Concept of an Electric Taxi

for Tropical Megacities

Sebastian Bender[1,2], Vinoth Pannirsilvam[1], Raymond Khoo[3], Pablo López Hidalgo[1,2], Maximilian Tschochner[1,2],
Pratik Sheth[1,2], Sebastian Osswald[2], Daniel Gleyzes[1], Heong Wah Ng[3], Markus Lienkamp[2]
[1] TUM CREATE Ltd.: RP4 & RP9, Singapore
[2] Technische Universität München: Lehrstuhl für Fahrzeugtechnik, Germany
[3] Nanyang Technological University: School of Mechanical and Aerospace Engineering, Singapore

Abstract — **In this paper, the development process of an electric taxi concept is presented. As future transportation modes will change, new vehicle and transportation concepts will be necessary. In Singapore, where taxis are a major part of the public transportation system, electric mobility is a major focus of current research. The research program TUM CREATE focuses on electric mobility to build a fully electric taxi called EVA. The aim is to demonstrate how the next generation of public mobility will look like. After reviewing the overall concept of the vehicle, the development process of selected topics is shown. This includes the packaging, the composite vehicle structure and the chassis integration. Furthermore, the development of the high- and low voltage system, the functional development and the infotainment system is covered.**

Keywords—electric vehicle concept, prototype development, BEV, megacity, taxi, Singapore

I. INTRODUCTION

From 7.2 billion today to 9.6 billion people in 2050, the world's population will increase by 33 % based on the latest world population predictions by the United Nations [1]. In 2011, 77.7 % of the world's population in more developed countries[1] lived in urban areas. In Germany it accounted for 73.9 % and in Singapore for 100 %. At this time, the urban population in Germany is more than ten times higher than the total population of Singapore [2]. By 2050, the total number of the urban population will increase to 85.9 % worldwide and in Germany to 81.8 %. These changes will also have a major impact on transportation and mobility services [3].

Millennials[2] from Germany already show an affinity towards sustainable transportation. A high quality of life and sustainability are more important rather than luxury cars as a status symbol. This is further demonstrated by their consumer behavior when it comes to the choice of daily transportation [4]. In Germany the younger generation uses car sharing options more often [4] [5]. Since taking a taxi is cheaper and more convenient, car sharing is not common in Singapore, thus the usage of public transportation is higher [6], which is why the transportation systems should be fast and reliable [7]. Both tendencies lead to new transportation opportunities in the future which Singapore sees in the development of their public transportation system including taxis [8].

To solve challenges of future mobility concepts TUM CREATE, a research program based in Singapore, developed an innovative vehicle concept named EVA. EVA is a fully electric taxi concept built for tropical megacities like Singapore and gives an idea about how future mobility could look like in the next 10 years. This development comprises of many challenges such as availability of manufacturing facilities, development methods and know-how acquisition: There is no established automotive industry in Singapore. In this paper, parts of the interdisciplinary research and development process of the project is presented ranging from concept decisions to specific topics such as functional development and the structural analysis of the Carbon Fiber Reinforced Plastic (CFRP) body structure.

After the introduction, the research entity TUM CREATE and Singapore are described in section II, followed by section III in which a detailed overview about the vehicle concept is given. In section IV to VI, the detailed development of the vehicle package, body structure and chassis system is shown. The high voltage (HV), low voltage (LV) and infotainment systems are presented in the chapters VII to X. The paper concludes with the description of the assembly process and a conclusion of this project.

II. BACKGROUND

A. *TUM CREATE and project EVA*

It is the goal of the National Research Foundation (NRF) to bring together international research institutes to partner with Singapore's universities, hence the CREATE (Campus for Research Excellence and Technological Enterprise) was founded [9]. TUM CREATE, a collaboration between the Nanyang Technological University (NTU) in Singapore and the Technische Universität München (TUM) from Germany, was established in 2011. The main targets of this collaboration are to find next-generation battery chemistries and systems, models for electric mobility infrastructure as well as electric vehicle (EV) concepts and components for tropical megacities.

---

[1] *"More developed countries comprise all regions of Europe plus Northern America, Australia/New Zealand and Japan."* [1].

[2] People born in the early 1980s to early 2000s.

Today, TUM CREATE has more than 130 international researchers and engineers working in ten different research projects (RPs). The development of an electric vehicle codenamed “EVA” was the first overarching project with participation of almost all RPs. The interdisciplinary two year project gave 40 students and young researches the opportunity to learn automotive technology in a hands-on project and to showcase the developments and innovations of all RPs in one drivable prototype. In addition, EVA will be used as a testing platform for future research topics in the automotive sector. The goal was to have a zero emission vehicle which can go into series production in 2020.

B. Singapore

Singapore is a city-state with 5.3 million inhabitants and is situated 142 km north of the equator. This causes a year round average temperature of 27 °C and a minimum humidity of 83 % [10]. As a city-state, it is the ideal testing environment for electric vehicles as distances travelled are small and the temperature does not fall below 21 °C [10] [11]. Singapore has no local automotive manufacturing industry beside sales agents and maintenance workshops but it houses logistic hubs for almost all original equipment manufacturer (OEMs) and Tier 1 suppliers of automotive components for Southeast Asia [12]. The local manufacturing companies are not able to offer all services needed to build up automotive prototypes, e.g. for precision welding of bigger structures or glass production.

In the 2013 the master plan of the Singaporean Land Transport Authority (LTA) was a shift in focus towards public transportation and the decrease in reliance on private transportation. 63 % of all peak hour[3] trips were made by public transportation in 2013. The LTA will increase this rate to 75 % in 2030 [8]. In order to promote more sustainable and greener travel, car and taxi owners of “environmentally friendly“-cars receive a 40 % discount on their Additional Registration Fee (ARF). It is also stated that for a “smooth-flowing traffic” they will further “restrain private car travel” [8]. To develop the public transport sector further includes the development of the taxi system.

27,516 taxis (as of October 2013) from seven taxi companies serve people in Singapore as a mode of transportation [13]. The total costs of ownership (TCO) for cars in Singapore are higher than in other countries, because on top of the selling price the ARF and Certificate of Entitlement (COE) fee is added. For example in November 2013 an Audi A3 1.4 TFSI (Ambition) cost S$ 199,150 in Singapore [14]. At the same time this car cost about S$ 41,850 in Germany [15]. Compared to other large cities, Singapore has one of the highest densities of taxis per person. The flag-down fare and the costs for the first kilometer of a taxi trip are cheaper than in other big cities as seen in Fig. 1.

Since January 2013 the LTA enforces taxi companies to have 65-70 % percent of their taxi fleet on the road. This will be increased to 80-85 % by 2015. Today it is required that 70 % of a taxi company’s fleet achieves a minimum mileage of 250 km a day, which will be increased by 2015 to 85 % [8]. This translates to around eight to nine hours of driving per day at six days a week. In 2010, taxis with one driver (one-shift taxis) drove in average 347 km a day. Taxis with more than one driver (two-shift taxis) made 260 km per shift and 520 km a day [16]. Two-shift taxis are always on the road, stopping only for washing, refueling or a driver change.

