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Multi-Moby – Smart solutions for safe, efficient and affordable light electric vehicles

Barbara Eichinger[a], Sabine Dullnig[a], Pietro Perlo[b], Marco Biasiotto[b], Javier Romo Garcia[c], Khadija El-Baraka[d], Didier Canitrot[d], Svetislav Jugovic[d], Walter Faedo[e], Andrea Mioni[e], Leonid Skigin[f], Nir Karasikov[f], Kai Man So[g]*, Gaetano Tavolo[b,g], Davide Taverninig[g], Aldo Sorniotti[g], Giuseppe Catona[h], Carlo Tanzi[h], Eric Verhulst[i]

[a]Infineon Technologies Austria AG, 9500 Villach, Austria
[b]Interactive Fully Electrical Vehicles srl, 10040 La Loggia (TO), Italy
[c]CIDAUT Foundation, 47151 Boecillo (Valladolid), Spain
[d]Valeo Powertrain Systems, 94000 Créteil, France
[e]DANA TM4 Italia, 36071 Arzignano (VI), Italy
[f]Nanomotion Ltd, 2069200 Yokneam Illit, Israel
[g]University of Surrey, GU2 7XH Guildford, United Kingdom
[h]BITRON Industrie SpA, 10095 Grugliasco (TO), Italy
[i]Altreonic NV, 3200 Aarschot, Belgium

Abstract

Multi-Moby is an ambitious project aiming at quickly finalising the results of a cluster of European projects, addressing the development of technology for safe, efficient and affordable urban electric vehicles (EVs). This paper presents developments in the first half of the Multi-Moby project, which involves low-cost M1 and N1 EVs manufactured via low-investment manufacturing techniques. Despite their low-cost, the Multi-Moby EVs have excellent passive safety, enhanced by pre-emptive active safety controllers. The EVs can be configured for 100 V or 48 V powertrains, both highly efficient. In addition, fast charging has been enabled by the novel hybrid supercapacitor-battery cells and high-powered wall box chargers. The next steps of the project are to examine low-cost autonomous driving solutions, based on software instead of expensive lidar or radar hardware.

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Keywords: Urban light electric vehicles; energy efficiency; passive and active safety; affordability; lean manufacturing; electro-mobility.

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* Corresponding author. Tel.: +44 (0)1483689688
E-mail address: a.sorniotti@surrey.ac.uk

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1. Introduction

Future urban electro-mobility requires the development of a new generation of light, affordable and functional electric vehicles (EVs), including smart solutions for enhancing user experience. This topic is addressed by Multi-Moby, which is an ambitious European Horizon 2020 project aimed at quickly finalising the results of a cluster of previous and ongoing European projects addressing the development of technologies for safe, energy-efficient and affordable urban electric vehicles.

This paper discusses the novel features of the multi-passenger and multi-purpose commercial vans developed in the first half of the ongoing Multi-Moby project, which will assure: i) best-in-class safety for occupants and vulnerable road users (VRUs) protection, as required by the M1/N1 regulations; ii) driving automation capabilities by adopting the most extensively tested sensing and computing platforms, with the addition of low-cost scanning and night vision functionalities; iii) highly efficient 48 V and 100 V powertrains; iv) robust battery packs based on hybrid supercapacitor-battery cells; v) efficient AC charging through an on-board charger, integrating a DC/DC converter optimized for the two voltages of interest, as well as DC charging at 48 V and 100 V; vi) advanced electric and electronic (E/E) architecture with secure procedures for remote updates and upgrades of the firmware, and predictive maintenance, by applying advanced artificial intelligence (AI) methodologies; vii) application of low-cost, flexible, agile and lean manufacturing through a low-investment micro-factory concept; viii) competitive price positioning with respect to existing and forthcoming fully electric urban passenger and commercial vehicles.

2. Vehicles

There are six Multi-Moby vehicles under development (Fig. 1), comprising:

- Passenger 4-door M1 vehicles with a 4-wheel-drive (4WD) on-board centralized powertrain architecture, with two 15 kW 100 V air-cooled highly efficient powertrains based on permanent magnet assisted synchronous reluctance motors. The vehicles are the upgrade of an original design meeting the Japanese Kei cars homologation regulations.
- Multi-purpose N1 pick-ups/vans, also with 4WD on-board centralized powertrain architecture, covering the needs of many commercial uses, including transport of general goods and delivery of food. One setup has two 9.5 kW 48 V air-cooled belt powertrain systems, while another configuration has two 15 kW 100 V air-cooled powertrains.

