are coupled to get the maximum power transfer. From the point of view of the vehicle, dynamic wireless charging systems theoretically solve the Electric Vehicle (EV) battery problem by delivering unlimited range and making it possible to use smaller batteries, which reduce the cost and weight, however the implementation will be limited by the availability of the charging infrastructure, which in turn is limited by its cost. This paper presents a literature review on the recent advancements of stationary and dynamic wireless power transfer used for EV charging addressing power limitations, electromagnetic interference regulations, communication issues and interoperability, in order to point out the technology challenges to transition from stationary to dynamic wireless charging and the implementation challenges in terms of infrastructure.

1 Introduction

In 2012, the U.S. Energy Information Administration reported that the US imported about 45 % of the petroleum used in 2011 (U.S. Energy Information Administration 2012). The Department of Energy (DOE) has established as one of its primary goals to reduce the amount of oil used. Since transportation sector

A. Gil (✉) · J. Taiber
Clemson University International Center for Automotive Research,
Greenville, SC 29607, USA
e-mail: agil@clemson.edu

J. Taiber
e-mail: jtaiber@clemson.edu

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_30,

represents 70 % of the oil usage (Morrow et al. 2010), electric vehicles (EV) are becoming the path to reduce this amount, but costumer acceptance is closely related to their range and cost. The battery is one of the most important components in an EV and it is also the one that contributes the most to the range and cost problem, because an increment in battery size (more range) leads to an increment in cost and weight (Lorico et al. 2011), therefore, another solution needs to be proposed. Furthermore, DOE goals for EV adoption are to have a vehicle capable of fully charging in 5 min and having a 300 km range (US Department of Energy 2013a), this implies about 1 MW charging capacity in each charging station, batteries are currently not capable of absorbing that amount of power, this is something that will not be achieved in the near future (Slezak 2013).

Dynamic wireless charging (DWC), also known as in-motion charging, can be thought as a mean to address the problem of EV adoption by using the infrastructure as an extension of the power supply system of the vehicle. This is achieved by reducing the battery size and placing charging coils embedded in the road to transfer energy wirelessly using some variation of inductive power transfer. Although in (Musavi et al. 2012), it is pointed out 6 types of wireless power transfer (WPT) technologies: Inductive Power Transfer (IPT), Capacity Power Transfer (CPT), Permanent Magnet Coupling Power Transfer (PMPT), Resonant Inductive Power Transfer (RIPT), On-Line Inductive Power Transfer (OLPT) and Resonant Antennae Power Transfer (RAPT), for DWC purposes, only RIPT and OLPT are considered because they are the most promising technologies in terms of performance, their concepts, which are similar, are explained in the following section.

This paper presents the challenges to implement DWC, Sect. 2 presents the basic concepts of wireless power transfer and system components, Sect. 3 addresses technology challenges, safety issues and infrastructure topics to migrate to DWC, Sect. 4 presents the current standards roadmap and their scope and Sect. 5 summarize the contents of the paper.

2 Stationary Wireless Charging System

2.1 Basic Concepts

IPT refers to the action of transmitting power without using a medium other than the air. According to Lentz's law, a time variant current in a conductor creates a time variant magnetic field around it; this will be called the primary. And, from Faraday's Law, a secondary loop located in the vicinity will capture the magnetic field and it will induce a voltage in the terminals of the loop as shown in Fig. 1. A load can be connected to the terminals, the circuit will be closed and a current will flow, hence, power will be transmitted to the load connected in the loop (Witricity 2012; Kazmierkowski and Moradewicz 2012).

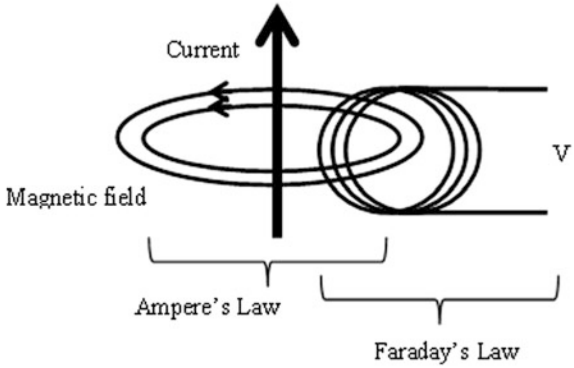


Fig. 1 Fundamentals of IPT (Covic 2013)

This configuration is not efficient because the intensity of the magnetic field decreases with the distance and the air reluctance is high (Sadiku 2001). To improve power transfer, series or parallel resonance topologies are applied to the primary and secondary to create resonant magnetic coupling (RMC) (Qiang et al. 2012). RMC occurs when two objects exchange energy through their oscillating magnetic fields and the natural frequencies of the two objects are approximately the same (Witricity 2012). To make the system resonate, harmonic oscillators are built in each coil by adding resonant capacitors. The effect of tuning is increase power transfer; the output power of the tuned system is given by Eq. 1:

$$P = \omega I_1^2 \frac{M^2}{L_2} Q \tag{1}$$

where ω is the resonance frequency, $I_1$is the current in the primary side, M is the mutual induction coefficient, L_2 is the self-inductance of the secondary and Q refers to the loaded quality factor from the impedance matching. This equation shows that the output power depends in four aspects: first, the operation frequency; second, the source current; third, the magnetic coupling, and fourth, the tunning factor (Q).