In average 6.5 out of 100 accidents per year involves a taxi. This means in a lifetime of a taxi (8 years) there is a 52 % chance of an accident per vehicle [17]. It is not mandatory for a Singaporean taxi driver to have child seats with them; the passengers below 1.35 m height are allowed to sit in the taxi without a child safety restraint system [18].

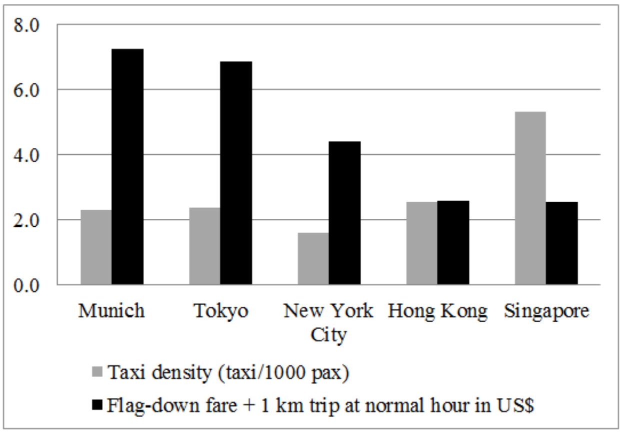

Fig. 1. Taxi density and flag-down fare for different cities [19] [20] [21] [22] [23] [24] [25] [26] [27].

C. Why focusing on a taxi?

One of the main reasons to decide for developing an electric taxi was the high leverage effect of CO2 emissions in Singapore. Taxis account for 3 % of all vehicles in Singapore, but they are responsible for about 15 % of the overall mileage driven [16], [28], [29]. Consequently, if all taxis are zero emission vehicles, the CO2 emissions could be reduced depending on the future methods of electricity production[4]. Furthermore, the planned measurements of the Singaporean government underline the trend towards an environmentally friendly way of public transportation, which TUM CREATE follows and supports with the development of EVA as electric taxi.

Like all OEMs of electric vehicles, TUM CREATE faced the current challenges of battery electric vehicle (BEV) limits. The targets to accomplish are a maximum daily range of 520 km for Singapore’s taxis and a reasonable charging time. Refueling a diesel taxi requires only a couple of minutes, while charging a current state-of-the-art BEV can take up to 7 hours[5]. This is a major disadvantage for EVs. Other premises for a

---

[3] From 6 am – 11 am and 5 pm - 12 midnight daily, except for weekends, public holidays and their eves.

[4] Fuel mix for electricity generation 2011 in Singapore: 18.4 % petroleum products, 78.0 % natural gas, others 3.6 % [43].

[5] Duration of a single charge of a Nissan Leaf battery (24 kWh) [42].

reasonable taxi concept are the cost factors. The required investment of the taxi company for a future taxi the taxi vehicle, the earnings of taxi drivers and the rates passengers are willing to pay for their taxi trip need to be lower than the ones of current taxis as in incentive to change to electric mobility.

These challenges of cost efficiency, driving range and charging time give TUM CREATE the opportunity to overcome some of the biggest hurdles of future electric transportation.

III. CONCEPT

A. *Development process*

As EVA is purpose-built as a BEV, the design differences to internal combustion engine (ICE) vehicles could be considered from the beginning. The overall design process started with the analysis of Singapore's taxi system. Beside legal requirements, the user behavior of taxi drivers and passengers was investigated in a fleet test and surveys. In subsequent workshops, expert groups decided about specific vehicle characteristics and parameters. Out of the first sketches, concept models, legal requirements and benchmarks the initial car concepts were developed (section IV).

B. *Overall concept and dimensions*

The decision to build a standard car rather than 2- or 3-wheel vehicle was made based on the driving stability, passenger safety, comfort and on the prospect of transporting more than two passengers with luggage. An internal study determined that 95 % of the daily taxi trips are with less than four passengers. Trips with only one passenger accounted for 64 % of all trips. The final passengers' ergonomics and space requirements were deducted from the outcomes of investigations in a seat box: the taxi was designed with three passenger seats, one in the front and two in the rear, all facing the driving direction. The space gained in the interior increases the comfort level, which was a main design criterion. We set the overall dimensions to 4.32 m x 1.79 m to house the occupants comfortably and minimize the overhangs while still considering the style requirements and benchmark sizes for crash safety in order to decrease the used space. This is important in megacities like Singapore where small parking spots and traffic jams call for short cars. The height of 1.68 m is due to the battery case, which is installed under the car and adds additional 200 mm in height. This increases also the height of the cabin floor and provides an easy entry especially for elder passengers. The overall size of EVA implies that it is considered as a C segment vehicle according to the euro market segment classifications [30].

C. *Battery and charging system*

The energy storage system (ESS) used in EVA should satisfy the requirements of taxis in Singapore in terms of range, the associated energy demand while requiring only a short time for recharging at the same time. Different concepts were evaluated in detail with respect to the provided energy, their impact on the vehicle design and energy consumption, feasibility of the required infrastructure, costs and possible revenue during the service life of the taxi. The selected concept was a battery with a fast charging capability. This allows the vehicle to cover the required range, while being charged once during a taxi shift and at the shift end in 15 min. The selection of fast charging as charging method entails the necessity for a high power capability of the battery. In order to satisfy the previously mentioned vehicle requirements under consideration of safety buffers and the desired end of life battery capacity, the battery was designed to have a total energy capacity of 50 kWh. This battery consists of 216 Li polymer cells, with a capacity of 63 Ah each. The cells are arranged in 18 stacks connected in series, so that two cells are respectively connected in parallel and 108 in series. In order to allow a range of 200 km with 15 min of charging time, a 3C-charging strategy[6] is used for the battery. This leads to a required power of 162 kW and a charging current of 360 A. This fast charging strategy causes high temperatures on the vehicle's charging system and especially in the battery, which might lead to a reduction of the battery life time. Therefore, a special cooling strategy for the battery was designed, as to cope with the high temperatures and avoid a diminishment of the battery life. The fast charging interface is composed of two sockets connected in parallel to deal with the high currents during charging. Additionally, it is possible to charge the vehicle with an integrated wireless charging system in the rear of the car (Fig. 3) or a Type 1 plug (AC slow charging).

D. *Drivetrain*

A single electric motor in the front was chosen to power the vehicle. Due to high comfort requirements wheel hub motors were not considered, because of their high unsprung masses. The detailed development process is stated in section VII. A Small combustion engine as range extender was dismissed as an option because of the local zero emission requirement. A fuel cell doesn't have a business case as previously mentioned. More information about the chassis and suspension system will be given in section VI.

