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48 V NETWORK ADOPTION FOR AUTOMOTIVE LIGHTING SYSTEMS

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Lighting systems with light-emitting diodes (LEDs) are the automotive industry default choice for exterior and interior lighting applications to improve customer quality, reliability and efficiency. Electrical and electronic vehicle architectures are highlighted to create the context between usual propulsion types to create the context of an overall approach. This article studies the trade-off between the 12 V network and the 48 V network with its benefits. The study is conducted by virtual simulation tools to simulate the power architectures of a vehicle and reflect the benefits of a 48 V network for lighting systems to improve power efficiency, reduce total vehicle weight and lower CO_2 emissions. Headlamp converter will be simulated to reflect real use case scenarios between different power networks with different harness mass and the likely scenario to bypass the step-up dc/dc drivers used on the 12 V network for the solid-state lighting sources.

1. INTRODUCTION

Automotive regulations worldwide, concerning CO_2 reduction, is forcing the industry to invest more in battery electric vehicles (BEV) and hybrid electric vehicles (HEV) development. Vehicle electrification based on electronic and electrical architectures is categorized by vehicle type, hybrid electrical vehicles (HEV), battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and vehicles with an internal combustion engine (ICE). For the HEV and PHEV we have different strategies applied between the ICE and the electrical motor (EM) positioned relative to the transmission gears, the topologies can be serial, parallel, and power split (hybrid topology between series and parallel topologies). For BEV, the difference is made by the number of electrical motors used and if a transmission is used or not. With high voltage levels for the power train, the harness cross-sections, size and weight are reduced, as well the inefficient components from the 12 V network [1–5].

Exterior lighting equipment on vehicles are using solid-state lighting sources or bulbs as the main source of light generators, the first category is present on the newest vehicle architectures and the latter on old vehicles or low-priced vehicles. Solid-state lighting sources are silicon-based illumination sources as LED, LASER and OLED’s, they come with the necessity of a driver to regulate the voltage and the current, the overall efficiency regardless of the driver type can be from 50 % in the case of linear regulators, up to more than 80 % in case of dc/dc switching regulators.

Different strategies for CO_2 emission reduction like energy recovery with regenerative braking, 48 V based components and lightweight materials are the appropriate low-cost solutions for the industry standard, the power network below 60 V is not requiring high voltage isolated components, like the power train in BEVs. The power efficiency with regenerative braking is under investigation for more improvements, the most promising are batteries and supercapacitors within the frame of 48 V network adoption [1] and CO_2 reduction is one of the main advantages of this system by supporting the advanced ignition technologies on HEVs like stop and start features, power load components, heating ventilation and air conditioning along with other manufacturer-specific features. Advantages over the components like air conditioning compressors, power steering pump, coolant and oil pumps made the 48 V system the desired choice by all vehicle manufacturers, the comfort functions with high power ratings like heaters are as well fitted on this network. The higher voltage power network helps ICE vehicles with the advantage to use efficient fuel technologies to run additional electric components like superchargers to improve the engine's overall horsepower and result in high performance with increased efficiency and lower emissions [2, 4, 6].

A current market trend is to use the 48 V network with the 12 V conventional network to have a minimal impact over the vehicle electrical and electronic platform architecture initially developed for ICE vehicles and adapted to sustain hybridization. For the 48 V network, the power provided is between 12 kW to 15 kW along with a fuel reduction of 10–20 % and emission reduction up to 15 %, the regulation trend is to set up Europe a limit of a maximum of 60 V for the onboard networks [2, 6], not applicable for the high voltage.

The paper is structured into 5 chapters. Section 1 is focused on the overall market benchmark orientation and trends, next to an overview for the automotive lighting system as a whole in Section 2, the electrical and electronic architecture of the subsystem in Section 3. Furthermore, in Section 4 a holistic approach and model based on Simulink are used to reflect the gain of the 48 V network adoption, focused on weight reduction, topology adjustment and overall efficiency of the system with emphasis on CO_2 reduction. Section 5 is dedicated to the overall conclusions. The paper ends with a meaningful and up-to-date list of references.