Fig. 1. Multi-Moby vehicles, from left: pick-up, van, and passenger vehicles.

All Multi-Moby vehicles share the same body frame using Super High Strength Steels (SHSS), modular battery packs for 48 V and 100 V applications, electrically controlled steering, dashboard and info panel, suspension systems, E/E architecture, interfaces for automated driving functionalities, auxiliaries, occupant safety, and VRU protection as required for the M1/N1 categories. The vehicles will meet the EuroNCAP 4-star car crash requirements, and include: i) optimized structure to obtain an occupant load criterion value lower than 45 g in the frontal crashes covered by the regulation or EuroNCAP procedures; ii) optimized elements of the restraint system (frontal and side airbags, steering column and seat belts); and iii) optimized design of their frontal part to support VRU protection. A step-by-step approach will consider the implications of the transition from the currently available advanced driver-assistance systems to conditional autonomy and full autonomy, with focus on integrated sensing and computing platforms that can be potentially produced at lower costs than most competing products. The vehicles also include smart photovoltaics with direct DC/DC connection to the high-capacity battery. Predictive maintenance techniques are adopted through the application of advanced artificial intelligence methodologies.

The Multi-Moby vehicles are modular, reconfigurable, flexible, agile, and made with lean manufacturing technologies, ensuring low-investment and low-cost manufacturing through the micro-factory concept developed by I-FEVS. With this concept, the most stringent crash tests can still be met, while avoiding production steps involving expensive moulds and stamping. Instead, only SHSS tubes and metal sheets are used for all major components, including body frames, doors, suspension arms, wheel hubs, axle frames, battery pack envelops and the rear enclosure of the N1 vans. No difficult to recycle resins are used.

3. Passive Safety

In Multi-Moby, special attention has been paid to passive safety. Small vehicles are hindered by the reduced space available to absorb energy in the event of a crash. This disadvantage has two direct consequences, the design of the structure is more challenging and the requirements of the restraint system to protect the occupants is greater.

To ensure the safety of the occupants, the methodology established has consisted of an optimisation of the vehicle structure by I-FEVS and CIDAUT, with three main targets – to maintain the integrity of the cabin, to ensure that the battery compartment does not suffer relevant deformation, and to obtain Occupant Load Criterion (OLC) acceleration values lower than 45 g. After achieving these three targets for different frontal and lateral crash configurations, the next step was to design a restraint system suitable for the acceleration pulses obtained in the different crash scenarios analysed.

The resultant vehicle structure is based on a tubular solution composed of SHSS, optimised with advanced virtual modelling (Fig. 2(a)). Several iterations were used to obtain the right geometry of the structure and to decide the quality of the high strength steel used in each of the tubes. In parallel, for the structure optimisation, stiffness and fatigue criteria have been considered.

Subsequently, the structural design of the vehicle was frozen, and the restraint system was optimised according to the acceleration pulse (Fig. 2(b)). The design of the restraint system covers mainly – the seat belt, the airbags, the seat, and the steering wheel – and the parameters to be optimised are related to the relative position of each item, the capacity of the airbags, the number and size of the airbag's valves, the airbag's time to fire, seat belt's pretensioner, the pretensioner's load, etc. Again, an iterative optimisation process was executed to find a balanced solution between all the crash scenarios considered for the design.

(a) (b)

Fig. 2. (a) Simulation results of the Multi-Moby vehicle under R137 crash after structure optimisation; (b) analysis of restraint system under R137.

Once the design was finished, four different vehicle prototypes were manufactured by I-FEVS for crash tests performed at CIDAUT, two of them for frontal (Regulation 94 (R94) and R137) and one of them for lateral (R95) crash tests (Fig. 3). The fourth vehicle was used for fatigue tests. The crash tests have ensured the three objectives were met – no deformation of cabin and battery compartments, and the maximum OLC in the most critical crash is 42.5 g. In addition, the protection of the occupants has fulfilled all the targets established by the standards. A detailed analysis of the crash test results can be found in Eichinger et al. (2022). Further tests will be carried out soon, such as the critical pole crash test.

Fig. 3. Crash test aftermaths of three Multi-Moby prototype vehicles, from left to right: R137, R94 and R95.

