Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2022) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

Transport Research Arena (TRA) Conference

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 Tavernini[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 ongoing and past European projects, addressing the development of technologies for safe, efficient and affordable urban electric vehicles (EVs). This paper presents the developments that have been implemented in the first half of Multi-Moby, which deals with low-cost M1 and N1 EVs, to be manufactured via low-investment and lean processes, techniques and plants. Despite their low cost, the Multi-Moby EVs have excellent passive safety characteristics, enhanced by pre-emptive active safety controllers. The vehicles can be coupled with highly efficient 100 V or 48 V powertrains. Fast charging is enabled by the integrated design of novel hybrid supercapacitor-battery cells and wall box chargers. The project will also consider low-cost automated driving solutions at different autonomy levels, with focus on gimbal-based camera systems for environmental sensing and detection.

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

---

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

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 EVs.

This paper discusses the main novel features of the passenger cars and multi-purpose commercial vans developed in the first half of Multi-Moby, which are characterised by: i) best-in-class safety for occupants and protection for vulnerable road users (VRUs), 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) energy-efficient wall box AC charging, integrating a DC/DC converter optimised 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 adopting advanced artificial intelligence (AI) methodologies; vii) application of low-cost, flexible, agile and lean manufacturing methodologies through a low-investment micro-factory concept; and viii) competitive price positioning with respect to existing and forthcoming fully electric urban passenger and commercial vehicles.

2. The Multi-Moby Vehicles

Six Multi-Moby vehicles are currently under development (Fig. 1). They include:

- 4-door passenger M1 vehicles with a 4-wheel-drive (4WD) on-board centralised powertrain architecture, including 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 in this case with a 4WD on-board centralised powertrain architecture, covering the needs of many commercial uses, including transport of general goods and delivery of food. One of the set-ups has two 9.5 kW 48 V air-cooled powertrains with belt transmissions, while other configurations have two 15 kW 100 V air-cooled or 48 V liquid-cooled powertrains.

Fig. 1. The Multi-Moby vehicles, currently under development; from the left: Multi-Moby pick-up, Multi-Moby van for food delivery, and Multi-Moby passenger vehicle.

All Multi-Moby EVs share the same body frame using Super High Strength Steels (SHSS), modular battery packs for 48 V and 100 V applications, electrically controlled steering systems, dashboard, suspension systems, E/E architecture, interfaces for automated driving functionalities, auxiliaries, as well as occupant safety features and VRU protection as required for the M1/N1 categories. The vehicles will meet the EuroNCAP 4-star car crash requirements and include: i) optimised structure to obtain an occupant load criterion value lower than 45 g in the frontal crashes according to the regulation or EuroNCAP procedures; ii) optimised elements of the restraint system (frontal and side airbags, steering column and seat belts); and iii) optimised 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 driverassistance 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 AI methodologies.

The Multi-Moby vehicles are modular, reconfigurable, flexible, and agile, and are 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 test requirements 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 compartments, and the rear enclosure of the N1 vans, without adopting difficult-to-recycle resins.

3. Passive Safety

In Multi-Moby, special attention has been paid to passive safety. Small vehicles have reduced space availability to absorb the energy in the event of a crash. This disadvantage has two direct consequences: i) the design of the structure is more challenging; and ii) the requirements of the restraint system to protect the occupants are more demanding.

To ensure the safety of the occupants, the Multi-Moby methodology has consisted of an optimisation of the vehicle structure, carried out by I-FEVS and CIDAUT, with three main targets: a) to maintain the integrity of the cabin; b) to ensure that the battery compartment does not suffer relevant deformation; and c) 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 following step was to design a restraint system suitable for the acceleration pulses obtained in the different crash scenarios.

(a) (b)

Fig. 2. (a) Simulation results of the Multi-Moby vehicle under the Regulation 137 (R137) crash, after structure optimisation; and (b) analysis of the restraint system under the R137 crash.

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

The resulting vehicle structure is based on a tubular solution composed of SHSS, optimised with advanced virtual modelling (Fig. 2(a)). Several iterations have been used to obtain the most suitable geometry of the structure, and to decide the quality of the high strength steel used in each of the tubular elements. In parallel, stiffness and fatigue criteria have been considered for the structure optimisation. Subsequently, the structural design of the vehicle was frozen, and the restraint system design – mainly covering the seat belts, airbags, seats, and steering wheel – has been optimised for the acceleration pulses (Fig. 2(b)). The optimisation parameters are related to the relative position of each item, the capacity of the airbags, the number and size of the airbag valves, the airbag time to fire, the seat belt pretensioner characteristics (e.g., the pretensioner load), etc. Also in this case, an iterative optimisation process has been developed and executed to find a balanced solution among all considered crash scenarios.