To increase the amount of power transmitted the following needs to be considered: There exists a trade-off between the frequency and the losses. The higher the frequency, the better the coupling, but also, capacitive effects are created and in the turns of the coils and losses also increase (Dimitrakakis and Tatakis 2008), hence there is a limit to which the frequency can be increased and still have a good efficiency. Also, increasing of the current in the primary also increases the losses (I_1^2R loses), so there are two approaches to maximizing the efficiency: (1) to increase the magnetic coupling, that could be achieved by a design that ensures that the coupling factor k is both high and has minimum variation with changes in the air gap (Boys and Covic 2012) and (2) to increase the tuning factor, which can be thought as solving the impedance matching problem (Kurs et al. 2007).

2.2 System Components

As observed in (Musavi et al. 2012), RIPT systems maximize the transferred power and optimize efficiency, increase distances, reduce electromagnetic interference (EMI) and it works in the kHz order of magnitude. The components involved in WPT are: (1) Utility interface, (2) High frequency power inverter and controller, (3) Coupling coils, (4) Rectifier, filters and regulator, and (5) Communications between the vehicle and the road side unit (Kesler 2012). They are shown in Fig. 2.

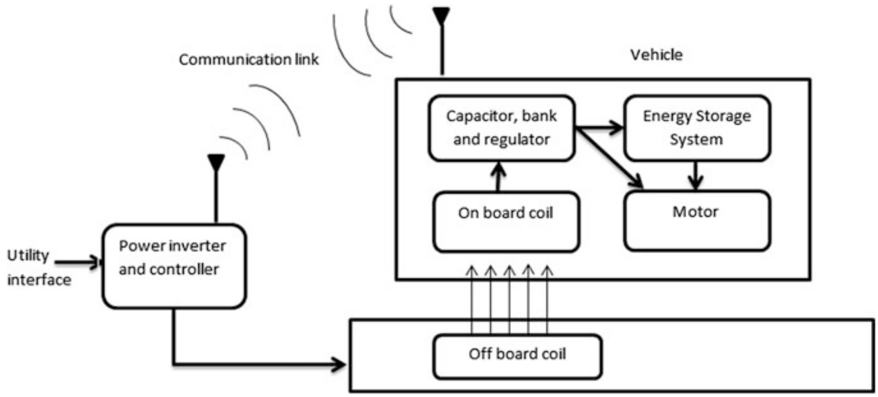


Fig. 2 Wireless power transfer system components

The system works as follows: The vehicle is located over the charging pad and when the identification process has taken place, the power inverter will convert the power from the utility to a high frequency alternating current, this will excite the resonant coils and the power captured in the on-board part will be rectified and sent to either to the battery or directly to the power train. To complete the loop a communication system is implemented to feedback the information from the vehicle to the grid side controller and vice versa. The overall system shall be capable of detecting any object between the coils and apply safety measures to avoid any incidents.

In order to have a successful implementation, the system needs to at least imitate the conductive charging solution, which has a high efficiency. To achieve this the vehicle should be correctly aligned, not represent harm for the user and the power levels should be at least similar to level 2 chargers (7.2 kW) (U.S. Department of Energy 2013b). Technology is mature in the stationary area, commercially available technology suppliers include: Conductix-Wampfler, Evatran, HaloIPT (Qualcomm) LG, Momentum Dynamics, and Witricity (Musavi et al. 2012).

3 Dynamic Wireless Charging System

Dynamic wireless charging (DWC) refers to the ability to charge a vehicle while it is in motion using resonant inductive power transfer. The implementation will inherit the problems from the stationary case, where the vehicle is parked, and it will introduce new ones. First, the vehicle will be in motion, thus the amount of time that the coils will be interacting is significantly smaller than in stationary case, this leads to the necessity of high power devices and also forcing the system to have high alignment tolerances to keep high efficiencies.