E. *Interior*

For an electric vehicle a middle tunnel is not required due to the omission of the exhaust system. To further increase the comfort level a flat floor in the passenger cabin was realized. Hence, the passengers on the rear bench can easily move from one side to the other in case it is only possible to enter or exit on one side.

The air conditioning (A/C) system, which is one of the biggest energy consumers in a vehicle, was investigated to save energy and guarantee a longer driving range. Therefore, an individual cooling concept is realized [31] and the air volume of the interior minimized with a wall between passenger cabin and luggage compartment. This partitioning eliminates the air exchange when the trunk lid is opened and increases the torsional stiffness of the car which leads to better driving

---

[6] A C-rate is the measure of the rate at which the battery is charged (or discharged), relative to its maximum capacity. For example: for a 5 Ah rated capacity battery, 1C-rate is 5 A; C/5-rate is 1 A; 2C-rate is 10 A; etc. [44].

behavior of the vehicle. To tackle the issue of lacking a proper child restraining systems in taxis (section II), TUM CREATE developed an innovative seat concept. The seat considers ergonomic aspects with the possibility of conveying children from nine months to twelve years old safely in EVA without any additional component that need to be carried around. Thus, a foldable child seat in the co-driver seat and a child booster on the rear bench were developed and integrated as seen in Fig. 2.

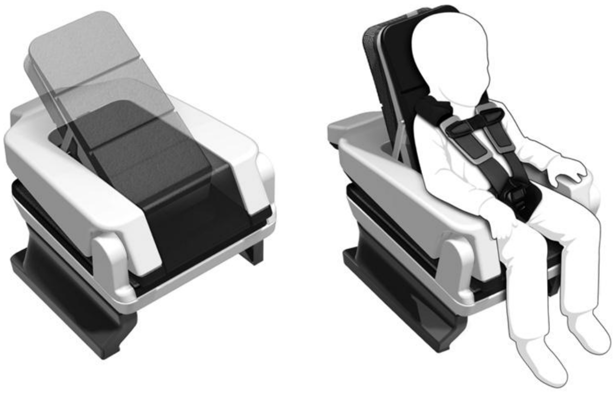

Fig. 2. Conversion of the front passenger seat into a child seat.

F. Exterior

With the advantage that all passengers have the same comfort level when entering the vehicle, a standard door concept was chosen. To save weight the doors are made out of CFRP with integrated composite crash beams. The poly carbonate windows in the rear doors and the trunk lid further reduce the vehicle's weight. The angles of the windshield and trunk lid were chosen to be steep to decrease the amount of sun radiation entering the car, thus less energy is needed to cool down the air inside the car. The allowed speed limit in Singapore is 90 km/h, while the average speed during peak hours on express ways is 63.1 km/h.

EVA has an electronically limited top speed of 111 km/h. The results of a fleet test showed that the average speed of a taxi is 21.3 km/h, which is why it was decided that the aerodynamics are not a main design criterion. Nevertheless, to keep the drag resistance at a minimum, a rear diffuser and a well-defined separation edge at the rear spoiler and side were designed.

G. Material concept

The reasons for the decision to produce the vehicle structure out of CFRP are described in section V. Due to the high corrosion potential of carbon fiber with metals all self-produced parts are made of stainless steel (SS304 or SS316) or anodized aluminum to guarantee their functionality over the vehicle life time. Some geometrical complex parts e.g. air distribution channels or light housings are made out of polyamide in a rapid prototyping 3D printing process. The bracketry is mainly made from sheet metal or milling parts out of aluminum or stainless steel.

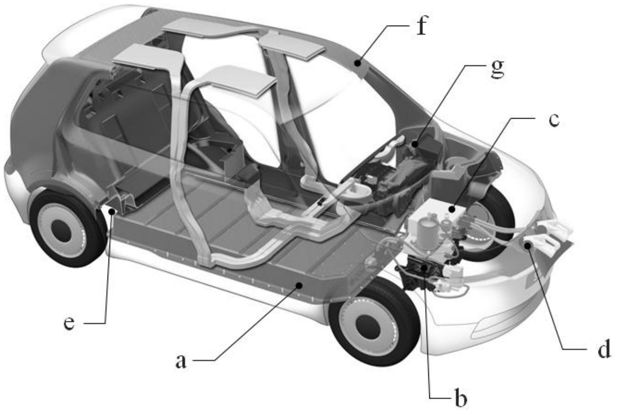

Fig. 3. Main components of EVA: a) battery, b) electric motor, c) HV components, d) charging sockets, e) wireless charging system, f) composite structure, g) A/C system

IV. PACKAGE

The packaging of the vehicle is the positioning of all components in a 3D computer aided design (CAD) program, in this project CATIA V5 was used. The total package model of a vehicle is also called a digital mock up (DMU) and shows the current progress of the development and is thus an important management tool in this process. It is the basis for other simulations and calculations such as multi body simulations, finite element analysis (FEA) or for the determination of the center of gravity (COG).

The packaging process is divided in five phases, which align with the overall vehicle development process [32]. The first two phases, the research & product planning and setting of main goals, were described in section III.

The goal of the third phase is the basic layout of the vehicle influenced by styling and legal requirements. Therefore box models, which represent the main components with tolerances, were implemented into the CAD system. A basic calculation model was developed in MS Excel to verify the COG in longitudinal and lateral direction. This model used the same main components with corresponding positions in the CAD program.

The traction battery (500 kg) was allocated between the vehicle axles because it is the safest position in the car. As the battery shifts the COG of the vehicle to the rear, the electric motor and all HV-elements are positioned in the front (Fig. 3). Hence an axle load distribution of 55:45 (front to rear) was established. Due to the small size of the electric motor compared to an ICE there is no detriment in occupant space or turning radius of the vehicle. The main advantages for a front wheel driven car are a higher applicable regenerative braking torque and a more voluminous luggage compartment.

Obtaining the main dimensions of the vehicle is the target of the fourth phase. In a benchmark analysis passenger vehicles with similar dimensions and taxis were compared. This validated the design and proportions of the DMU.

In the fifth phase, detailed 3D models of the vehicle components are consolidated into a complete DMU which will be used for production of the vehicle. This process considers functional, physical (thermal, mechanical, chemical, etc.), ergonomic and styling requirements.

To correctly identify parts and their assignments, a specific naming system including identification number, author initials and part/assembly name was given to every component in the CAD system. For the virtual design a modified skeleton part approach, as described in [33], was used on a subassembly level. In this approach all mature dimensions, additional information as design surfaces and main geometrical elements are stored in the skeleton, to be used in other parts of the assembly via publications[7]. A product data management system (PDM) was integrated to manage file versions and to facilitate the simultaneous usage by different users.

