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Structural and energy storage retrofit of an electric bus for high-power flash recharge

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Abstract

The activity here presented describes the retrofit performed on a small-size electric urban bus, which has been transformed in a laboratory vehicle for flash charge functionality using energy transfer between supercapacitors. The existing motor and driveline has been maintained, while the energy storage, originally based on lead batteries, has been modified reducing battery capacity and installing high voltage supercapacitors; such hybrid energy storage system is able to accept high recharge power (approximately about 150kW-peak in the used configuration), while smoothing power load on battery during traction. The system is therefore also able to extend the life of aged batteries. The so-called flash charge occurs through a pantograph connection to the infrastructure, typically in case of bus stops, during ascent and descent of passengers. The structure of the vehicle used for the transformation, which is still widely used worldwide, is constituted by as a glass fiber bodywork installed on a steel frame; since the body was not designed for the support of a significant mass as the one of the pantograph, it has been necessary to install an additional frame anchored to the main vehicle frame; such auxiliary frame has been designed also to substitute the internal fittings of the vehicle, in order to be used as stanchions for the standing passengers. In parallel, the battery compartment has been redesigned in order to install the supercapacitors and the new power converters needed. The contents of the article include the description of the mechanical components installed for the retrofit, the definition of the main power management strategy for the new powertrain and the results of preliminary testing activities.

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1. Introduction

The use of electric heavy vehicles for city services such as public passenger transport has been proposed as commercial solution since the early 90's, especially in order to fit the needs of historical city centers especially in terms of noise and air pollution avoidance. A significant example is represented by electric buses such as the Tecnobus Gulliver, which is able to transport up to 28 passengers and has been on the market since early 90s. In comparison with recently proposed vehicles, early generations of such buses were equipped with lead batteries, driving range being a compromise between installed volume and mass of the energy storage and the need for long daily service per vehicle. Also due to this reason, some versions of the vehicle were also constructed in order to facilitate battery swap, a solution which was preferred to fast charging systems (Padin, 1996).

In recent years, a couple of such small-size buses have been used for joint research activities between ENEA Research Center and Academic Institutes, aiming to design, demonstrate the feasibility and test the effectiveness of solutions for innovative energy storage and for integration in city infrastructures.

The retrofit of the vehicle in terms of substitution of lead batteries with lithium based-ones, for example, proved not only the increase of the achievable daily range, but also the overall reduction of energy consumption per km due to the significant variation of the battery mass, a clear advantage of high energy density cells. A reduction of energy consumption up to about 15% is therefore possible, final value being about 500Wh/km (Alessandrini et al., 2017) for the vehicle and the conditions under study.

Further research activities include the application of high power systems to be used for opportunity charging, a suitable solution to extend working shift of vehicles which are subjected to systematic stops such as public transport and also garbage collection vehicles (Reatti et al., 2017) not only to satisfy current range needs, but also reducing the size and the cost of the battery installed (Barbieri et al., 2018) or even preparing the conditions for continuous use in case of introduction of self-driving systems in the next years. For the case study here presented, the choice has been to retrofit the existing bus with a contact power transfer system adopting a roof top pantograph, while the power is transferred between two supercapacitors systems. Such devices are suitable to support high current loads with satisfactory efficiency due to their low impedance; supercapacitors are also resistant to ageing in case of frequent cycling (Burke and Miller, 2011). The proposal can be described as "flash" recharge (Alessandrini et al., 2019a). The activity here presented is part of the three-year project called "Ricerca di Sistema" for flash charging infrastructure development.

The document is organized as follows. Section 2 describes the whole solution including the retrofit of vehicle powertrain, of bodywork structure and the characteristics of the infrastructure prepared. Section 3 is focused on the analysis of the auxiliary structure needed for pantograph installation in the existing vehicle, which has been verified with Finite Element (FE) modelling. Section 4 provides details on preliminary system testing. Final observations and description of next research steps are presented in the conclusion section.

2. Electrical and mechanical retrofit of the vehicle

The Tecnobus vehicle used for the transformation is one exemplary of the early series of the product and has been used in the Florence area (Barbieri et al., 2016), thus it is originally adopting lead batteries. The structure of the vehicle comprehends:

- a steel frame composed by welded profiles of large section
- axle systems (traction being on the front one); pneumatic suspensions are adopted
- a full composite bodywork, constituted by large glassfiber parts eventually glued or riveted together (see Fig. 1)
- a box installed on the rear part of the vehicle which hosts the batteries, moving on wheel runners to enable battery swap using simple forklifts.

Looking at the interior, the vehicle has 8 seats and can transport further 20 standing passengers; 4 main vertical stanchions are installed on the pavement to be used for the passengers. Main aim of the retrofit in respect of vehicle layout have been:

- to preserve the passenger compartment for demonstration use
  - the consequence is that large parts (converters, batteries and supercapacitors) have to be installed in the existing battery compartments
- to support the pantograph without stressing the glassfiber bodywork
  - the consequence is that an additional frame anchored to the main steel frame has to be adopted and integrated with the interiors in order to not interfere with passengers
- to maintain as much as possible the existing powertrain system for cost and reliability reasons
  - the consequence has been that lead batteries, power converters and control systems have been maintained.
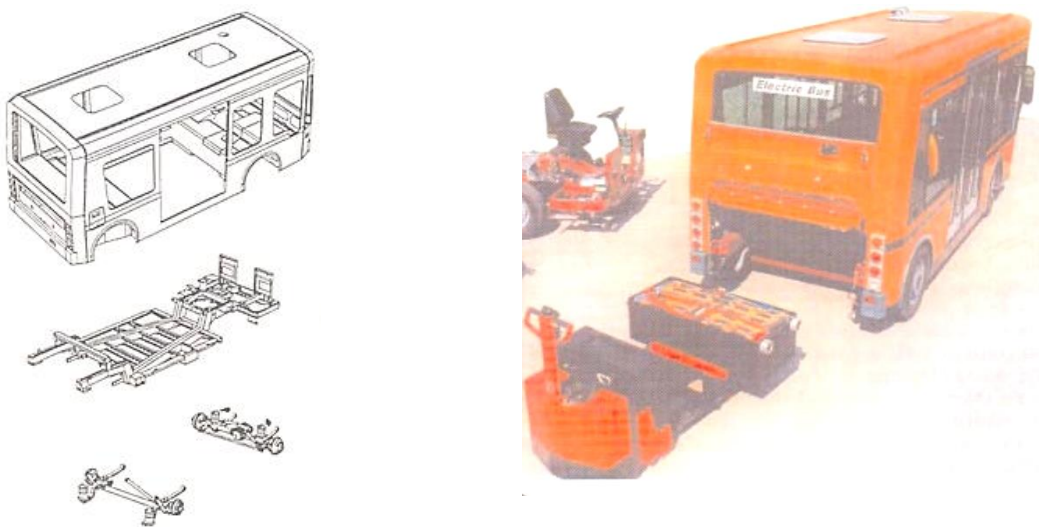

Fig. 1. Structure of the vehicle adopted for the retrofit. Left: full glassfiber bodywork and steel frame subdivision. Right: Moving boxes for lead battery installation and swap demonstration.