3.1 Technology Challenges

Using a Nissan Leaf as a benchmark, whose battery capacity is 24 kWh with a range of 74 miles (Leaf owner's manual 2012), it is necessary to define what type of service dynamic wireless charging will provide. Will it be designed to fully charge the vehicle or just an external range extender? The former case, as stated by Landreman (Landerman 2012), will require 30 miles of resonating coils to take the vehicle from 0 to 80 % of the full charge while driving at 60 mi/h, assuming that the fastest technology currently available is being used, and taking into account that Lithium Ion batteries get damaged when using fast charging. The latter case, assuming that the system is designed to add 30 miles of range, which is the average daily commuting distance (9.6 kWh), driving at 60 mi/h in a one-mile length charging lane, assuming 90 % of overall efficiency, it will require a power supply of almost 650 kW.

Another approach is that the vehicle is charged in a distributed manner, i.e. usage of several charging locations to extend the range instead of only one to balance the amount of power taken from the batteries and from the infrastructure. For this approach, the discussion about charging spots location and length is addressed by Pantic et al. in (Pantic et al. 2009). Three driving cycles were considered (UDDS, HWFET and VAIL2NREL), and three type of vehicles (compact car, large car and SUV). Several power levels for the charging station were tested (up to 60 kWh); the results are the optimal length of the charging lanes, location in the drive cycle and battery size. It was concluded that when minimum DWC track length is the only optimization criterion the DWC track length becomes very short. Therefore, it is beneficial to size the batteries to easily meet the peak power requirements. Since passenger vehicles usually do not follow a specific drive cycle in their normal operation, this approach is more suitable for transit vehicles because their route, stops and velocity profile are known.

All the scenarios presented before require a steady amount of power delivered and high power levels. Currently, scholars are investigating how to address this problem; the proposed approaches include but are not limited to: Magnetic field shaping (Ahn et al. 2012), dynamic parameter identification (Xin et al. 2010), reactive VAR compensators (Dixon et al. 2005), active rectification (Onar 2013), soft switching topologies and fast dynamic controllers (Wu 2012).

3.2 Safety

WPT systems are essentially resonant antennae, since they're devices for radiating and receiving radio waves (Merriam-Webster 2013). The transmitter transforms electric power into radio waves that are captured by the receiver, which means that the system intentionally generates and radiates energy. WPT operate in the near field of the magnetic field; research efforts should be aimed to works in the non-radiating reactive zone (Miller 2012). Due to the power amount that is transmitted, the fact that this system is not designed to transmit information and that it works in the near field zone, common regulations for antennae cannot be applied to them (Intertek Laboratories 2012).

Exposure to radio frequency magnetic fields is harmful for humans because it might induce current in tissues (ICNIRP 2010), and as it is observed in Fig. 3, exposures in the near field are more difficult to specify because the field patterns are more complicated and both electric and magnetic fields must be studied or measured separately (Hai et al. 2012). The following comparison is made to have an idea of the magnetic field levels when charging EVs, the experiment that MIT researchers presented in (Kurs et al. 2007), transmitting power to a 60 W bulb using a system that works at 10 kHz, produced a magnetic field of 1–8 A/m. For the implementation of DWC to be worthwhile, the system must supply at least the amount of power to move the vehicle over the charging lane, for a Nissan Leaf, 25 kW are needed for driving at 60 mi/h. This power amount will create a magnetic field approximately 30 times bigger than the one measure by MIT researchers.

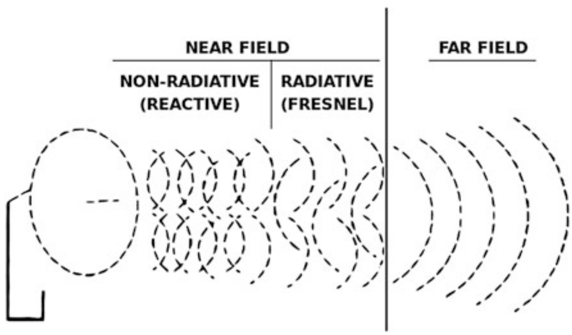


Fig. 3 Near field and far field regions of a time varying electromagnetic field (Djuknic 2003)

IEEE has determined that the maximum permissible exposure of magnetic field for controlled and uncontrolled environments is 163 A/m from 3 to 100 kHz, which are the frequencies at which the stationary systems work (IEEE 2006), from the calculations presented above, DWC would violate the permissible exposure if no active shielding is performed. The regions in the system that need to be analyzed are, in between the coils, around the coils and around the vehicle. The first two are not normally exposed to humans or animals but the last one is (Hai et al. 2012). Even if the vehicle is appropriately shielded and people inside the vehicle are safe, pedestrians, motorcycles and road workers and other people external to the system that can be in the vicinity are not protected reason why there is a need for safety measurements that take these actors into account (Landerman 2012).