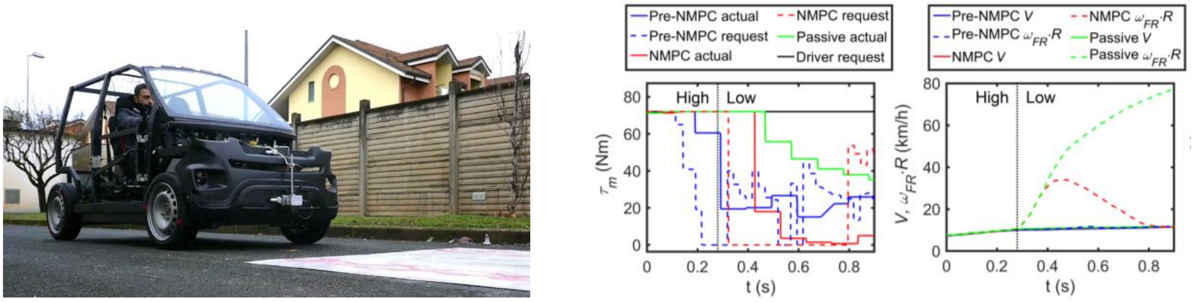
4. Active Safety

V2X technologies will be widespread in the next generation of passenger cars and enable the development of novel vehicle control functionalities. Although a wide literature describes the energy efficiency benefits of V2X connectivity, e.g., in terms of optimized vehicle speed profiling and platooning, there is a gap in the analysis of the potential of vehicle connectivity in enhancing the performance of active safety controllers. To highlight the impact vehicle connectivity could have on future active safety systems, University of Surrey has developed two novel control functions for connected vehicles, benefitting from the precise knowledge of the expected path and tire-road friction conditions ahead, as well as the current position of the ego vehicle.

4.1. Pre-emptive traction control

The first function is pre-emptive traction control, in which the information of the expected tire-road friction coefficient profile ahead, coming from the cloud and based on the estimation outputs of preceding vehicles, is used by the wheel slip controller of the ego vehicle to pre-emptively reduce the torque demand to prevent longitudinal slip ratio oscillations, and compensate for the powertrain actuator delays. In particular, the implemented and experimentally assessed (Fig. 4(a)) pre-emptive nonlinear model predictive control (NMPC) algorithm considers both the variations of the reference slip ratio and tire-road friction factor according to the V2X cloud-derived map. The results in Fig. 4(b) show significantly less wheel spinning for the pre-emptive NMPC controller, compared to a benchmarking non-pre-emptive NMPC controller and the passive case.

For an in-depth discussion on the proposed traction controllers, readers may refer to publications by the same research team, namely Scamarcio et al. (2022), Tavolo et al. (2022), and So et al. (2022).



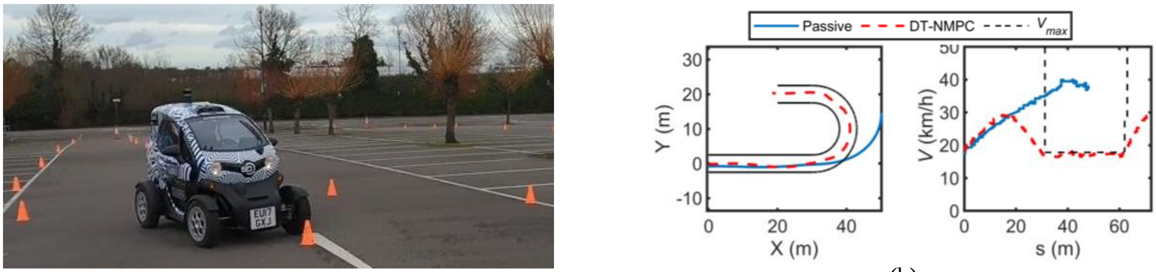
(a) (b)

Fig. 4. (a) Multi-Moby EV prototype during a traction control test with a step change from high (dry tarmac) to low (white boards covered with water and soap) tire-road friction coefficient; (b) experimental traction control test results in time domain for pre-emptive NMPC ('Pre-NMPC), non-pre-emptive NMPC ('NMPC') and Passive configurations. The figure shows from left: motor torque τ_m; longitudinal speeds V and tangential front-right (FR) wheel speeds $\omega_{FR}R$ (i.e., speed of single wheel). The vertical dotted line separates the high and low friction sections.

4.2. Pre-emptive stability control

The second function is pre-emptive stability control. The information on the expected road curvature ahead is sent to an NMPC braking controller, which pre-emptively slows down the vehicle by controlling its torque demand to ensure desirable levels of agility and sideslip angle in limit handling conditions, without the need for costly chassis actuators. Fig. 5 shows an experimental assessment of the controller, where the NMPC controller successfully slows the vehicle before a U-turn and the vehicle stays on track. In contrast, the passive vehicle exits the track due to its high speed.