The calculation model for the COG was refined in terms of the details of components. Additionally, further information such as the specific name, material and manufacturing/ordering status was integrated to use it as a planning tool. To consider important dimensional chains, MS Excel tables were used to link all dimensions and tolerances. Providing a good overview of all coupled dimensions the chain tables simplified the understanding and thus improved the communication with team members. So the lowering of the height above the rear passengers could be managed although it depended on 15 dimensions of different components.

Fig. 4. Front compartment with HV, LV and cooling components.

Another important method was the positioning via 2D allocation sketches realized with MS Visio. These sketches created fast allocations concepts of multiple components under consideration of the connection requirements. The creation and change of concepts were much faster than in CAD, thus saving crucial development time. With this method the positions of the components in the motor bay were defined. The goal was to accommodate all components in the space above the motor, below the bonnet hood and between the two crash elements. To secure the components while driving they needed to be mounted on a lightweight structure. Under consideration of cable bending radii, accessibility and connection to the structure for each component, multiple concepts were sketched and discussed with the responsible persons. The final result was then implemented into the CAD system. The result of this can be seen in Fig. 4.

V. VEHICLE STRUCTURE

A. Assessment of prototype structures

A study of vehicle structure types was conducted to evaluate industry practices and align the concept of the electric taxi vehicle structure. We evaluated and narrowed down the structural types based on manufacturing/tooling parameters and research potential shown in TABLE 1.

Future vehicle structures are shifting towards multi-material constructions. The majority of production vehicles on the road are still based on steel unibody and in the premium end based on aluminum unibody or space frame constructions. In the premium performance segment some cars feature light weight carbon composite constructions. Battery electric vehicles show a great opportunity to implement lightweight design to offset the weight penalty of the battery pack (e.g. BMW i3, Tesla Model S).

TABLE 1. STRUCTURAL TYPE RATINGS WITH MANUFACTURABILITY AND RESEARCH INNOVATION.

Structural Type	***Manufacturing difficulty / Tooling cost (Cost & effort)***	***Research Potential***
Steel unibody	++++	+
Alumnium space frame	+++++	++
Tubular spaceframe	++	+
Exoskeleton spaceframe	++	++
Composite body	+++	++++
Multi material concept	+++	++++

Manufacturability is a big veto factor, manufacturing quality and tolerances are important for the assembly process to ensure the final structure quality. Tubular space frame has its drawbacks because exterior design panels would still have to be manufactured by a technique which requires mold tooling technology. High tooling costs for metallic stamping excluded the unibody construction from our considerations. Carbon fiber composite constructions offer superior weight reduction and are perfectly suited for producing one-off prototypes. This coupled with engineering support from local firms with carbon composite experience further affirms the choice for CFRP construction.

B. Development and manufacturing process

Selected development criteria have been prioritized for the structural development, namely the functional integration of the design concept, manufacturability, package space for future development, lightweight construction and safety. Strength, stiffness in bending/torsional modes and crash performance were the main requirements of the vehicle structure. International crash standards from EuroNCAP, IIHS and NHTSA were chosen as the benchmark for the structure

---

[7] Geometrical elements which can be used from all other parts.

development (ECE 94/95/32 FMVSS 216a). We followed UNECE regulation standards with the best effort for road worthiness. Standards concerning safety and operational critical measures were given extra priority referring to ECE 11/14/17/23/33/32/94/95/125. The manufacturing method used for CFRP fabrication is a vacuum resin infusion process. The benefits of this process include the ability to produce class A surfaces, large parts, to have no restriction in resin working time and lower mold construction cost.

C. *Structure design by FEA*

With the short timeframe of the project, a concurrent engineering method was employed. Development, definition and requirements of various sub-systems followed a progressive iterative feedback loop process. The vehicle structure development started out with the preliminary package model (H0) which progressed iteratively to (H1) and the final prototype (H2) as shown in Fig. 5. The mechanical properties of the composite material and the structural adhesive were obtained from experimental tests. Hot-wet condition material tests were conducted to ensure mechanical performance under hot and humid tropical environmental conditions. For complete structure simulation, the package and material data were imported to the FEA-simulation tool ABAQUS. Tsai Wu and Tsai Hill criteria were used for the definition of failure [34]. Results as stress concentrations and failure points/areas were analyzed and the changes to the design were implemented in an iterative loop. The changes from H1 to H2 were mostly geometrical optimization without major changes in layup direction and number of plies.

Fig. 5. FLTR: H0, H1, H2 the development phases of the vehicle structure.

During the development multiple auxiliary FEA simulations were conducted on sub-systems to verify that the stiffness, strength and performance are adequate for the desired operating conditions (i.e. seats, door under abuse conditions, aluminum crash structure). Fig. 6 shows an example of an auxiliary FEA simulation.

Fig. 6. FEA contour plots of doors under side impact load.

VI. EVA CHASSIS ENGINEERING

A. *Integration of the suspension system*

EVA's suspension system is based on an existing platform with similar weight and wheelbase to EVA, to reduce the overall development time. The suspension selected utilizes a McPherson strut system for the front axle and a multi-link suspension system for the rear axle. This set up is cost efficient (McPherson) and yet provides good comfort with the combination of the rear multi-link system. In order to reduce the overall rolling resistance of the wheels, Continental e.Contact tires designed for EV's were selected.

The suspension was first converted into point cloud data by using a FARO Laser Arm 3D scanner to scan all the suspension components, including the mounting points for the platform. The point cloud data was then rebuilt into CAD data by means of a combination of 3D scanning software Geomagic Qualify and CATIA. With the CAD model of the complete suspension the kinematics of the suspension such as caster angle, kingpin inclination, scrub radius, camber and toe were determined.

The existing suspension needed to be modified according to the shortened wheelbase. The required spring rates and damping for front and rear suspension based on predefined weight distribution data of EVA were determined with the multi body simulation software ADAMS Car. Based on the simulations, the handling characteristics were found to be stable, meeting the requirements for ISO lane change test, fish-hook manoeuvre and roll over tests. The suspension CAD model was then integrated into the vehicle package as a parameter based model where suspension compression and rebound could be input to see the change in geometry for the suspension as well as the space required for the movement of the individual components.

In order to achieve the optimum spring rates and damping required as calculated from the simulation, an aftermarket 3-way adjustable coil-over suspension strut was integrated. This allowed for the adjustment of the normal level of the vehicle, adjustable damping in rebound, and adjustable damping in compression. The springs can be changed for different rates if required. Hence, the handling characteristics of EVA can be adjusted, even if there are deviations from the predefined weight and handling criteria set early in the design process.

B. *Driveline*

In order to have the highest efficiency and least driveline related losses, the driveshaft angle was fixed at a maximum of five degrees. To reduce torque steer, equal length driveshafts were designed. Splined ends made a reuse of the constant velocity joints from the donor platform possible.

C. *Steering system*

The steering system was carried over from the same platform and modified based on the seating position of the driver in the vehicle. This included adapting mounting points for the steering column and changing the length of the steering column links.