3.3 Infrastructure

In addition to safety other challenges need to be considered. Since coils will be part of the road surface, they need to follow the same regulations as the road. The design of a road includes, among others, choosing the pavement material and how to handle rainwater and utility lines (U.S. Department of Transportation 2004). The coils need to be (1) as elastic as the pavement material, because they will support the weight of the vehicles, (2) waterproof, in case a crack lets water reach the coils, (3) reliable, to lead to zero maintenance, (4) noninterfering with periodic maintenance of the road and 5) coordinate with the existing utility lines to connect with the grid. The last characteristic also implies that there is a need for an upgrade in the distribution system because current designs are not prepared to handle the amount of power that the wireless charger will withdraw from the grid (Green II et al. 2011). Studies realized to stationary wireless charging of EV ensure that the distribution grid is capable of handling EVs charging between 1 and 6 kWh, but that the introduction of EV would force the grid to operate nearly at full capacity at all hours of the day, leading to deterioration of distributions transformers. Smart charging and smart grid are suggested as possible solutions to overloaded distributions systems (NY 2009; Kintner-Meyer et al. 2007).

Also, new infrastructure solutions are needed in the communication area. Vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication play an important role to determine the position of the vehicle in the lane and the presence of obstacles, also to monitor the charging process. In 1999, Federal Communication Commission (FCC) allocated 75 MHz of spectrum at 5.9 GHz to be used exclusively for V2V and V2I communication in the U.S. called Dedicated Short Range Communication (DSRC) (Federal Communication Commission 1999). DSRC technology is the preferred solution because it provides fast network acquisition, low latency, high reliability when required, priority for safety applications, interoperability and security and privacy (U.S. Department of Transportation 2012). Even though ad hoc network is a mature problem in the communication field, and several solutions already exist, there is still a need for research that evaluates how the network performs in terms to latency, bandwidth, such that no important information is lost, the control strategy behaves as expected and the system does not become a threat due to miscommunication.

4 International Standards

Currently there exist several commercial stationary charging technologies, most of them are incompatible with each other because the absence of standards by the time they were developed. There are several active groups working now in standardization of stationary wireless charging, as SAE J2954 and UL 2750. And other related standards as SAE J2847/6, SAE J2931/6 and SAE J2836/6 (Taiber 2013). Currently IEC subcommittee TC69 is working on developing a new standard for EV wireless power transfer systems, which is intended to be published as IEC 61980 (IEC 2013).

The topics to standardize in performance are: Alignment methods, interoperability, frequency, power levels, location of the coils in the vehicle. In terms of safety: Obstacle detection, communication, magnetic field levels, maximum temperature, and electric shock, among others (Schneider 2013). Recently, This IEEE Standards Association Industry Connection Activity approved a working group for pre-standardization in dynamic wireless charging; these efforts address the range limitation of EV as well as the cost aspect of the vehicle energy storage and complement the current standardization activities of the SAE J2954. This is currently the only group working on DWC; this activity will be expected to be finalized by June 2015 (Taiber 2013).

5 Summary

A review of the wireless power transfer concepts for EVs was presented. This paper investigates the technology challenges to transition from stationary to dynamic wireless charging. The purpose was to present the key technological components that need to be analysed in order to provide an overview of the problem of dynamic charging and to determine the feasibility of implementation. For that purpose, power transfer challenges, safety issues and infrastructure needs topics were addressed and discussed; in addition, an overview of the standardization activities for stationary and dynamic wireless charging was presented.

References

Ahn W, Jung S, Lee W, Kim S, Park J, Shin J, Kim H, Koo K (2012) Design of coupled resonators for wireless power transfer to mobile devices using magnetic field shaping. In: 2012 IEEE international symposium on electromagnetic compatibility (EMC)

Merriam-Webster (2013) Antenna. (March 2013) http://www.merriam-webster.com

Boys J, Covic G (2012) IPT fact sheet series: No.1—basic concepts. In: Qualcomm, 2012

Covic G (2013) An introduction to wireless power transfer: past, present and future directions, pre-conference tutorial. In: Conference on electric roads and vehicles (CERV), Utah