For a detailed discussion on the proposed stability controller, readers may refer to Guastadisegni et al. (2022) and So et al. (2022), published by the same research team.



(a) (b)

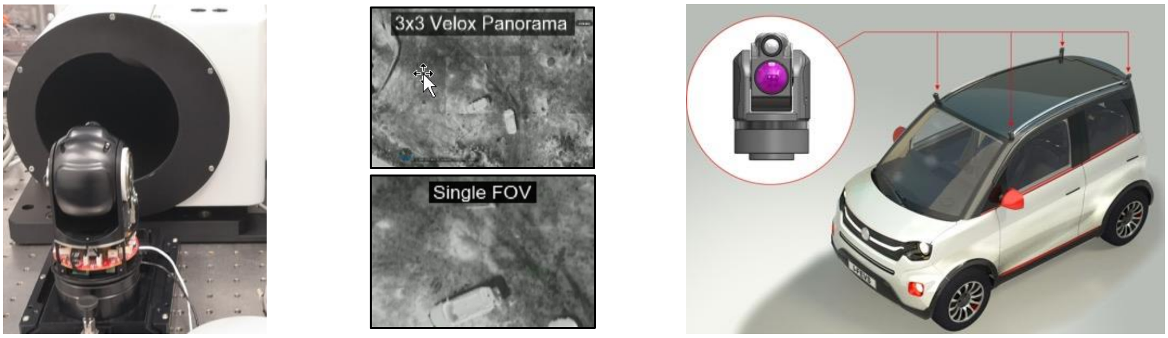
Fig. 5. (a) ZEBRA EV during a U-turn test (Passive configuration); (b) experimental results on the ZEBRA EV showing the pre-emptive double-track NMPC (DT-NMPC) and Passive configurations. The figure shows from left: trajectories in the XY inertial frame; vehicle speed V, as a function of the distance s along the track centreline.

4.3. *Towards autonomous driving*

Current autonomous driving technologies involve computational demanding sensing suites based on a multitude of cameras, lidars and radars. Multi-Moby instead proposes an affordable high performing fully autonomous vehicle solution, equipping vehicles with “system-eyes”, known as a miniature gimbal payload system, developed by Nanomotion.

The “system-eyes” concept is derived from an animal’s head and eyes, which are capable of rotating and seeing in the infrared spectrum. In Multi-Moby, each “eye” (or miniature payload, see Fig. 6(a)) has a pre-processing capability and adapts to the illumination of the environment. A system of “eyes” has an associated local AI brain with adaptive learning and is connected to a low-cost central computational power unit that controls the actuators driving the vehicle.

The novel miniature payload has unique capabilities – the first capability is stabilized step and stare. This feature overcomes the straw effect of cameras, especially in the infrared (IR) and short-wave IR (SWIR) range, where the number of pixels is limited and provide a high resolution of a broad field of view by mosaic of frames (Fig. 6(b)). The second capability is a very high angular resolution. This allows applying AI-based triangulation to derive 3D information, passively, in all weather and illumination conditions, such as in the setup shown in Fig. 6(c).



(a) (b) (c)

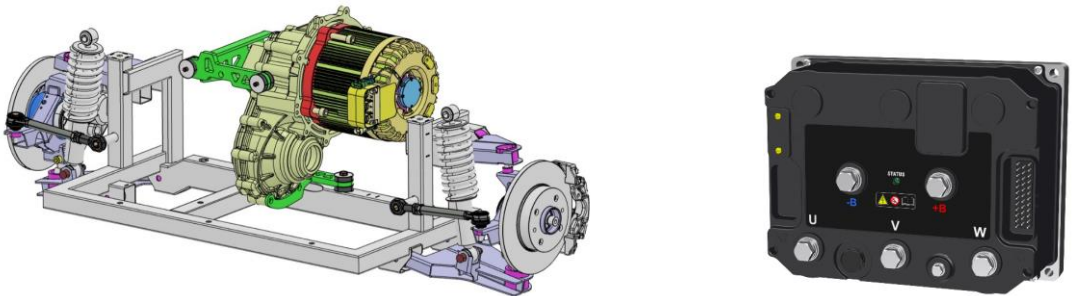
Fig. 6. (a) Testing of miniature gimbal payload in front of a collimator; (b) stabilized step and stare; (c) four payloads installed on the roof of the Multi-Moby vehicle, forming a “system-eye”.