2.1. Layout of the electrical system

In order to let the flash recharge occur, two corresponding systems have to be installed in the transport system comprehending vehicle and infrastructure. The systems have been designed in order to provide in working condition up to 300 Wh/charge, that is significant for the size of the bus adopted since it can cover the energy consumption for approximately 0.5km. Scaling up is possible to support larger vehicles, the consumption being approximately 2kWh/km for a heavy 12m bus.

Regarding the infrastructure, as described in literature (Ortenzi et al., 2018, 2019), the core of the system is constituted by an energy storage comprehending a stack of supercapacitors modules. The features can be synthetized as follows:

- the power source for the infrastructure energy storage is a modular multilevel converter connected to the grid; the total power of the system is 8kW.
- six supercapacitor modules – each one being composed by a bank of series-parallel units in order to achieve a nominal capacity of 63F and 125V as maximum – are installed on the infrastructure, and their layout as series elements can be modified using a group of contactors.
- once that the vehicle is connected to the infrastructure using a pantograph – contact bars dome interface, the system closes the contactors accordingly to the effective status of energy storage on the vehicle. Then, current flows to the supercapacitor banks on the vehicle using an inductor as power limiting device. The

configuration of the contactors can vary for a same charging event depending on the voltage variation of both vehicle and infrastructure supercapacitors; usually, energy transfer is subdivided in 2 or 3 steps.

Typical currents during flash recharge phases are in the range of 400-500A, while peak power is 180kW.

Regarding the vehicle, the hybrid storage system adopted (Alessandrini et al., 2019b) is composed by a series of three supercapacitor modules identical to the ones of the infrastructure, operating in the range of voltage from 188 to 375V. Considering that the system has been introduced as pure retrofit of the existing powertrain, the dc-bus operating at the nominal value of 72V has been maintained, while DC/DC power conversion systems are installed to provide power transfer between batteries, dc-bus and supercapacitors. The converters are buck-boost type, so that it is also possible to transfer energy from the low voltage DC-bus to the high voltage supercapacitors during regeneration. The assembly of the three therefore constitutes an hybrid energy storage system; however, the additional high voltage unit can be disconnected, letting the vehicle work in standard configuration, although with reduced range and peak power to the need and the will to downsize the battery. Finally, a motorized pantograph can connect the supercapacitors to the infrastructure through the bars protected by a plastic dome.

As known from literature (Kuperman and Aharon, 2011; Thounthong et al., 2009; Yu et al., 2011), the effectiveness of the system in terms of efficiency, peak power capability, optimal ageing of battery and supercapacitors strongly depends on the power management strategy implemented. For the presented application, a simple proportional rule aimed to reduce the current on the battery has been applied as preliminary implementation. The simplified layout shown in Fig. 2 shows the main loads on the low-voltage DC-bus: traction converter/motor group, 24V converters for auxiliary and comfort systems, and services such as air compressor for the suspensions and power steering pump. All the elements are installed in the existing battery compartment; lead elements have been substituted reducing the total capacity of the original battery from 585Ah (flooded lead cells, series of 36 units, 2V each) to 120Ah (AGM sealed lead battery, series of 6 blocks, 12V each). As a consequence, the mass installed in the compartment decreases from the about 1200kg of the original configuration to an approximated value of 550kg, estimated considering the mass of the installed elements and of all necessary fittings such as cables, connectors and mounting hardware. Details are provided in Table 1.
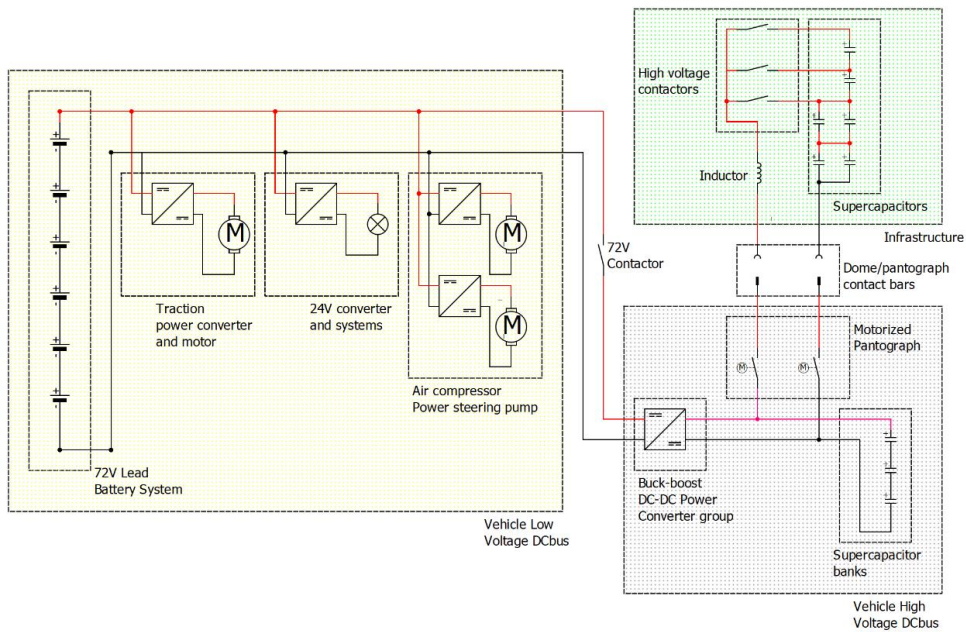

Fig. 2. Simplified layout of the electric system comprehending vehicle low voltage DC-bus, high voltage DC-bus and infrastructure energy storage.

Table 1. Summary of electric systems installed on the vehicle and of vehicle performances.