Dimitrakakis GS, Tatakis EC (2008) Investigation of high frequency effects on layered coils. In: Power electronics and motion control conference
Dixon J, Moran L, Rodriguez J, Domke R (2005) Reactive power compensation technologies: State-of-the-Art review. Proc IEEE 93(12):2144–2164
Djuknic G (2003) Method of measuring a pattern of electromagnetic radiation. U.S. Patent 6657596
Federal Communication Commission (1999) FCC allocates spectrum in 5.9 GHz range for ITS uses. Press release Oct 1999
Green II RC, Lingfeng W, Mansoor A (2011) The impact of plug-in hybrid electric vehicles on distribution networks: a review and outlook. Renew Sustain Energy Rev 15(1):544–553
Hai J, Brazis P, Tabaddor M, Bablo J (2012) Safety considerations of wireless charger for electric vehicles: a review paper. In: 2012 IEEE symposium on product compliance engineering (ISPCE), pp 1–6, 5–7 Nov 2012
ICNIRP (2010) Guidelines for limiting exposure to time varying electric and magnetic fields
IEC TC69 (2013) Electric road vehicles and electric industrial trucks. Electric vehicle wireless power transfer systems
IEEE (2006) Standard for safety levels with respect to human exposure to radio frequency, IEEE C95.1-2005, 19 April 2006
Intertek Laboratories (2012) Wireless power. Cutting the cord in today's mobile world
Kazmierkowski M, Moradewicz A (2012) Unplugged but connected: review of contactless energy transfer systems. IEEE Ind Electron Mag 6:47–55
Kesler M (2012) Wireless charging of electric vehicles using strongly coupled resonance. National Electric Transportation Infrastructure Working Council, Atlanta
Kintner-Meyer M, Schneider K, Pratt R (2007) Impacts assessment of plug-in hybrid electric vehicles on electric utilities and regional U.S. power grids: part 1: technical assessment. In: 2007 Electric utilities environmental conference
Kurs A, Karalis A, Moffatt R, Joannopoulos JD, Fisher P, Soljačić M (2007) Wireless power transfer via strongly coupled magnetic resonances. Science (6 July 2007) 317(5834):83–86. Published online 7 June 2007
Landerman P (2012) Wireless power transfer to moving vehicles. Submitted as coursework for PH240. Stanford University, Fall
Lorico A, Taiber J, Yanni T (2011) Inductive power transfer system integration for battery-electric vehicles. In: Proceedings sustainable automotive technologies conference
2012 Leaf owner's manual, Nissan Motor Co., Ltd., Publication no. OM2E-OZZEOU2, April 2012
Miller J (2012) Wireless plug-in electric vehicle (PEV) charging. In: 2012 U.S. DOE hydrogen and fuel cell programs and vehicle technologies program annual merit review and peer evaluation meeting, May 2012
Morrow W, Lee H, Gallagher K, Collantes G (2010) Reducing the U.S. transportation sector's oil consumption and greenhouse gas emissions. Harvard Kennedy School, Cambridge
Musavi F, Edington M, Eberle W (2012) Wireless power transfer: a survey of EV battery charging technologies energy conversion congress and exposition (ECCE), IEEE
NY ISO (2009) Alternate route: electrifying the transportation sector. Technical report
Onar O (2013) A wireless power tranfer system with active rectification on the receiver side. In: Conference on electric roads and vehicles (CERV), Utah
Pantic Z, Sanzhong Bai, Lukic SM (2009) Inductively coupled power transfer for continuously powered electric vehicles. In: IEEE Vehicle power and propulsion conference, 2009 (VPPC '09), pp 1271–1278, 7–10 Sept 2009
Qiang H, Huang X, Tan L, Ji Q, Zhao J (2012) Achieving maximum power transfer of inductively coupled wireless power transfer system based on dynamic tuning control. Sci China Technol Sci 55(7):1886–1893
Sadiku M (2001) Elements of electromagnetism. Oxford University Press, Inc., New York
Schneider J (2013) Emerging international standards, roundtable. In: Conference on electric roads and vehicles (CERV), Utah

Slezak L (2013) U.S. Department of energy update. In: Conference on electric roads and vehicles (CERV), Utah

Taiber J (2013) Electric vehicle wireless power transfer. Industry connections activity initiation document (ICAID). Version: 1.2, 12 Feb 2013

US Department of Energy (2013a) EV-everywhere challenge blueprint, Published 31 Jan 2013

U.S. Department of Energy (2013b) Plug-in electric vehicle handbook for public charging station hosts

U.S. Department of Transportation (2004) How to build an interstate. In: 50th anniversary of Eisenhower interstate highway system

U.S. Department of Transportation (2012) Dedicated short range communications. ITS Research fact sheets, Nov 2012. http://www.its.dot.gov

U.S. Energy Information Administration (2012) Energy in brief: How dependent are we on foreign oil? Published 13 July 2012. http://www.eia.gov

Witricity (2012) Witricity Technology: The Basics. Online: http://www.witricity.com

Wu H (2012) Wireless power transfer for electric vehicles. Energy dynamics laboratory (EDL). Utah State University Research Foundation (USURF), Utah

Xin D, Yue S, Chunsen T, Zhihui W, Yugang S, Yanling L (2010) Dynamic parameters identification method for inductively coupled power transfer system. In: 2010 IEEE international conference on sustainable energy technologies (ICSET), pp 1–5, 6–9 Dec 2010