D. Braking system

As EVA is designed as a BEV, there is no vacuum source to power the brake booster. A vacuum pump had to be integrated to produce the required vacuum. A brake booster pressure sensor controls the vacuum pump for optimal operation. All other braking components such as the brake calipers and rotors were carried over without modifications.

VII. HIGH VOLTAGE SYSTEM

The high voltage system comprises of all components and systems whose voltage level is above 60 V DC[8]. This section describes those components as well as the necessary safety measures concerning the HV level. The high power requirements of electric vehicles imply high currents and voltages. As a general safety measure, the voltage in the HV system is maintained as high as possible, so that the current can be maintained at low levels. Besides the increased safety, this allows for smaller cable diameters, reducing the required weight and space in the vehicle. In EVA the nominal voltage of the high voltage system is 400 V during normal operation and 450 V during charging.

TABLE 2 provides an overview of the main components of the HV system. In addition to these components, the HV system is composed of the charging interfaces, the high voltage junction box (HVJB), the climate compressor controller (CCC), and the HV wiring harness. The charging interfaces comprise of the wireless charging system as well as the fast and standard charging plugs. The HVJB acts as the distribution and switching interface among the different components of the HV system. These components were then interconnected to the HVJB and other components by the wiring harness. The components were selected under consideration of their functional requirements, while ensuring the compatibility to other components. Special attention was given to the fulfillment of the requirements on voltage and current ratings. In the cases where the components did not fully comply with the requirements, we worked closely together with the suppliers in order to achieve the desired ratings. This was e.g. the case for the design of the CCC and during the selection process of the plugs for the HV wiring harness.

TABLE 2. MAIN COMPONENTS OF THE HIGH VOLTAGE SYSTEM.

Component	**Specifications**	**Ratings**
DC-DC Converter Brusa BSC624-12	Continous output power	2.8 kW
	Efficiency	94.4%
	Input current (@ 400 V)	7.4 A
Inverter Brusa DMC524	Max. input current (@ 400 V)	207 A
	Efficiency (337.5 V, 79 kW, $\cos\varphi = 0.9$)	97 %
	Continuos output	79 kW
Battery On-Board Charger Brusa NLG 5	Charging capacity	3.3 kW
	Charging current	12.5 A
	Efficiency	93 %

One of the main features of EVA is its super fast charging system, introduced in section III. The 50 kWh EVA battery is charged with 360 A and 162 kW, allowing the battery to be charged to 80 % of its total capacity within only 15 min. Since these ratings are considerably high[9] special measures need to be taken so as to guarantee the safety of the passengers, maintenance personnel and researchers when EVA is driving, in the garage or in case of accident. Among others, Büttner in [35] and Neuhold in [36] have exposed the risks and dangers involving the HV system in electric vehicles. During the development of EVA an assessment of the Automotive Safety Integrity Level (ASIL) based on ISO 26262 was carried out and following measures were taken in what regards the HV system: The HV power supply of the different components can be individually switched in the HVJB, this helps to avoid e.g. a spontaneous acceleration of the vehicle while it is charging. Secondly, the switching relays are in a loop with the crash sensors and the first responder loop; so that in case of an accident the HV power supply of the whole vehicle is automatically deactivated. Furthermore, the service personnel can deactivate the power supply using the low voltage disconnect. If required, specially trained staff can completely deactivate the current supply from the battery, using the service disconnect in accordance with the regulations stipulated in [37].The main components of the HV system are all inherently safe, ensuring a safe discharge of their respective capacitances when the component is disconnected from the HV power supply. In cases the inherent safety of the component is not guaranteed, a special switching strategy guarantees the safe discharge of the capacitances.

VIII. LOW VOLTAGE SYSTEM

A. EVA electronics architecture

The low voltage system includes all electronic systems operating with voltage levels below 60 V. Thus the EVA LV system encompasses all the functional and auxiliary electronics, the real-time communication systems like Controller Area Networks (CAN), and the software programming of the electronic control units (ECUs). However, there are two additional major domains separated into independent topics. These topics are the functional development of the vehicle (section IX), and the infotainment systems (section X).

The electrical architecture of EVA is based on a pyramidal control architecture. At the top level of this architecture is a central control unit (CCU), which is based on a rapid prototype controller called MicroAutoBox II (MABx) from dSpace. Along with this, there are a few other top level controllers i.e. the air conditioning control unit (ACCU), battery management system (BMS) and the fast charging station controller (FCSC). These units all control basic systems that are either safety relevant or drive/stability relevant. Below these are the auxiliary controllers. Each functional location of the vehicle is serviced by an ECU, at the middle level, dedicated to its

---

[8] According to [37] high voltage comprises voltages > 60 V and ≤ 1500 V direct current (DC) for automotive applications.

[9] As a benchmark: The Tesla Model S 85 kWh battery is charged to 80 % of its capacity with 135 kW in 30 min [41].

functioning. These ECUs are interfaced to the various sensors/actuators and connect them to the high level controllers. The LV development of EVA was divided into three areas.

1) *The ECU development and electrical integration*

The ECUs are based on an off-the-shelf family of control units. These control units are augmented by dedicated interface boards to ease the electrical integration into the vehicle. The ECUs are integrated functionally by a serial communication network.

2) *The serial communication network*

The backbone of EVA LV functional integration is CAN based communication busses. The EVA network is divided into multiple busses for functional, safety and security related reasons.

3) *The software development for the auxiliaries*

Software development of EVA mainly focuses on embedded programming for the ECUs. Since all control units are of the same family, a substantial development effort can be common for all the ECUs and so reused. Some of these reused sections include the CAN stack and the I/O drivers interface.

B. *Design challenges and methodology*

Due to the short timeline several non-research oriented parts were taken over from automotive suppliers or other vehicles. This presented new challenges, since parts that are available from state of the art vehicles do not come with a spec-sheet or operating manuals. The parts had to be reverse engineered and characterized before they could be interfaced into the vehicle.

The methodology applied was based on flexibility in rework as more data became available, and ease of extendibility as more features and technologies were incorporated. The flexibility was achieved by developing tools to automate data import/export and to increase the error free data exchange between various teams. The tools also ease future rework and extensions. Alterations of the requirements only requires new input in the tool to generate the data and the simulation and application files. These files can be easily exchanged with other teams and integrated into the vehicle.

C. *Electronics development*

The development of the electronics hardware of EVA was based on a "building blocks" approach. Different building block circuits for integrating various sensors/loads and functions were identified. The most optimal of these were selected for as many applications as possible, even if it meant oversizing them for certain applications. Consequently, the number of different building blocks was limited which shortened test and development times. These building blocks were tested on prototype boards and once verified, integrated into the EVA control units. Some examples of building blocks include high side load drivers, H-bridge load drivers, 5 V power supply and analog sensor inputs.