Component	Characteristics	Notes
72V Lead battery	6x12V 120Ah nominal capacity	Mass: 38 kg each
Traction unit	DC series – Max power 24.8 kW peak	
Vehicle systems	DC air compressor: 265W	
	DC steering pump: 1800W	
24 Converter for auxiliary and comfort systems	24V DC – 900W peak	Power is estimated.
Supercapacitors module	Maxwell heavy transportation BMOD0063 P125	Mass: 60.5 kg each
	Max Voltage: 375V	3 units on vehicle
	Usable min voltage: 187.5V Approx.	6 units on infrastructure
	Capacity: 63F	
Buck-Boost DCDC converter	TAME Power COMET converters	Adapted from manufacturer
	Low Voltage side: 50-90V; 90A peak	1, 2 or 3 units installed depending on configuration
	High Voltage side: 170-400V; 30A peak	
		Mass: 11 kg each
Dome and Pantograph	Schunk Smart Charging	Mass on the vehicle: 90 + 10 kg (pantograph arm and pantograph head holder)
	Voltage: 1000V max;	
	Current: 1000A – 30s; 500A – 15min; 150A – 6h	Mass of contact dome on infrastructure: 45 kg
Nominal performances	Max speed: 35 km/h	
	Max acceleration: 1.35 m/s^2	
	Estimated range: 60 km in optimal conditions for original configuration	

2.2. Design of mechanical components for vehicle retrofit

The retrofit of the vehicle required the definition of two main assemblies, which are the new battery compartment and the auxiliary frame for the support. The first one is shown in Fig. 3; it fits the same size of the original rolling compartments (originally hosting 2 separate small boxes) and can host all the power components of the hybrid energy storage. It has been built using steel sheets and considering the mass reduction in comparison with the original part, the design of such part is not demanding and only simplified verifications have been performed to ensure sufficient stiffness. A cutaway layout of the retrofitted vehicle is shown in Fig. 4.
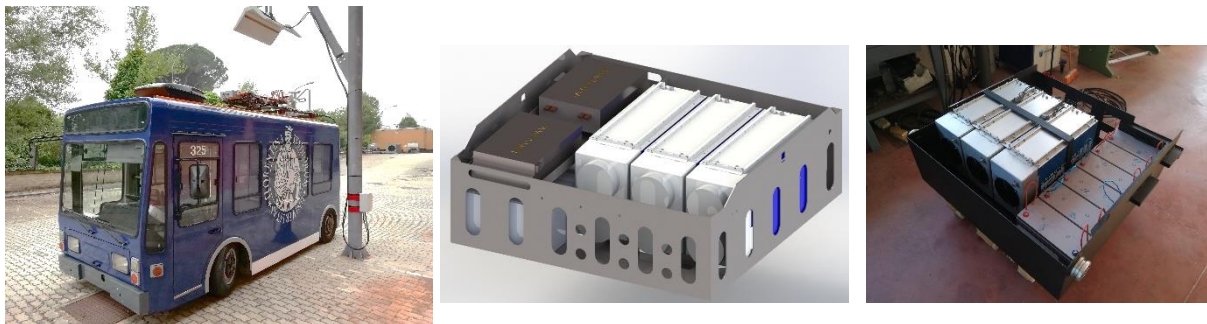

Fig. 3. Left: final version of retrofit vehicle under charging infrastructure. Center: rendering of new battery compartment including lead blocks, supercapacitors and power converters. Right: mounted battery compartment (power converters still not installed).

Even if certain bus vehicles use bodywork as structural components (Kepka et al., 2019), an examination of the glass fiber top of the vehicle suggested the design of an frame for the support of the 100 kg pantograph over the roof.

For this part, an additional investigation has been proposed. Due to the reduced size of the vehicle, of the seat layout and of the presence of a large door, it was not possible to install a frame close to side walls. Therefore, original stanchions (fixed to the pavement in point which were not corresponding to the main vehicle frame) in the center of the vehicle pavement have been removed and substituted by 4 steel tubes which have to work both as stanchions and structural support; the use of a maximum diameter of 40mm was recommended for proper hand grip for standing passengers (Uetake and Shimoda, 2006).
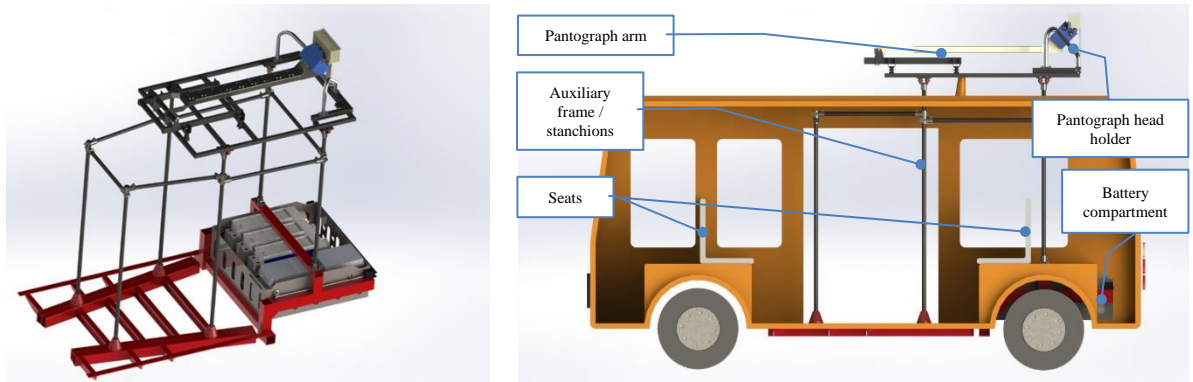
Fig. 4. Left: transformed vehicle layout; red profiles represent the existing vehicle frame. Right: simplified cutaway showing integration between bodywork, frame and new elements.

In addition, a third row couple of tubes not usable as stanchions has been installed in the area behind the seats (see Fig. 4) in order to increase longitudinal stiffness. Commercial aluminum pipe joints have been adopted.

3. Finite Element modeling and analysis of auxiliary frame

The auxiliary frame has been modelled using FE in order to verify deformation and stress under dynamic loads which can occur during the use of the bus, which can be critical considering the vertical size (pantograph is installed above 2300mm from vehicle frame) and the limitations for transversal size, maximum width between tubes being 1230mm due to the need to intercept main vehicle frame bars.

Depending on part characteristics, different elements have been adopted. The choices are summarized in Table 2.