2. LIGHTING SYSTEM OVERVIEW

2.1 LIGHTING COMPONENTS

The lighting domain, design and systems trend is evolving from functionality and artistic requirements which adds complexity and bottlenecks for the bulb architectures, with more power and with CO_2 roadmap, LED-based solutions are a must to use. Lighting systems are to become more intelligent and attain an active role within the ADAS systems for safety and visibility with different approaches

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based on LED, OLED, LASER source lights, like matrix-beams which are comprised of complex opto-mechatronics. For the headlights development, the next generation is the adoption of high resolution ‘pixel light’ systems to provide the same functional behaviour as a video projector. The new opto-mechatronic systems can drive more than 100K pixels individually and overpass the matrix-beam based lamps by offering the perfect lighting distribution adaptation for each use case dependent or not by the driver, improving the overall road safety by glare reduction, road sign highlighter and pedestrian warnings [7].

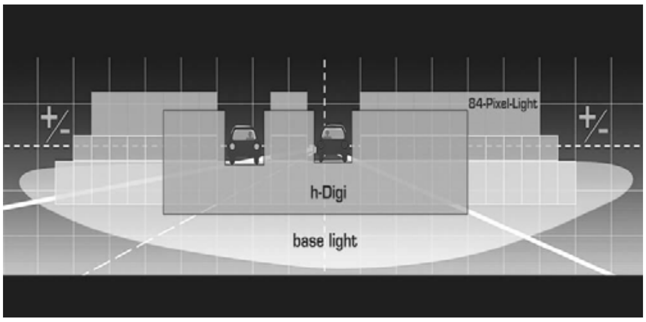


Fig. 1 – Superimposition of the light projections and complementary generation of the light functions for the total light distribution through 3 modules: h-Digi, 84-pixel matrix light and base light projectors [7].

Headlights based on LED, HID (high-intensity discharge) or Xenon use dedicated drivers to charge the loads and achieve start-up, standard filament bulbs don’t require special electronics, the dedicated drivers are boosting the input voltage level up to the LED string voltage, more than 12V and up to thousands of volts to generate the electrical arc for HID or xenon. From the efficiency perspective, LED loads have small radiation losses but the most heat losses, presented in Table 1:

Table 1

The efficiency of lighting loads [8]

Light source	Loss in Radiation [%]	Heat loss [%]	Lumen per Watt [lm/W]
Incandescent lamp	81-86	5-6	6.7-20.7
Fluorescent lamp	30-32	44	33-83
HID (mercury)	62-65	16-22	100
HID (metal halide)	57-74	7-20	100
HID (sodium)	47.3-63.3	10-23	100
LED	0-0.2	80-88	20-130

2.2. SOLID STATE-ORIENTED APPLICATIONS

The automotive trend for lighting systems migrates towards LED-based lamps and are replacing the bulbs for power efficiency gain, up to 10 times than bulb-based lamps [8]. High LED lamp efficiency is possible when dc/dc converters or even LDO (low drop-out) are used, where the first can achieve power efficiency higher than 85 % and the latter below 90 %, due to the design-dependent approach and required output power [10,11]. The approach for satisfying the appearance, from an esthetic point of view along with the functional diversity, animation and photometrical regulation, forces the in-vehicle networking to manage over the communication medium as CAN (controller area network) or LIN (local interconnect network) the lighting control, avoid the wire-by-wire control and reduce the number of wires used [9]. On automotive products, dependent on the lamp type, the LED topologies can be different due to rated power, type of driver, safety constraints, regulations and desired lighting diffusion, the topology can be either series, parallel or matrix for the LED strings.

For the series topology, from Fig. 2, the output is a high voltage output and usually needs a dc/dc driver to boost the input voltage, in case of the 12 V power network, up to LED forward voltage of the string, when high power LED’s are used, this voltage is in the range of 30 V up to 50 V. In the case of linear drivers, this output is usually the same as the input voltage or below due to internal regulation of the electronic circuit, hence the LED forward voltage of the string cannot be higher than the range for the input voltage based on the working functionality area, usually the lowest end should be 8 V or 9 V. The constant current sources are used to ensure the desired current through the string, they are placed on the LED board or driver, to avoid fluctuations between the strings luminous flux [10].