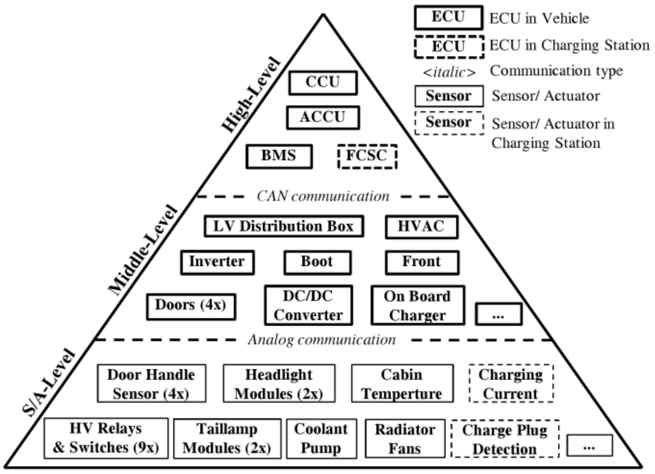

Fig. 7. The pyramidal control architecture for EVA.

D. *CAN network management*

One of the most dynamic and evolving parts of the LV system during the development phase is the CAN data matrix. The CAN data matrix holds the information on how usable data can be identified and extracted from the raw data available on the communication channel. This data are also one of the main interlinks between the LV development, infotainment and the functional development. This interlink was accomplished by creating a CAN network management tool (CANTool). This MS Excel based tool contained all the relevant data, which could be easily read and managed. The tool would then generate the relevant files in the right format as acceptable to the functional development and infotainment system teams. The following file formats are exportable by this tool

a) .dbc file for use within Vector simulations and for import into the dSpace environment by the functional development team

b) XML file for import by the infotainment team

c) Vector simulation files for rest-bus simulations in CANoe.

d) .mdb database and .c and .h files for use in the programming environment used by the LV ECUs.

With the usage of the tool, the data source for all these files was centralized, the errors introduced in the exchange of data were eliminated which helped to reduce the development time.

E. *Software Development*

Software development for EVA was also based on developing standard building blocks which could be reused across all the ECUs. However, due to minor differences across different control units in the same family, "wrapper functions" were developed to ease portability of the code blocks across the ECUs. These building blocks were tested before being reused in other ECUs. A software tool was developed which would offer GUI based drag and drop functionality to rapidly create a software program for these ECUs from the building blocks. The tool will ease future development by even non-programmer experts for specific domains like chassis control or HVAC etc.

IX. FUNCTIONAL DEVELOPMENT

A. *Overview & organization*

Functional development is the coordination of the vehicle's functional aspects across system and domain boundaries. In a first step, this includes the determination of vehicle functions itself and the definition of convenient function access routines for driver and passengers. In a second step it is defined how these functions are implemented in hardware and software. The development process was oriented on the common V-Model approach for mechatronic systems. For a transparent documentation, mainly UML state charts, UML activity diagrams and decision lists were utilized.

B. *CCU development & testing*

Beyond coordination, the functional development also included the implementation of software for the CCU in the vehicle. The code for the CCU was developed in Matlab Simulink (for continuous signal processing) and Stateflow (for logical processes and decisions). Because software development needed to start at a very early stage, the physical hardware systems were not available for most of the time. This made it necessary to extensively use the model-based development approach with Model-in-the-Loop and later, with partially available hardware, Hardware-in-the-Loop simulations. For the rest bus simulation we developed a tool using the Simulink API to automatically generate Simulink messages and signals congruent to the CAN data matrix and with respective default values and interfaces. If dynamic signal feedback instead of time constant default values is necessary for realistic environment simulation it is possible to attach logical simulations of the respective components to those interfaces. This is functional in a Simulink environment without proprietary controller blocks. Moreover, it is time efficient in case of frequent CAN data matrix redefinition. This functionality is also integrated in the earlier mentioned CANTool

To assure code quality and reduce manual test effort every time after frequent changes during the development, formal verification and test automation methods were examined and applied. Fail safe and fail operational, error detection and error handling methods have been examined but only implemented on a rudimentary level to assure safe operation in a prototype environment. This is a main focus of future research and development, together with broader and more elaborate investigation and application of test automation methods throughout the future development process.

C. *Software architecture & communication concept*

Core of the CCU and therefore the core functions control is a Stateflow chart with the main top-level "Operation Modes" (OMs) of the vehicle. This is depicted in a simplified pseudo state machine in the upper half of Fig. 8. The OMs are BOOT, MOVE, CHARGE, ERROR and OFF. OFF is a theoretic OM and is actually never reached because the MABx containing the CCU will already be switched powerless. These OMs define a static state of the whole vehicle with a certain configuration of all components. Some of them are hierarchically further divided as depicted for MOVE in the lower half of Fig. 8. All OMs are exclusively active. Transitions between the OMs are established by "Transition Modes" (TMs). These are "dynamic" modes, which mean during those, reconfiguration of the vehicle's components is in progress. With a series of TMs (illustrated with and contained in the doted boxes in Fig. 8) certain switching processes can be issued and checked in sequence. OMs and TMs for readability were coded as enumeration types with a systematic binary number hierarchy and defined throughout the vehicle. The binary number is broadcasted over the CAN buses to the other controllers cyclically and updated every time a new mode is reached.

All high-level controllers in the vehicle (Fig. 8) are programmed according to the above described principle. Because only modes are exchanged this concept is denoted as "Coupled State Machines by OM/TM exchange". The most important advantages of this concept are

- Only modes are transferred, independent of necessary technical hardware procedures. If they change, necessary changes stay local.
- Lower CCU and CAN bus load, because only summarized information is communicated.
- With the CCU centered approach for the vehicle core functions and the enumeration types, system observation and debugging is conveniently possible.

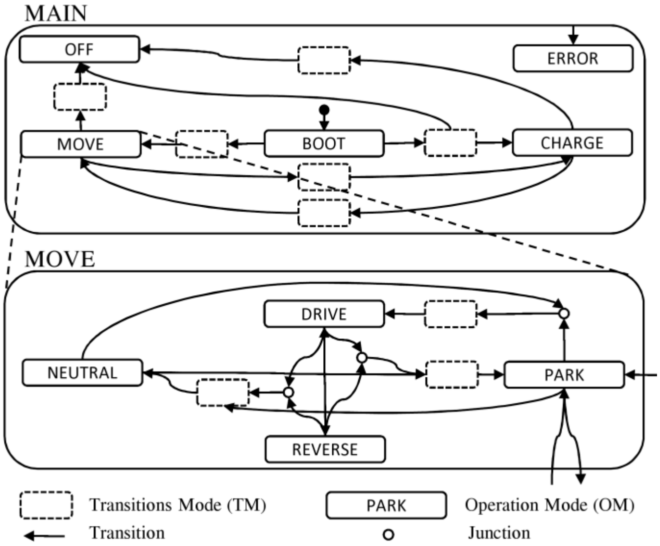

Fig. 8. Pseudo state chart showing modes for vehicle core functions.