Once the virtual design was completed, four vehicle prototypes were manufactured by I-FEVS for crash tests that were performed at the CIDAUT facilities, two of them for frontal (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 confirmed the achievement of objectives a)-c), i.e., no deformation of cabin and battery compartments occurred, and the maximum OLC in the most critical crash was 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, such as the critical pole crash test, will be carried out soon.

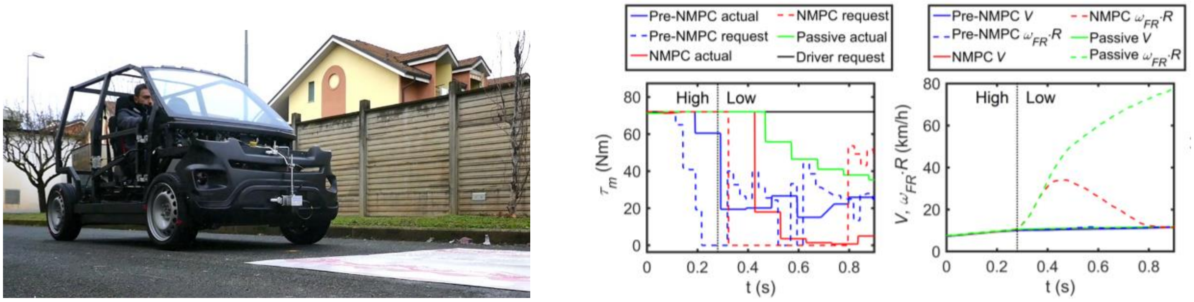
4. Active Safety

V2X technologies will become 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 optimised 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, the 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 – pre-emptive traction control – uses the expected tyre-road friction coefficient profile ahead, coming from the cloud and based on the estimation outputs of preceding vehicles, to pre-emptively reduce the torque demand, prevent longitudinal slip ratio oscillations, and compensate for the powertrain actuation delays. 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 tyre-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 algorithm, compared to a benchmarking non-pre-emptive NMPC implementation and the passive case.

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



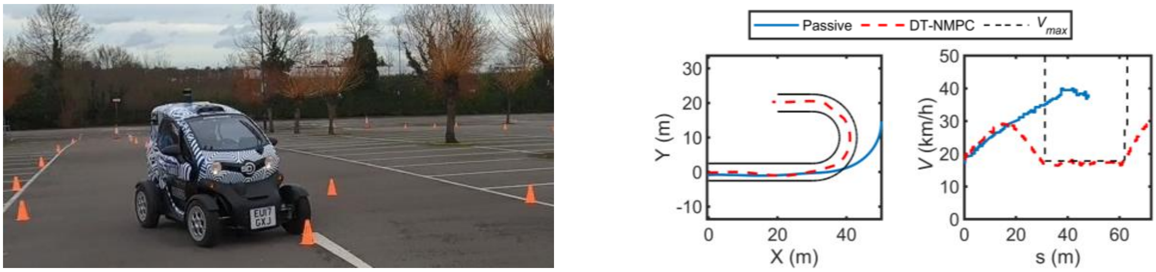
(a) (b)

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) tyre-road friction coefficient; (b) time profiles during experimental traction control tests for the pre-emptive NMPC ('Pre-NMPC'), non-pre-emptive NMPC ('NMPC') and Passive configurations. The figure shows from the left: motor torque, τ_m; longitudinal vehicle speeds, V, and tangential front right (FR) wheel speeds, $\omega_{FR}R$. The vertical dotted lines separate the high and low friction sections.

4.2. Pre-emptive braking control

The second function is pre-emptive braking 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 example of experimental assessment of the controller on the ZEBRA EV of the University of Surrey, where the NMPC algorithm successfully slows the vehicle before a U-turn, and the vehicle stays on track. In contrast, the passive vehicle exits the track because of its high speed.