Table 2. Characteristics of the FE model.

| Component type	Characteristics	Element type	Typical Mesh size	Material	Young Modulus
Square profile	40x40mm; 3mm thickness	Quad4 Shell	4mm	Steel	210 GPa
Circular profile (pipe)	40mm diameter; 3mm thickness	Quad4 Shell	4mm	Steel	210 GPA
Joints	Commercial size – typical thickness: 8mm	Tetra-meshing solid	2mm	Aluminum	69 GPa
Insulators	Type 1: 30mm height; Type 2: 60mm height	Circular-drag hexa-meshing solid	1mm	PA + 30% GlassFiber	5 GPa
Screws	M8	Pre-loaded beam, 7500N		Steel	210 GPa
Loads	See Fig.1	Concentrated mass		Supported by RBE3 elements	
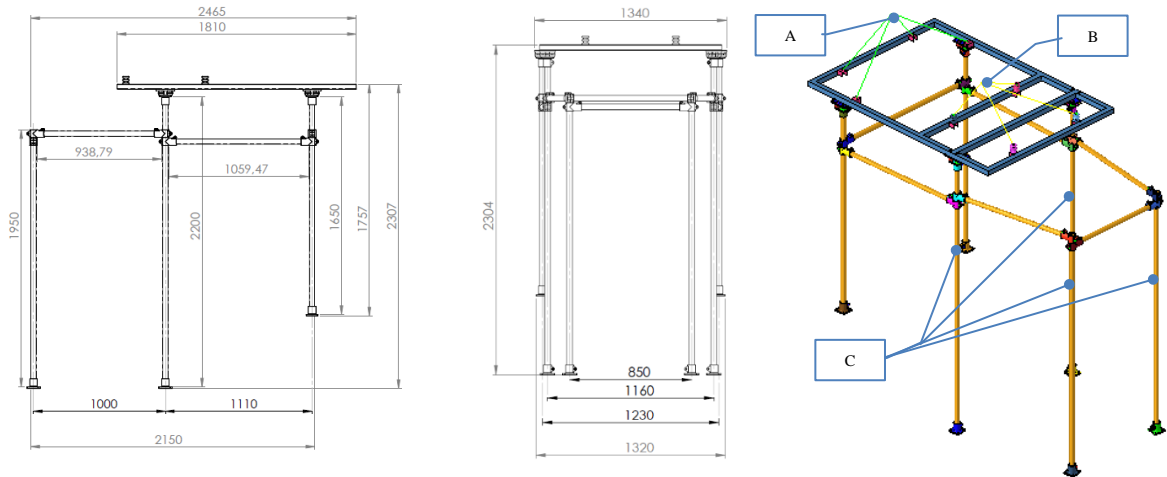
Fig.1. Left: Frame assembly size. Right: Additional masses corresponding to pantograph head holder (A), pantograph arm (B) and passengers holding at the stanchions (C - 120kg per tube, distributed from 150 to 180mm height).

A group of glass-fiber Poliammide (PA) insulators has been used to support the upper part of the frame, to guarantee the insulation in case of electrical damage of the pantograph. As visible in Fig.1, the model includes concentrated masses to represent the load on the frame, constituted by pantograph assembly (arm and holder) and by an equivalent passenger mass holding at the stanchions. The mass of the full FE model is 97kg, which is in accordance with the assembled unit.

After meshing the whole assembly, proper characteristic have been defined for the connection between elements which constitute the constraints of the system:

- Vehicle frame is represented by a small plate below each bottom aluminum joint, each node being fixed
- Plain contacts between surfaces (e.g. joint to frame; insulators to joints) are represented by contacts, slide type (see Fig.5).
- The link between circular pipes and aluminum joint is represented by contacts, freeze type.
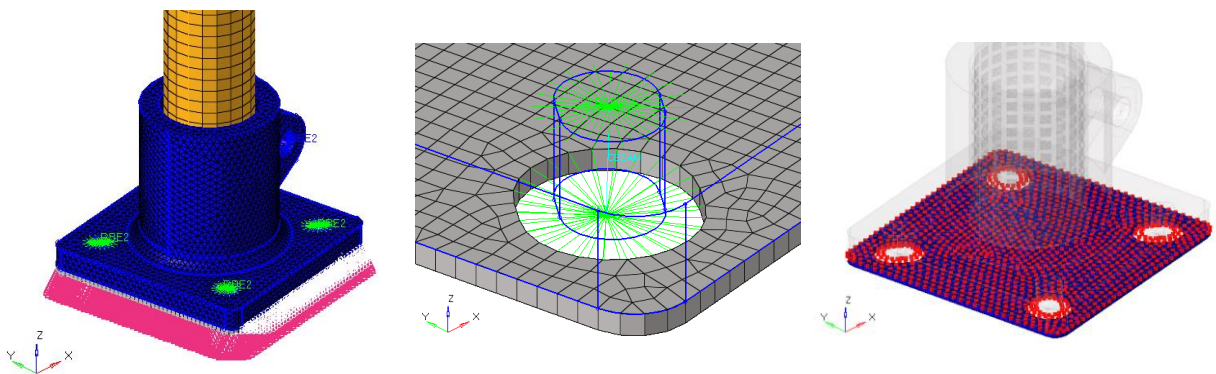

Fig.5. Left: Constraints of small plate (gray) representing vehicle frame. Center: detail of screw connection; gray plate is the fixed part, while the joint is transparent. Right: Slide contact elements between plate and joint surface.
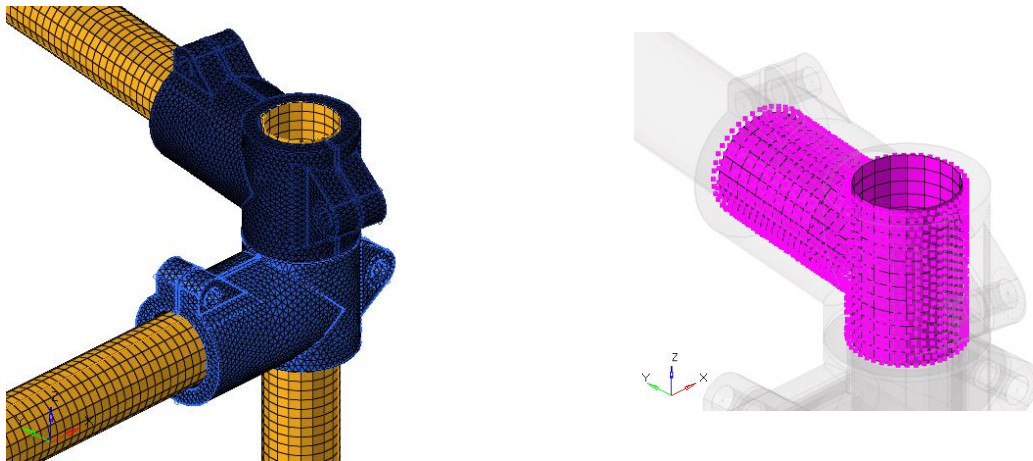
Fig.6. Left: Joint (solid) and tubes (shell modelled on midsurface) assembly. Right: details on contact elements.