5. Powertrains

5.1. 100 V powertrain

The M1 and selected N1 Multi-Moby vehicles have a 100 V powertrain. DANA has developed a highly efficient and cost effective 100 V 15 kW motorized axle (Fig. 7(a)), where the high efficiency of the synchronous reluctance motor technology enables a low running temperature, a high reliability and low maintenance costs. The motor design with improved rotor robustness allows a maximum running speed up to 10 krpm, and coupled with the gearbox, provides high starting torque and power. This motor uses a low quantity of magnets because the largest part of the torque (~ 80%) is generated by the reluctance instead of magnets. It also has significant advantages compared with other machine types, in terms of cost and power factor, making it more efficient and sustainable over the complete speed-range. The high efficiency (>98 %) inverter (Fig. 7(b)) is made with custom power modules based on Direct Copper Bond (DCB) technology that embed the latest available technology of bare dies soldered directly into the DCB substrate, which allows the reluctance machine to achieve the best performances over the entire speed range.

All the components of the 100 V motorized axle are air-cooled, and the mechanical shaft layout of the transmission makes the installation simple and intrinsically cheap. Thanks to a proprietary patent, it is possible to realize a scalable solution, in three power sizes, with the same form factor. In summary, the advantages include: i) efficiency – reduction in energy consumption for increased range or cost savings; ii) flexibility – benefit in electrifying multiple configurations with the same powertrain; iii) scalability – three power sizes are available in the same overall dimensions; iv) integration – simple integration with other on-board devices; v) packaging – improved vehicle mounting for optimised space and cooling; vi) weight – weight reduction providing additional payload or more battery capacity; vii) cost – optimised cost of all components.



(a) (b)

Fig. 7. (a) 100 V motor and transmission; (b) 100 V/375 A inverter.

5.2. 48 V powertrain

The remaining N1 Multi-Moby vehicles are powered by innovative high efficiency, low-cost, low voltage 48 V powertrain systems, developed by Valeo. Two such powertrains have been developed – the first powertrain has a belt-based transmission system (Fig. 8(a)), with a nominal power of 9.5 kW, and air cooled with integrated Si-MOSFET inverters. The second system is made of beltless motors (Fig. 8(b)), with a nominal power of 15 kW, water-cooled with inverters based on parallel Si-MOSFETs embedded in power module substrate (Fig. 8(c)).

(a) (b) (c)

Fig. 8. (a) 48 V motor with belt-based transmission and integrated inverter and reducer; (b) 48 V beltless motor with; (c) corresponding inverter.

Both 48 V and 100 V powertrains consist of state-of-the-art rotor positioning sensors and coreless stray-field robust current sensors provided by Infineon, utilising Hall technology based on next generation automotive current sensing devices, specifically TLE4972/TLE4973 for automotive inverter applications.

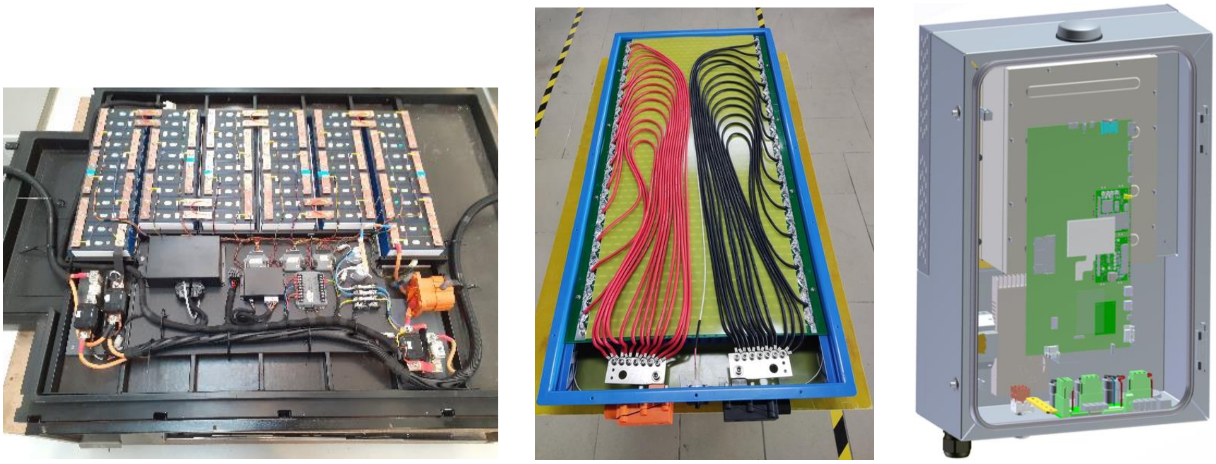
6. Energy Storage

Within the Multi-Moby project, different technologies of battery types and chemistries have been evaluated for use in light urban EVs. I-FEVS has developed two different types of battery packs using traditional Lithium-ion, the first with nickel-manganese-cobalt (NMC) pouch cells for 100 V applications, and the second with lithium ferrophosphate (LFP) in a prismatic cell form factor for both 48 V and 100 V powertrains (Fig. 9(a)).