Virtual Mock-Up Hybrid Electric Vehicle Development

V. Croitorescu, M. Oprean and J. Anthonis

Abstract The hybrid electric and electric mobility constitutes a revolutionary technology for the automotive industry. In response to the stringent regulations and requirements enforced, vehicle manufacturers are developing new strategies, using hybrid electric or electric powertrain solutions. In order to reach the goal of using alternative powertrain solutions, it is important to integrate different devices from the early development stages and to optimize their behaviour. However, with a minimum of one electric machine, two different energy storage devices, and one transmission architecture, a hybrid electric powertrain triggers more concerns surrounding energy flows. The virtual mock-up hybrid electric vehicle was developed following the "V" cycle. Three basic steps during which the mechanical systems are developed in conjunction with the electronic systems characterize the virtual mock-up development. Starting by choosing the powertrain architecture it is needed to select the components and the control system design. In the end, the validation for the obtained mock-up is required. The powertrain components were integrated in the mock-up virtual hybrid electric vehicle to study their behaviour during a predefined driving cycle. In order to validate the mock-up vehicle, a real time simulation and testing rig has to be used to evaluate and improve interaction of control systems on several levels, indicating interaction problems between several virtual and physical components during an early stage of the system development process.

V. Croitorescu (✉) · M. Oprean
Automotive Engineering Department, University Politehnica Bucharest, Splaiul Independentei 313, 060042 Bucharest, Romania
e-mail: valerian.croitorescu@gmail.com

J. Anthonis
Engineering Serivices, LMS International, Interleuvenlaan 68, 3001 Leuven, Belgium

J. Wellnitz et al. (eds.), *Sustainable Automotive Technologies 2013*,
Lecture Notes in Mobility, DOI: 10.1007/978-3-319-01884-3_31,

1 Introduction

Concerning new European Regulations, the vehicle research focuses on unconventional powertrain solutions and the automotive manufacturers are developing an array of many promising technologies. As the automotive industry is progressing faster than ever, it is needed to develop systems that can ensure the new regulations demand to reduce climate change by improving fuel economy. The main interest for vehicle manufacturers is to develop new and innovative products that have to meet also the most stringent customers' requirements and to comply with the strict regulations with regard to pollution.

The main objective for a hybrid vehicle powertrain consists in increasing global efficiency in terms of fuel consumption and pollutant emissions. This can be reached by optimizing the behaviour for powertrain components. Pollution control devices used on vehicles cannot eliminate the car's CO_2 emissions, they only can reduce them partially. Less CO_2 emissions and better fuel consumption will be obtained by combining more control devices. Although, many strategies for improving fuel consumption and pollutant emissions already exists, being frequently used. They refer at not only engines downsizing, alternative fuels and cylinders deactivation, but they take into account electric mobility (Croitorescu 2008). With the electrification of road vehicles, several new design-engineering challenges emerge. New components and subsystems such as batteries and electric drive systems are introduced. The performance parameters such as energy consumption get a new meaning because of the intrinsic range implications. The specific nature of these components and their vehicle integration requirements imposes to critically investigate the design engineering process itself and explore new tools and approaches.

Therefore, the hybrid powertrain development consists in bringing together other devices and new control approaches besides the specific hybrid technology.

The vehicle development process, within respect to the above mentioned few requirements contain more than one development level for designing the model. The primary level may be used for developing and optimizing the control strategies. Another level may include only partial physical aspects, trying to find an optimal balance between mathematical algorithms and physical data. Using all the previous levels it is mandatory to add a more developed level as a need for the detailed physical subsystems.

More frequently, the virtual mock-up vehicle is used to simulate different processes during different cycles of functioning. Being a virtual device of a full-sized vehicle, it is able to provide at least part of its functionality and enables testing its architecture. Therefore, automotive industry is using virtual mock-ups vehicles as part of their development process more often.

2 Virtual Development Approach

Most of the mechatronic systems are highly complex and using simulation tools for their development is more than necessary. Such systems have to follow a continuous development process that includes several stages. For some of the stages it is needed to use more than one simulation platforms to perform in deep analysis before developing the final mock-up. However, a common practice is to overcome these analysis stages in favour of developing the next stages. Nevertheless, sometimes it demonstrates that skipping virtual development, the costs and the time to the market increase. Due to the complexity of simulation tools, a system can be entirely designed using the virtual environment. When the optimal solution is achieved, the real mock-up can be developed and the preliminary results can be validated.

The virtual mock-up vehicle was developed by taking into account the different design and development stages using multiple simulation softwares. There were used two different modelling and simulation softwares—LMS.Imagine.Lab.AMESim and MATLAB-Simulink.

Developing the model in AMESim consists in linking submodels from various software libraries. The submodels are shown as icons. After linking the icons (which represent each component of the vehicle/powertrain) in sketch mode and choosing the proper submodel in the submodel mode, the parameters are able to be set. Each icon covers a fragment of C code, written using the specific equations for the system.