The load on the structure is represented by the masses applied on it combined with proper acceleration. Masses include pantograph assembly, frame assembly and an equivalent passenger mass, estimated as follows.

Maximum grip forces for various categories of passengers measured in literature (Uetake and Shimoda, 2006) are comprehended in the range from 250N to 500N, but for 40mm tubes this value can be reached only in pushing direction, while it falls to a 60-70% for pulling. A value of 300N per passenger can be therefore considered as typical maximum. To represent this value, it has been considered that 4 passengers can grip to each pipe, and that an equivalent mass of 30kg per passenger can be sustained in case of strong grips; an acceleration of 1.1g thus provide a total force of about 1300N (320N per passenger).

Typical accelerations of bus vehicles have been measured as having a maximum of 0.3g in case of braking and 0.25g in case of accelerating (Beurier, 2012; Schubert et al., 2017). For the first load case, an enhanced value of 0.5g has been used to analyze limit driving conditions; a second load case of 1.1g is considered to represent abnormal events such as emergency stops. Therefore, 0.5g and 1.1g have been applied both in longitudinal direction (representing braking) and in transversal direction (representing cornering). As additional load case, vertical acceleration of 3g has also been imposed.

Passenger mass has been excluded for modal analysis.

Table 3. Loads adopted for the analysis

Analysis type	Mass	Acceleration
Modal	Pantograph arm: 90kg	Not applicable
	Pantograph head holder: 10kg	
	Total: 100kg	
Vertical bump		Vertical: 3g
Braking (max driving condition)	Pantograph arm: 90kg	Vertical: 1g; Longitudinal: 0.5g
Braking (abnormal events)	Pantograph head holder: 10kg	Vertical: 1g; Longitudinal: 1.1g
Lateral acceleration (max driving condition)	Equivalent passenger mass per pipe: 120 kg	Vertical: 1g; Transversal: 0.5g
	Total mass: 100kg (only pantograph) or 580kg (20 passengers)	
Lateral acceleration (abnormal events)		Vertical: 1g; Transversal: 1.1g

3.1. Results of FE analysis

As a preliminar step, the linear modal analysis has been performed in order to verify the integrity of the model and main modes of the structure. The analysis has been performed maintaining bottom constraints to vehicle frame and looking for frequencies up to 200 Hz; 43 modes have been found. The first ten modes are listed in Table 4.

The frequency of the first 3 modes is below 10Hz; they correspond to lateral, longitudinal and twist oscillations respectively, as shown in Fig.7. The minimum frequency emerging from modal analysis (which is 6.80 Hz) is considered acceptable for the case study, roughly assuming the natural frequency of suspension between 1 to 2 Hz. Modes from the 4th on correspond to significantly higher frequencies (approx. 30Hz).

Table 4. Vibration mode of the structure (first 10 over 43 found).

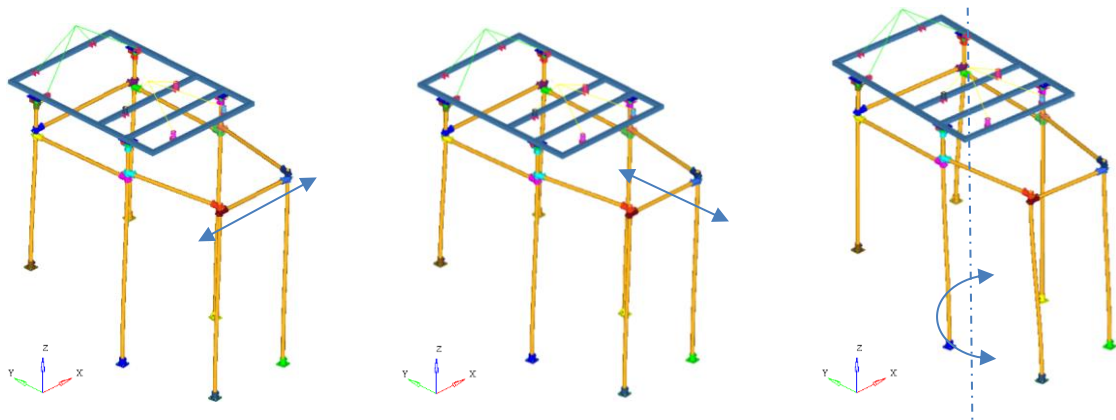| Mode number	Frequency
1	6.80E+00
2	7.40E+00
3	9.24E+00
4	3.07E+01
5	4.16E+01
6	4.46E+01
7	4.75E+01
8	5.29E+01
9	5.72E+01
10	5.93E+01

Fig.7. First vibration modes deformation. Left: Mode 1, transversal oscillation (parallel to x-axis) of structure. Center: Mode 2, longitudinal (parallel to y-axis) oscillation. Right: Mode 3, structure twist on a vertical axis approximately located at the center of the structure.

Then, the analysis has been performed for the case studies listed in Table 5, which are the combination of hypotheses load defined in Table 3. The results highlighted that that loads on screws, joints and insulators where appropriate; such data are trivial and omitted in order to focus on the stress of the tubes of the structure.

The results of the vertical acceleration analyses, shown in Fig.8, highlight very limited displacement as well as limited stress on the whole structure.