In addition, a new cell has been developed by Altreonic for the 48 V powertrains, with hybrid supercapacitor-battery technology in a single cylindrical cell (Fig. 9(b)), combining the high-power densities of capacitive energy storage with high-energy densities of batteries. The design activities have been focused on: i) packaging design to improve cabin space for passenger comfort; ii) proper cell connections to minimise electric resistance, iii) thermal isolation and heat dissipation to reduce cell ageing and risk of damage, including a battery tray made of polymeric composite with thermal insulating properties, iv) customised electronic battery management to improve battery life and performance, v) effective mechanical assembly, vi) safety according to UN/EC R100 safety regulations.

The performance of hybrid supercapacitor-battery packs was verified by developing a load simulator, whereby a load profile is applied on a specified pack configuration. This allows optimising the hybrid pack configuratuin and estimating the calendar life before the pack is assembled. The load simulator can be found online at Altreonic NV, 2022.

LFP and hybrid supercapacitor-battery cells provide different challenges, impacting the operational use of the vehicles. The developed LFP battery pack provides more capacity per volume, and hence more range compared to the hybrid cells. The newest generation of LFP cells are capable of high charging and discharging rates, but still require real time monitoring of both temperature and state of charge to avoid damaging the batteries. In contrast, the developed hybrid supercapacitor-battery pack has a lower energy density but can operate at high C-rates, providing a peak of 66 kW at 48 V. Hence a smaller capacity can still deliver the maximum power while the battery can be charged in 5 to 10 minutes. The lower energy density, and therefore range, can be compensated by frequent quick recharging stops.



(a) (b) (c)

Fig. 9. (a) LFP prismatic cells in a 100 V configuration; (b) hybrid supercapacitor-battery cells assembled in the battery compartment; (c) 7 kW DC wall box charger, with front door removed.

7. Charging System

For fast EV charging, using SiC instead of Si devices can reduce charging losses by 30% while requiring 30% fewer components. Bitron and Infineon are collaborating on a new 7 kW DC wall box charger (Fig. 9(c)), operating at both Multi-Moby powertrain voltages. Charging power will peak at 3 kW for 48 V powertrains and 7 kW for 100 V powertrains. The charger human-machine-interface (HMI) will include a touch screen display, showing main charging parameters to the user. The charger will be connected to the vehicles according to the well-established CCS2 standard.

The mains supply input voltage will be single-phase, 230 Vac. Power conversion stages will be based on latest generation CoolSiC MOSFETs in SMD discrete package developed by Infineon. The CoolSiC MOSFETs allow highly efficient EV charging over a wide range of voltages (400 V-1200 V), and are based on a trench design, in contrast to the mainstream planar technology, which allows for a promising cost-down perspective for customers and makes Infineon a market frontrunner. The devices combine top performance with highest reliability and can be used at high temperatures and harsh environments, while integrating novel bi-directional functionality for improved energy storage and grid-balancing.

8. Conclusion

This paper described the activities of the first half of the Multi-Moby project. Six low-cost 4WD vehicles are developed via low-investment manufacturing, which demonstrates that classic manufacturing techniques of moulds and stamping can be avoided. Despite their low-cost, these vehicles are designed with passive safety in mind, and perform well in the stringent crash and fatigue tests. The Multi-Moby project also involves developing active safety controllers which can pre-emptive slow down the vehicle based on the path ahead, as well as pre-emptively reduce wheel spin on low tire-friction surfaces. In addition, a radically new solution for automated driving is under development using gimbal payloads, which is intended to become a low-cost alternative to lidars and radars on existing autonomous vehicles. Furthermore, new highly efficient 48 V and 100 V modular and flexible powertrains have been developed, in association with their corresponding energy storage solutions involving NMC pouched, LFP prismatic and hybrid supercapacitor-battery cells. A new DC wall box is also under development to charge both types of powertrain voltages. These developments will lead to safe, energy-efficient and affordable urban electric vehicles.

Acknowledgements

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