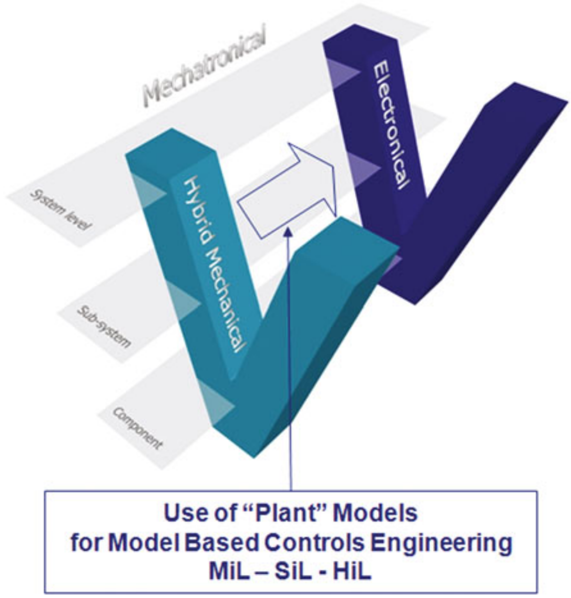
Developing the control using Simulink refers to the control unit development. The control unit is used as the electronic control unit of the vehicle. It allows to define and to control all the signals and the associated parameters of the model. The signals are time variables, while the parameters are helping to define the dynamic behaviour of the system. Both the signals and the parameters can be defined based on their data type, dimensions, complexity and initial status. The simulation using Simulink consists in using mathematical algorithms that are able to determine system dynamics performances.

Working with both simulation platforms, AMESim and Simulink, generates the design of a co-simulation interface. Co-simulation procedure consists in using both platforms and their solvers to satisfy the requirements for developing the complex virtual mock-up vehicle. Having the vehicle model developed in AMESim, the optimal approach is to import the Simulink control unit in the AMESim sketch as an interface for co-simulation (Croitorescu 2012).

3 Powertrain Development Phases

The virtual mock-up development follows the V-cycle. The V-cycle is used for simplifying the understanding of the complexity associated with systems development to detailed, rigorous development lifecycle models, including system level, sub-system level and component level. It is characterized by three basic stages based on the mechanical systems and the electronic systems development (see Fig. 1). The mechanical system development will continually communicate with the electronic system development. Developing hybrid electric powertrain contains simple components development, which combined makes subsystems, while combining the sub-systems makes final systems.

Fig. 1 V-cycle basic stages



The powertrain development following V-cycle consists in three main stages: chosing the powertrain architecture, selecting the powertrain components and the control system, and seting the verification and the validation procedure (see Fig. 2). Each of the development phases are part of the development cycle.

3.1 Powertrain Architecture

It is essential from the outset to achieve the hybrid powertrain architecture and to set its components' parameters that are needed for the further energy management analysis. The needed powertrain architecture has to complete the maximum fuel economy and the lowest values for the harmful emissions. In addition, vehicle dynamic performances should be higher. The chosen powertrain architecture is the post-transmission parallel hybrid electric one, equipped with a continuous variable transmission.

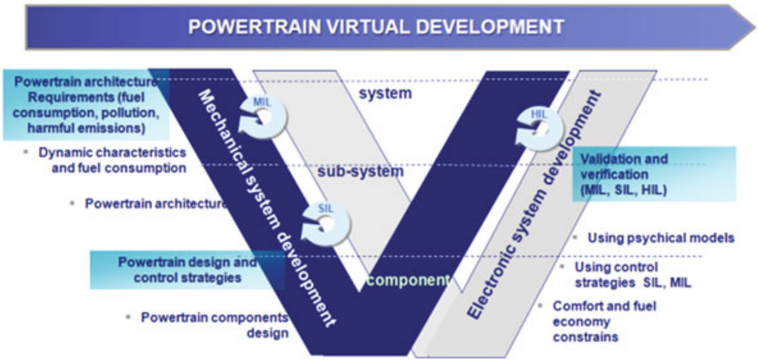


Fig. 2 The detailed V-cycle

3.2 Powertrain Components and Control System

The powertrain containing components are added starting from a basic configuration, in which the virtual mock-up hybrid vehicle is as simple as possible. The components are added one by one. After each of the components is added, the simulation has to be performed and the model should properly work, after all the verifications needed.

The virtual vehicle operation must follow a predefined driving cycle, followed by the virtual driver. The internal combustion engine and the electric motor are providing the power, taking their energy from the fuel tank and from the battery package. The transmission allows transferring the torque to the wheels. The wheels are part of the vehicle, which is more a mathematical representation of the dynamic behaviour of a real vehicle.