In case of braking, the mass of the pantograph itself without considering the passenger determines a maximum displacement of 2.5 mm and 5.5 mm in the top joint respectively for maximum driving acceleration (0.5g) and for abnormal events (1.1g), stress being below 75MPa in any case. Adding passenger mass determines a strong increase of deformation and stress; maximum values are estimated to be respectively of 13.5mm (top joint) and 183 MPa for 0.5g load case and 30mm and 403MPa for 1.1g load case. Fig.9 shows the results of braking maneuver (0.5g with full mass applied on the system). Lateral acceleration, as expected from modal analysis, is the most demanding condition; in full passenger conditions, accelerations can determine displacements up to 26mm (top joint) and 208MPa stress for 0.5g (see Fig.10), which rise to 57mm and 453MPa for 1.1g.
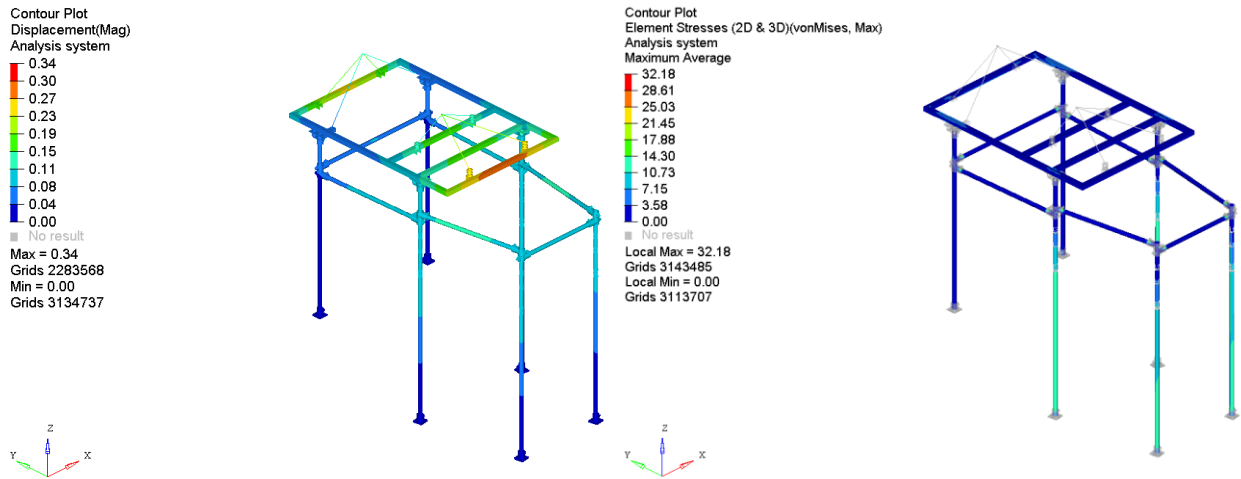
Fig.8. Left: Displacement of frame. Right: Frame tube stress (equivalent Von Mises). Load case: Vertical acceleration 3g, full mass (LC2 according to Table 5).
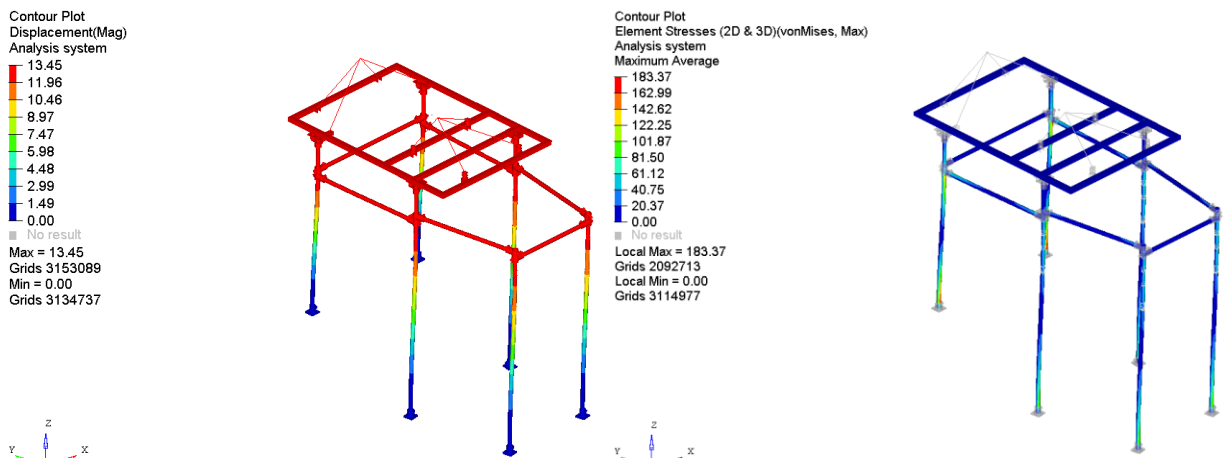

Fig.9. Left: Displacement of frame. Right: Frame tube stress (equivalent Von Mises). Load case: Braking 0.5g, full mass (LC4 according to Table 5).

According to Fig.11, which represents the most demanding condition for lateral acceleration, limited stress is localized on the insulators, while the maximum stress is localized on the connection with bottom joints. Regarding the final design of the structure, therefore, a few observations can be summarized as follows:

- The frame is adequate for the pantograph itself, but notable displacements and stresses are possible in case of strong accelerations with full load of passengers
    - For this reason, the interface between frame pipe and existing roof requires an adequate freeplay to avoid the participation of the roof itself to structure stiffness, if this feature is not desired. In the final assembly, a rubber cone has been used to obtain sealing while ensuring limited force exchange between roof and tube.

- To ensure that no plastic deformation occur in case of acceleration above 1g (an event which is, in any case, far above normal driving conditions), a steel alloy with adequate yield limit – above regular construction steel such as S355 – is needed.
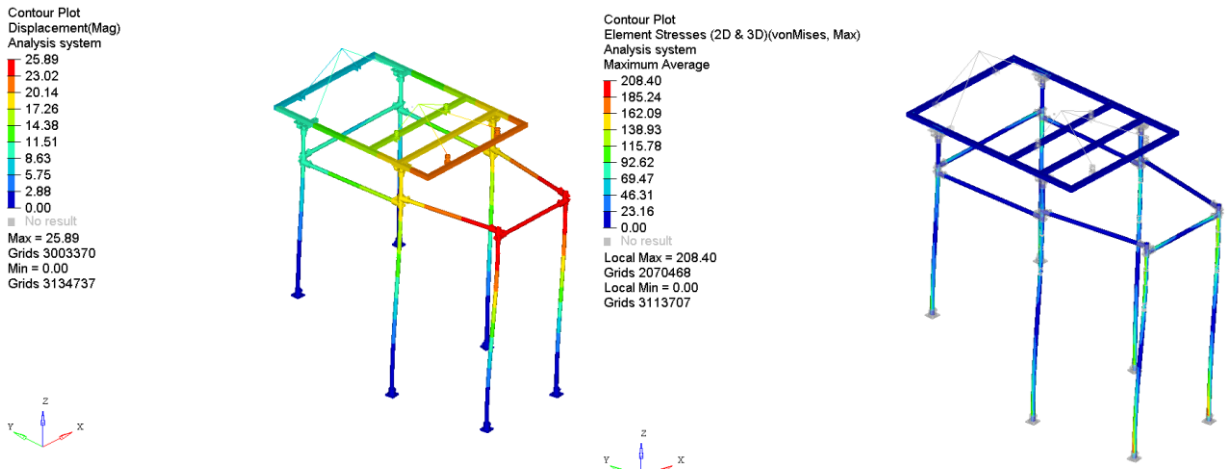