X. INFOTAINMENT SYSTEM

The conceptual development of the infotainment system was done in a three-stage process. In the first phase six requirement studies were conducted to determine desired functionalities and system features by the taxi drivers and passengers [38]. In the second phase design guidelines following the approach of universal design [39] were applied, which acknowledges the heterogenic target user group of taxi drivers and an assumed long life expectancy of a vehicle (+ 10 years). This includes further a corporate design for all interfaces in the car and a well-defined set of interaction features to not mentally overload the driver while driving. These features were clustered in four categories addressing the driving related functionality (e.g. speedometer, state of charge), vehicle safety (warnings and errors), comfort features (e.g. air conditioning, entertainment), and taxi related functionality (booking system, taxi status).

In the third phase the definition of the hardware and the data connections between the components followed the goal to design a flexible system that allows for multiple input (data and user input) and output solutions (interfaces for itself, as well as single interface elements). This was realized by applying the Android operating system as a basis for the graphical user interfaces and by making use of Bluetooth, Wi-Fi and the CAN. For a greater flexibility and to provide the wireless network in the vehicle with the internet connection, a CarPC was used as the backbone of the infotainment system. The instrument cluster and the central information screen in the central console are smart devices that are able to process information on its own. Both devices were connected via Wi-Fi to the CarPC and the instrument cluster was further connected via a Bluetooth module to the CAN of the vehicle [40]. To ease the interaction with the information system, a scroll wheel was implemented as an interface changer for the instrument cluster and the levers on the back of the steering wheel are used to control the central information screen and to accept and decline taxi bookings.

The third smart device in this cluster, are the smartphones of either the driver or the passengers. The smartphones allow for adjustment of comfort features, to book, follow, and pay the taxi and to choose a music source. The smartphones are logged into to the vehicle Wi-Fi via Radio-frequency identification (RFID) tags that are placed in all doors. Each tag provides the unique information of the respective seat and enables the passengers to change comfort functions for their own seat. In these private zones each passenger and the taxi driver can listen to any chosen music source without being disturbed by the other passengers. After the conceptual development the system was implemented in an iterative process. The system was tested continuously during the implementation phase to ensure consistency regarding the defined system requirements and specifications. The four major parts (smart devices and backbone) of the systems were developed in parallel and connected via the on-board network in the car for the first time. After debugging initial communication errors, the whole system was successfully tested including a simulation mode for all major functionalities.

XI. VEHICLE ASSEMBLY

A. Parts status tracking

With the part count increasing and in order to manage the assembly of the vehicle in time, we had to come up with an assembly method. In the beginning a bill of materials (BOM) of the vehicle was generated from the vehicle package. This list was checked and modified to include items that were required but not in the CAD model. The progress status of each part was updated in the list according to the deadline for completion of design and manufacture along with the status of the item, if it was already purchased or manufactured. Every team member was able to monitor and update the component data.

B. Assembly sequence planning

The vehicle package was used to virtually simulate the assembling the vehicle, thereby the ideal sequence of assembly was determined. This helped to foresee problems we would have during the assembly process as the fit of every single component and its assembly was checked and verified. The order of assembly was planned in detail, resulting in a document indicating the exact sequence in which the vehicle should be assembled.

C. Assembly/production timeline planning

Based on the assembly sequence, it was apparent that certain parts would have to be available before others. Thus it was necessary to compile a full timeline to control both the assembly and the production of parts, including the manufacture of the CFRP parts for the vehicle structure. Certain parts were prioritized over others in order to facilitate a smooth assembly and post processes such as painting.

XII. CONCLUSION

Fig. 9. Final prototype of EVA.

Fig. 9 shows EVA when it was successfully presented on the 43rd Tokyo Motor Show in Japan. TUM CREATE has shown that it is possible to develop a prototype vehicle to high standards, despite having no existing automotive industry in Singapore. With an optimized charging concept and a large battery, EVA can fulfill the requirements of daily usage as a taxi. With lower emissions, better cost efficiency and taxi features like the integrated child seats; EVA benefits several customers, including taxi companies, taxi drivers and passengers. Compared to other taxis on Singapore’s roads EVA has more luggage space and weighs only 1.5 t despite fulfilling ECE safety standards. With an electric taxi, everyone will be able to experience electric mobility, especially if electric mobility will be substituted and introduced in large scale. With this concept, Singapore is ready for an electric future in the public transportation sector.

ACKNOWLEDGMENTS

This work was financially supported by the Singapore National Research Foundation under its Campus for Research Excellence And Technological Enterprise (CREATE) programme. We like to thank TUM and NTU for realizing TUM CREATE and A. Schwab, G. Marinkovic, R. Gujarathi, R. Brzozowski, P. Bartsch, S. Schickram, R. Kochhan, F. Römer, C. Große, S. Zainalabidin, S. Menon, P. Stuke, R. Sellmair, P. Mundhenk and D. Zehe - without whom EVA would still be unfinished. For their support we thank F. Wunner, H. Wack, S. Kraft, J. Seewald and A. Sauer. Further we thank A. Schwingenschlögl, S. Matz, P. Burda, S. Lee, V. Naido, M. Wilkinson, S. Zaremba, C. T. Fook, P. K. Ng, M. Acklemore, S. Steinhorst and S. Andalam for their assistance and advice during the project.

REFERENCES

[1] United Nations, "World Population Prospects: the 2012 Revision, Highlights and Advance Tables," *Department of Economic and Social Affairs,* vol. Working Paper No. ESA/P/WP.228, p. 1, 2013.

[2] United Nations, "World Urbanization Prospects: The 2011 Revision," *Department of Economic and Social Affairs, Population Division,* vol. CD ROM edition, 2012.

[3] P. Krix, "Revolution Mit Leichtigkeit," in *Automobilwoche SPEZIAL 2013*, Oberpfaffenhofen, Crain Communications GmbH, 2013, pp. 4-8.

[4] M. Winterhoff, C. Kahner, C. Ulrich, P. Sayler and E. Wenzel, "Zukunft der Mobilität 2020, Die Automobilindustrie im Umbruch?," Frankfurt am Main, 2009.

[5] T. Kuhnimhof et al, "Mobilitat junger Menschen im Wandel - mulitmodaler und weiblicher," München, 2011.

[6] A. d. Schmidt, "Teilen und Fahren, Carsharing für E-Mobile," *emobility tec,* no. 04/2013, pp. 10-13, 04 2013.

[7] J. Lim, A. Schwab and R. Kochhan, "Psychological Attributes of Travelling Mode Choice in Singapore," in *Singapore International Transport Congress and Exhibition (SITCE) 2013*, Singapore, 2013.

[8] Land Transport Authority of Singapore, "Land Transport Master Plan 2013," Land Transport Authority of Singapore, Singapore, 2013.