The control systems include the electronic control unit and the simulation platforms that are used to run the simulation. The electronic control unit was developed in Simulink. The electronic control unit contains two different working levels. The first level estimates and calculates the power demand, based on the current demand. This decides when the driver should ask for acceleration, deceleration or constant speed for cruising. The second level switches between the six different operating modes, taking into account the power demand, the vehicle status, the driver's behaviour and the requirements of the each operating mode.

The operation modes and the control devices are defined as part of the detailed powertrain design. Defining the operation modes for the hybrid powertrain must be prior to determining the architecture, being necessary to follow these operation modes all through the design stages.

3.3 Verification and Validation Procedure

The verification and the validation of the mock-up will be possible using a real time simulation platform and several control strategies. For validating each of the vehicle components, it is needed to develop test benches for each of them and to set the proper configurations. Starting from the hardware-in-the-loop test bench requirements and from the need to link real components with mathematical models, the synchronization between them is mandatory. Plenty of solutions are available to allow the proper functioning for the real time simulation, any solution being helpful.

4 The Virtual Vehicle Model

The developed virtual vehicle model followed the previous constrains and it can be used for different scenarios, including optimizing and changing different components. It is the result of the previous presented approach (Fig. 3). The virtual mock-up vehicle represents the debut of a more complex virtual vehicle. The integration of several sub-models is a mandatory and available solution for further energy management analysis. For each of the powertrain components it is necessary to attach a thermal model and a cooling system in order to estimate the power consumption. The thermal models are investigated in respect with its geometry, material made of and functional behaviour (Debal 2009). Some results after simulation for both the simple and the complex model were presented in related papers of the first author (Croitorescu 2008, Croitorescu 2012).

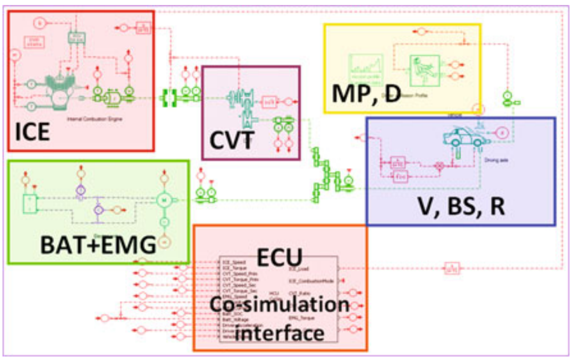


Fig. 3 The virtual mock-up vehicle—sketch (*ICE* internal combustion engine, *CVT* continuous variable transmission, *MP* mission profile, *D* driver, *BAT* battery package, *EMG* electric motor/generator, *ECU* electronic control unit, *V* vehicle, *BS* braking system, *R* road)

5 Conclusion/Discussion

During the development processes of a vehicle, conflicts of objectives often occur between the design of a vehicle and its requirements economic, in terms of performances, marketing and economically. The virtual mock-up vehicles allow a realistic investigation very early in the vehicle development process, using the latest technologies in virtual reality (Anthonis et al. 2011). The virtual mock-up vehicle is a sum of information that describes vehicle's behaviour. The model configuration, including architecture and parameters, can be easily changed and updated any time is necessary. The designed model represents the basic model equipped with specific elements of a hybrid drive that can be used for further investigations of power losses and improvement in terms of energy behaviour. The strategy underlying the design of the propulsion system includes compliance dynamic performance and fuel economy proposed in conjunction with providing comfort and reducing manufacturing costs. The approach presented in this paper covers the V-cycle development phases in order to accomplish the functionality of a real vehicle.

Acknowledgments The present paper is mainly a part of the first author's PhD thesis, being accomplished during his training period with full support of LMS International, Engineering Services.

References

Aarnoutse P, Kenda R, Van der Auweraer H, De Bruyne S, Moncel T (2010) Hardware in the loop testing of a CVT for a hybrid vehicle. In: Virtual powertrain conference

Anthonis J, Santos F, Croitorescu V, Van der Auweraer H (2011) Multiscale thermal and NVH models for EV/HEV integration of SR-based Drivetrain. In: Proceedings of virtual powertrain conference, Pune, India

Croitorescu V (2012) Modern drives using unconventional energy storage devices—hybrid electric vehicles. PhD Thesis, Bucharest, Romania

Croitorescu V, Maciac A, Oprean M, Marin A, Andreescu C (2008) Hybrid powertrain simulation. In: Proceedings of industrial simulation conference, Lyon, France

Debal P, Faid S, Bervoets S, Tricoche L, Pauwels B (2009) Development of a post-transmission hybrid powertrain. In: EVS24 international battery, hybrid and fuel cell electric vehicle symposium, Norway