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



(a) (b)

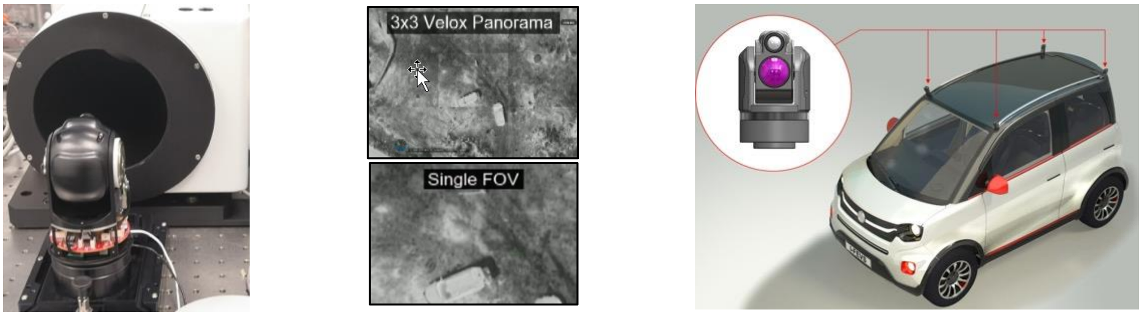
Fig. 5. (a) ZEBRA EV of the University of Surrey during a U-turn test (Passive configuration); (b) experimental results on the ZEBRA EV with the pre-emptive double-track NMPC (DT-NMPC) for pre-emptive braking and Passive configurations. The figure shows from the left: trajectories in the XY inertial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

4.3. *Towards autonomous driving*

Current autonomous driving technologies involve computationally demanding sensing suites based on a multitude of cameras, lidars and radars. Multi-Moby explores an affordable high performing fully autonomous vehicle solution, based on vehicles with "system-eyes", i.e., miniature gimbal payload systems, developed by Nanomotion.

The "system-eye" 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 processing 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 range, where the number of pixels is limited, and provides 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 set-up shown in Fig. 6(c).



(a) (b) (c)

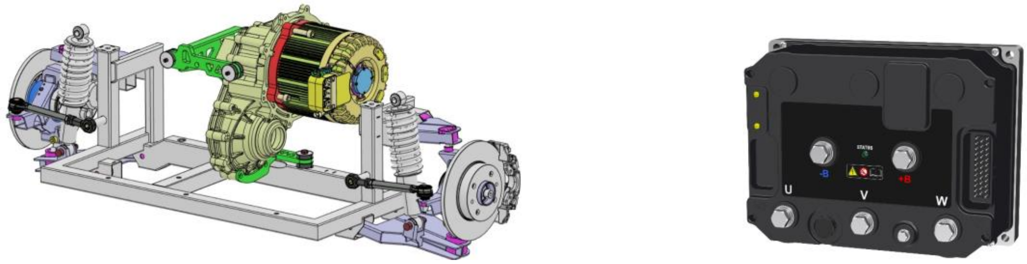
Fig. 6. (a) Testing of miniature gimbal payload in front of a collimator; (b) stabilized step and stare; (c) four payloads installed on the roof of the Multi-Moby vehicle, forming a "system-eye".

5. Powertrains

5.1. *100 V powertrains*

The M1 and some of the N1 Multi-Moby vehicles have 100 V powertrains. In this respect, DANA has developed a highly efficient and cost effective 100 V 15 kW motorised axle (Fig. 7(a)), where the high efficiency of the synchronous reluctance motor technology enables low operating temperatures, high reliability, and low maintenance costs. The motor design with improved rotor robustness allows maximum running speeds up to 10 krpm, and, coupled with the gearbox, provides high starting torque. This motor uses a low quantity of magnets because the majority of the torque (~80%) is generated by the reluctance rather than the magnets. The machine topology 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, which embeds the latest available technology of bare dies soldered directly into the DCB substrate, thus enabling the reluctance machine to achieve its best performance over the entire speed range.

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



(a) (b)

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

5.2. 48 V powertrains

The remaining N1 Multi-Moby vehicles are powered by innovative high-efficiency, low-cost, low-voltage 48 V powertrain systems, developed by Valeo. Two set-ups of these powertrains have been implemented. The first powertrain, with a belt-based transmission system (Fig. 8(a)) and a nominal power of 9.5 kW, is air-cooled, and integrates Si-MOSFET inverters. The second system is made of a beltless motor (Fig. 8(b)) with a nominal power of 15 kW, and is water-cooled, with inverters based on parallel Si-MOSFETs embedded in power module substrate (Fig. 8(c)). Both the 48 V and 100 V Multi-Moby powertrains include state-of-the-art rotor positioning and current sensors utilising Hall-effect technology.