[9] Nature Japan K.K., "Taking care of the big picture," 2013. [Online]. Available: http://www.natureasia.com/en/nature/special-issues/singapore-feature-2013.

[10] Department of Statistics Singapore, Yearbook of Statistics Singapore 2013, 2013 ed., Singapore, 2014.

[11] Land Transport Authority of Singapore, "Singapore Land Transport Statistics in Brief 2013," Land Transport Authority of Singapore, Singapore, 2013.

[12] Singapore Economic Development Board, "Future Ready Singapore, Emerging Businesses," 05 07 2013. [Online]. Available: http://www.edb.gov.sg/content/edb/en/industries/emerging-businesses/emerging-businesses.html#automotive. [Accessed 15 01 2014].

[13] Land Transport Authority of Singapore, "Monthly statisitics summary of Taxi Fleet in Singapore," Land Transport Authority, Singapore, 2013.

[14] One motoring, "Cost (S$) for cars registered in Nov 2013," onemotoring, 1 12 2013. [Online]. Available: www.onemotoring.com.sg.

[15] M. v. Maydell, „Preiswert, leise und vergnüglich," 02 2013. [Online]. Available: http://www.auto-motor-und-sport.de/einzeltests/audi-a3-14-tfsi-ambition-preiswert-leise-und-vergnueglich-6391393.html.

[16] G. Sun, "Statistics of monthly taxi mileage 2009/2010," Land Transport Authority, Singapore, 2010.

[17] C. C. Hoong and H. L. Huang, "Safety assessment of taxi drivers in Singapore," *Transportation Research Record : Journal of the Transportation Research Board,* pp. 47-56, 2009.

[18] Singapore Police Force, "SPF Media Information Centre," Singapore Police Force, 23 12 2011. [Online]. Available: http://www.spf.gov.sg/mic/2011/111223_seat_belt.htm. [Accessed 14 01 2014].

[19] Information Service Department, "Hong Kong: The Facts," Hong Kong Special Administration Region Government, Hong Kong, 2013.

[20] N.N., "München in Zahlen," 2013. [Online]. Available: http://www.muenchen.de/sehenswuerdigkeiten/muenchen-in-zahlen.html. [Accessed 30 01 2014].

[21] M. Schreiber, "A century of Tokyo taxis," The Japan Times, Tokyo, 2012.

[22] Taxi-München eG, "Tarif und Preise des Münchner Taxigewerbes," 2014. [Online]. Available: http://www.taxi-muenchen.com /privatkunden/tarif-und-preise.html. [Accessed 30 01 2014].

[23] Tokyo Metropolitan Government, "Overview of Tokyo," 2010. [Online]. Available: http://www.metro.tokyo.jp/ENGLISH/PROFILE/overview03.html. [Accessed 30 01 2014].

[24] U.S. Census Bureau, "State & County Quick Facts," 17 12 2013. [Online]. Available: http://quickfacts.census.gov/qfd/states/36/3651000.html. [Accessed 30 01 2014].

[25] The World Bank, "Population (Total)," The World Bank Group, 2014. [Online]. Available: http://data.worldbank.org/indicator/SP.POP.TOTL. [Accessed 06 01 2014].

[26] S. Wimmer, "Konkurrenz auf der Straße," Süddeutsche.de, München, 2013.

[27] R. Stiles, L. Siegel, J. Garber, H. Neger and A. Ullah, "2014 Taxicab Factbook," Taxi & Limosine Commission, New York City, 2014.

[28] Land Transport Authority, "Motor Vehicle Poulation by Vehicle Type," Land Transport Authority, Singapore, 2011.

[29] Land Transport Authority, "Statistics in Brief," Land Transport Authority, Singapore, 2011.

[30] Office for Official Publications of the European Communities, *REGULATION (EEC) No 4064/89,* Luxemburg: Office for Official Publications of the European Communities, 1999.

[31] P. Stuke and K. Bengler, "Interior air conditioning for electric vehicle EVA," in *Conference on future automotive technology 2014*, Garching bei München, 2014.

[32] G. W. Stuart Macey, H-Point, The fundamentals of car design and packaging, Pasadena: Design Studio Press, 2009.

[33] E. Braß, Konstruieren mit CATIA V5 Methodik der parametrisch-assoziativen Flächenmodellierung, München: Carl Hanser Verlag GmbH & Co. KG, 2009.

[34] S. W. Tsai and E. M. Wu, "A general theory of strength for anisotropic materials," *Journal of Composite Materials,* vol. 5, pp. 58-80, 1971.

[35] A. Büttner and W. Triefenbach, "Risk Protection in Series Production for Alternative Drive Systems," *ATZautotechnology Worldwide,* vol. 12, no. 3, pp. 60-64, 2012.

[36] M. Neuhold, "Safer Handling of High-Voltage Components," *ATZautotechnology Worldwide,* vol. 5, no. 1, pp. 14-17, 03 2012.

[37] DGUV Gesetzliche Deutsche Unfallversicherung, Qualifizierung für Arbeiten an Fahrzeugen mit Hochvoltsystemen, Berlin: Deutsche Gesetzliche Unfallversicherung (DGUV), 2012.

[38] S. Osswald, D. Zehe, P. Mundhenk, P. Sheth, M. Schaller, S. Schickram and D. Gleyzes, "HMI development for a purpose-built electric taxi in Singapore.," in *Proceedings of the 15th international conference on Human-computer interaction with mobile device and services,* New York, USA, 2013.

[39] B. Shneiderman and H. Hochheiser, "Universal usability as a stimulus to advanced interface design," *Behaviour and information technology,* vol. 20, no. 5, pp. 367-376, 2001.

[40] S. Osswald, P. Sheth and M. Tscheligi, "Hardware-in-the-loop-based evaluation platform for automotive instrument cluster development

(EPIC)," in *In Proceedings of the 5th ACM SIGCHI symposium on Engineering Interactive computing systems (EICS 13)*, New York, 2013.

[41] F. B. Schmidt, "Mit dem Tesla auf dem Highway der Zukunft," Frankfurter Allgemeine Zeitung, 20 1 2014. [Online]. Available: http://www.faz.net/-gya-7lga5. [Accessed 20 1 2014].

[42] B. Berman, "Nissan Gives Leaf Owners a Preview of the 2013 Model," 01 02 2013. [Online]. Available: http://wheels.blogs.nytimes.com/2013/01/13/nissan-gives-leaf-owners-a-preview-of-the-2013-model/?_php=true&_type=blogs&_r=0. [Accessed 15 01 2014].

[43] Energy Market Authority, "Energizing our Nation, Singapore Energy Statistics 2012," Energy Market Authority, Singapore, 2011.

[44] MIT Electric Vehicle Team, "A Guide to understanding battery specification," 2008. [Online]. Available: http://web.mit.edu/evt/summary_battery_specifications.pdf. [Accessed 07 01 2014].