Fig.10. Left: Displacement of frame. Right: Frame tube stress (equivalent Von Mises). Load case: Lateral acceleration 0.5g, full mass (LC8 according to Table 5).
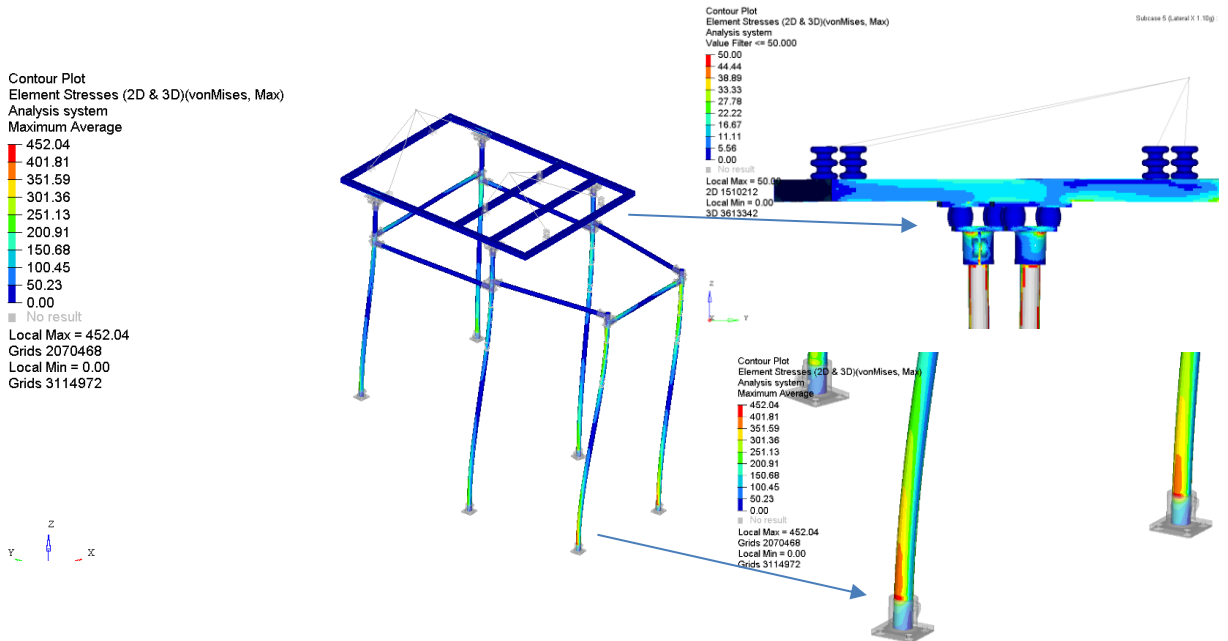

Fig.11. Left: Frame tube stress (equivalent Von Mises) of frame. Right:. Stress on the insulators; stress on the most stressed point of pipe (bottom pavement joint). 1.1g, full mass (LC10 according to Table 5).

Table 5. Results of analyses performed on auxiliary frame per each load case. Stress data are referred to tubes since screws have been verified separately.

Load case number	Acceleration	Mass on vehicle	Maximum deformation (mm)	Max Von Mises stress (MPa)
LC 1	Vertical bump	100 kg	2.60E-01	3.22E+01
LC 2	Vertical bump	580 kg	3.40E-01	3.22E+01
LC 3	Braking (max driving condition)	100 kg	2.48E+00	3.36E+01
LC 4	Braking (max driving condition)	580 kg	1.35E+01	1.83E+02
LC 5	Braking (abnormal events)	100 kg	5.46E+00	7.31E+01
LC 6	Braking (abnormal events)	580 kg	2.96E+01	4.03E+02
LC 7	Lateral acceleration (max driving condition)	100 kg	3.01E+00	3.67E+01
LC 8	Lateral acceleration (max driving condition)	580 kg	2.59E+01	2.08E+02
LC 9	Lateral acceleration (abnormal events)	100 kg	6.61E+00	8.33E+01
LC 10	Lateral acceleration (abnormal events)	580 kg	5.70E+01	4.52E+02

4. Preliminary calibration and vehicle testing

After preliminary test-bench calibration, the system has been tested adopting the control logic described in (Alessandrini et al., 2019a), whose main points are:
- A PID control based on battery current is adopted to reduce the battery current itself
  - Preliminary test use a pure proportional control, with P coefficient set at 0.95
- Current values below 18A are not considered to start power converters using supercapacitor energy, since this value corresponds to the maximum idle power consumption of the vehicle (auxiliaries full working).