(a) (b) (c)

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

6. Energy Storage

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

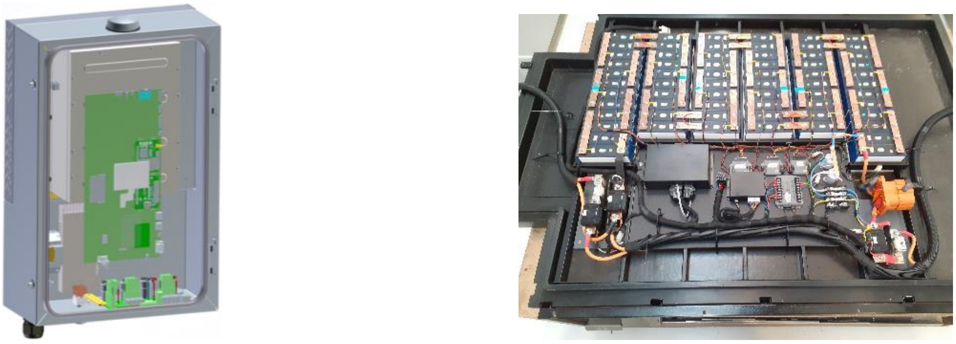
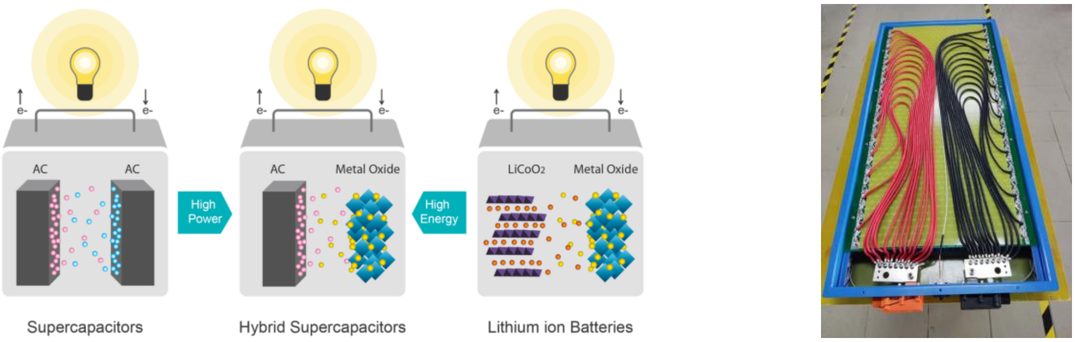

(a) (b)

Fig. 9. (a) 7 kW DC wall box charger, with front door removed; (b) LFP prismatic cells in a 100 V configuration.

In addition, a new energy storage cell has been developed by Altreonic for the 48 V powertrains, which is based on hybrid supercapacitor-battery technology using cylindrical cells that pose no fire risk. The hybrid supercapacitor utilises one electrode from a supercapacitor and another electrode from a lithium-ion battery (Fig. 10(a)), combining the high power density of capacitive energy storage with the high energy density of batteries.

The design activities have been focused on: i) packaging the design to improve cabin space for passenger comfort; ii) optimising cell connections for minimising electric resistance; iii) thermal insulation and heat dissipation for reducing cell ageing and risk of damage, including a battery tray made of polymeric composites with thermal insulating properties (Fig. 10(b)); iv) customising the battery management system to improve battery life and performance; v) effective mechanical assembly; and vi) safety according to the UN/EC R100 regulations.



(a) (b)

Fig. 10. (a) Simplified schematic of a hybrid supercapacitor-battery cell; (b) hybrid supercapacitor-battery cells assembled in the Multi-Moby vehicle battery compartment.

The performance of the hybrid supercapacitor-battery packs was verified by developing a load simulator, whereby a load profile is applied to a specified battery configuration. This allows optimising the hybrid pack and estimating the calendar life before the pack is assembled. The load simulator is available online, see Altreonic NV (2022).

The 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 longer range in comparison with 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 pack. 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 5-10 minutes. The lower energy density, and therefore range, can be compensated by frequent and quick recharging stops. New cell technologies that double the energy density are currently being investigated.

7. Charging System

For fast EV charging, the adoption of SiC devices to replace the conventional Si devices can reduce the charging losses by ~30%, and decrease the number of components. Within Multi-Moby, Bitron and Infineon Austria are collaborating on a new 7 kW DC wall box charger (Fig. 9(a)), operating at both voltage levels (48 V and 100 V) of the Multi-Moby powertrains. The charging power will peak at 3 kW for the 48 V powertrains, and 7 kW for the 100 V powertrains. The human-machine-interface (HMI) of the charger will include a touch screen display, showing the main charging parameters to the user. The charger will be connected to the EVs according to the well-established CCS2 standard.

The mains supply input voltage will be single-phase, 230 V AC. Power conversion stages will be based on the latest generation of CoolSiC MOSFETs in the surface-mount device (SMD) discrete package developed by Infineon. The CoolSiC MOSFETs allow highly efficient EV charging over a wide range of voltages, and are based on a trench design, in contrast to the mainstream planar technology, which enables a promising cost reduction perspective for the customers, and makes Infineon a market frontrunner. The devices combine top performance with high reliability, and can be used at high temperatures and in harsh environments, while integrating 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 electric vehicles have been developed, based on low-investment manufacturing technologies, avoiding the classic manufacturing techniques of moulds and stamping. Despite their low cost, the Multi-Moby vehicles are designed with passive safety in mind, and perform well in the most stringent crash and fatigue tests. Multi-Moby also develops active safety controllers that can pre-emptively slow down the vehicle based on the curvature of the path ahead, as well as pre-emptively compensate wheel spinning on low tyre-friction surfaces. New solutions for automated driving are under development, through the use of gimbal payloads, which are intended to become a low-cost alternative to the widely adopted lidars and radars. New highly efficient 48 V and 100 V modular and flexible powertrains have been implemented, in association with their corresponding energy storage solutions involving NMC pouch, LFP prismatic, and hybrid supercapacitor-battery cells. A new DC wall box is being prepared, suitable for energy storage charging at the two Multi-Moby battery voltage levels. In summary, the Multi-Moby developments will lead to safe, energy-efficient and affordable urban EVs. Further details about the project can be found at Multi-Moby (2022).

Acknowledgements

This work was supported by the European Union’s Horizon 2020 program under grant agreement no. 101006953 (Multi-Moby project).

References

Altreonic NV, 2022. Battery Builder. Last accessed on July 11, 2022, https://kurt.energy/battery-builder.

Eichinger, B., Dullnig, S., Perlo, P., Biasiotto, M., Romo, J., El-Baraka, K., Canitrot, D., Faedo, W., Baron, F., Skigin, L., Karasikov, N., Tavernini, D., Sorniotti, A., Catona, G., Tanzi, C., Verhulst, E., 2022. Electric urban light vehicles structural integrity and occupant protection validation through experimental crash tests, Transport Research Arena. Lisbon, Portugal.

Guastadisegni, G., So, K.M., Parra, A., Tavernini, D., Montanaro, U., Gruber, P., Soria, L., Mantriota, G., Sorniotti A., 2022. Vehicle stability control through pre-emptive braking. International Journal of Automotive Technology (under review).

Multi-Moby, 2022. Multi-Moby – H2020 project. Last accessed on July 11, 2022, https://www.multi-moby.eu.

Scamarcio, A., Caponio, C., Mihalkov, M., Georgiev, P., Ahmadi, J., So, K. M., Tavernini, D., Sorniotti, A., 2022. Predictive anti-jerk and traction control for V2X connected electric vehicles with central motor and open differential. IEEE Transactions on Vehicular Technology (in press).

So, K.M., Tavolo, G., Tavernini, D., Grosso, M., Pozzato, S., Perlo, P., Sorniotti, A., 2022. Novel pre-emptive control solutions for V2X connected electric vehicles, Transport Research Arena. Lisbon, Portugal.

Tavolo, G., So, K.M., Tavernini, D., Perlo, P., Sorniotti, A., 2022. Nonlinear Model Predictive Control for Preview-Based Traction Control, 15th International Symposium on Advanced Vehicle Control. Kanagawa, Japan.