Fig.12 shows the power transfer from infrastructure to the vehicle; starting from about 245V, the maximum value of 375V is achieved with a 2-step flash sequence. Subsequently, the vehicle is driven in real-world similar scenario (a closed area similar to an urban route) in order to verify the functionality of the system. The setup comprehended the adoption of 2 power converters, able to supply about 180A on the low-voltage DC-bus, equivalent to about 13kW. For the test shown in Fig.13, boost capabilities (i.e. delivering power to supercapacitors instead of batteries) were disabled; their implementation is part of future improvements. Looking at Table 6, the energy delivered with such configuration for a full discharge of the supercapacitors is about 50% of the whole energy used by the vehicle, thus reducing significantly the average power adopted. In particular, considering that battery losses are proportional to the square of the current, the "power peak shaving" – clearly visible from current plot, Fig.13 - is also able to reduce significantly the maximum load on the battery, thus letting such energy storage system work at higher efficiency, that is particular useful in case of partially aged battery – which determines a degradation of internal impedance. A simplified analysis based on a simple constant resistor model shows that for a battery similar to the one adopted (internal resistance approximately equal to 0.05Ohm) such discharge efficiency, for the cycle of Fig.13, increases from about 87% to 95%; the battery-only initial value, in fact, is particularly low due to the downsizing of the battery.
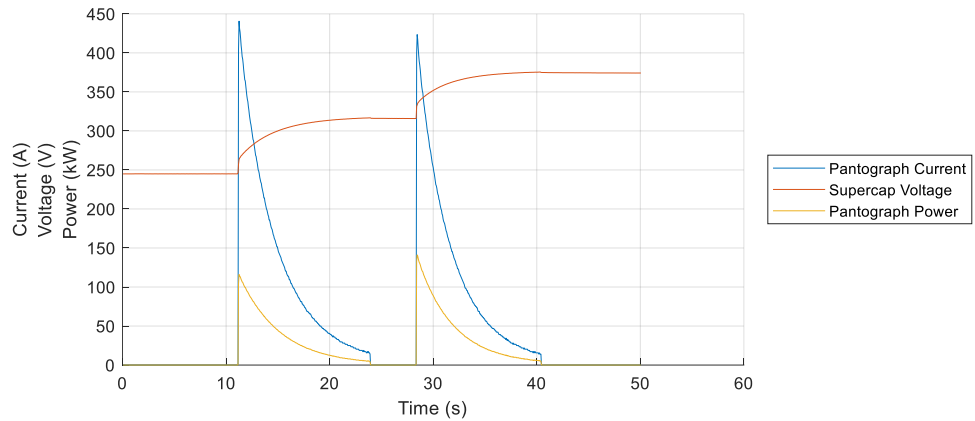
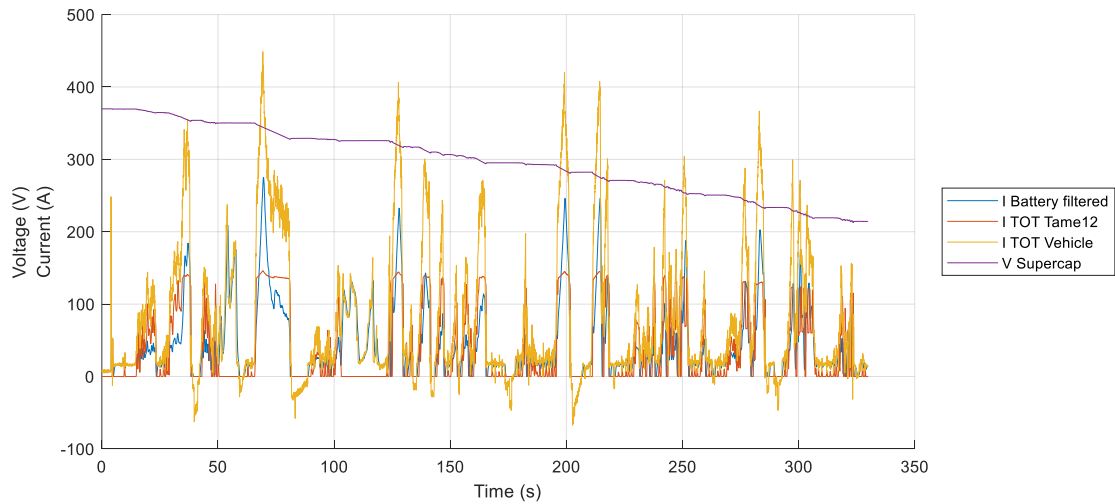Fig.12. Flash charge event, adopting a 2-step sequence.

Fig.13. Vehicle test. I TOT vehicle is the whole current on the DC-BUS; I Battery filtered is the current of the battery, filtered with 1 pole transfer function having a time constant of 0.2s to smooth the power request to the converters; I TOT Tame12 is the current provided by the converter on the DC bus. V Supercap is the voltage of the supercapacitors, that for the sequence shown reach its lower possible value.

Table 6. Energy balance of the test shown in Fig.13

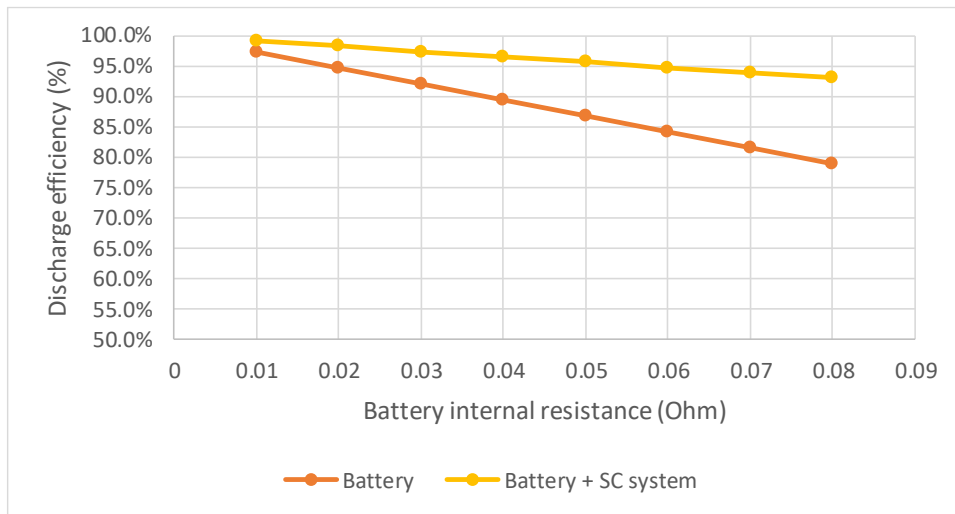|	Energy delivered (Wh)	% on total needed
Vehicle (Total)	529.9	100%
Battery	272.0	51%
DC-DC Converters	257.9	49%

Fig.14. Estimated battery efficiency depending on its internal resistance, using the current load profile defined by the test of Fig.13.

5. Conclusions

The retrofit of a small-size electric bus for flash-charge experimentation required the definition of both mechanical and electric energy storage improvements, due the volume and mass of new components such as supercapacitors and pantograph. A light auxiliary frame has been designed aiming to use it for pantograph support and for standing passenger stanchions. The structure proposed has been analyzed to quantify stiffness, displacement and stress over a set of scenarios, some of them defined using literature data coming from ergonomic studies. The results highlight that it is fit to support the mass of the pantograph itself with small displacements, while in case of full load of the vehicle, the equivalent forces applied on the pipes emulating passenger push/pull efforts can determine significant displacement and stresses. Therefore, proper construction precautions have to be applied, providing sufficient freeplay between vehicle bodywork (estimated to be not capable to sustain additional load on the roof part) and pipes and adopting suitable steel for frame pipes. Modal analysis showed a satisfactory diversification between first mode frequency (approx. 6.80Hz) and typical suspension cut-off frequencies.

Looking at the electrical system, the adoption of supercapacitors together with power converters controlled for current-following performances is demonstrated to be suitable to reduce battery energy consumption and to improve overall discharge efficiency through significant peak shaving, even if the experimented system is adopting a simplified calibration. High power "flash" recharge has also been demonstrated using the full system (infrastructure and assembled vehicle).

Future work will be focused on the improvement of the electrical power system, providing a calibration able to increment as much as possible the whole system efficiency and installing other power converters (conceived as a modular system) to increase the peak-shaving effect due to higher peak power.

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