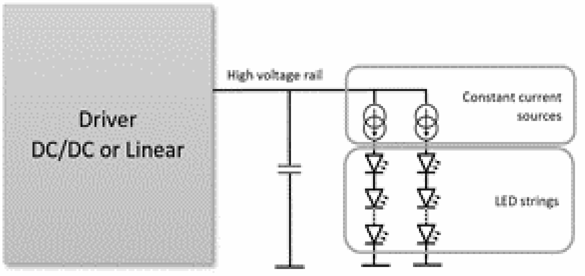


Fig. 2 – Illustration of LED series topology diagram.

For the parallel topology, from Fig. 3, the output is the LED forward voltage, when small loads are used less than input voltage during the worst case, the linear driver is preferred. Current sinks are used for stable current for the LED’s and protection during failure modes, one string in open load, one of the advantages of the parallel topology is the compliance and adaptability with the EU regulations, N-1 rule. The lamp has to ensure a constant output flux in case of one LED fails or to provide a tell-tale in the dashboard to inform the driver about the issue [12]. If cannot be achieved, then a diagnostic strategy must be integrated and the system to inform the user about the issue [20].

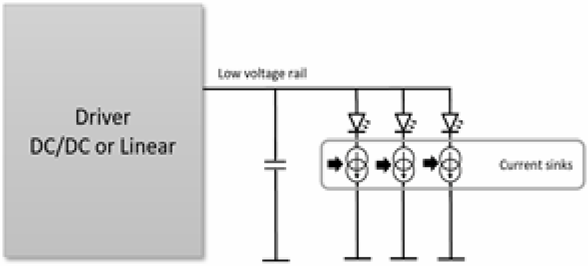


Fig. 3 – Illustration of LED parallel topology diagram.

Matrix LED topology use is like a mesh where the strings can be driven independently, if one of the LED’s is malfunctioning the string is turned off, we see the topology in Fig. 4, used with low power source lights in applications such as taillights and side-marking lights with decorative purposes if they are not impacting the regulatory functions. In practice, this topology is used with up to 20 or 40 LED’s controlled independently by string or by functions, all driven by one driver with high adaptability [12].

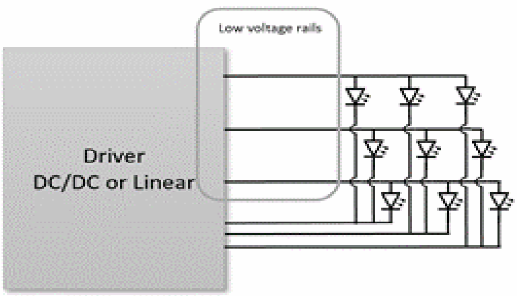


Fig. 4 – Illustration of LED matrix topology diagram.

The lighting driver unit of the lamp is a must-have, due to LED’s or other solid-state lighting sources which cannot function without a specific driving strategy, complex drivers as dc/dc, linear drivers or constant current sources or even resistive drivers for small applications where the light fluctuations or high dependability is not required [10,11]. Quality and perceived effect from LED-based lighting sources is a constraint imposed by the styling of the product and of the associated features desired to be integrated. Dimming strategies are linked with the driver topology and associated use cases such as using one LED string for multiple functions or protecting them at high temperature, we choose either linear, direct current reduction or analogue dimming in Fig. 5. PWM dimming in Fig. 6, can be employed where a high reaction is needed and we have the driver capability to achieve it, a hybrid dimming can be used for achieving specific behaviour according to the design requirements [10,11].

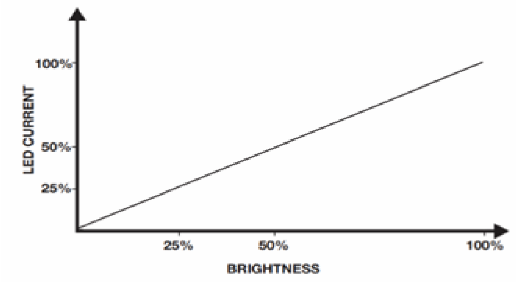


Fig. 5 – Analog dimming [13].

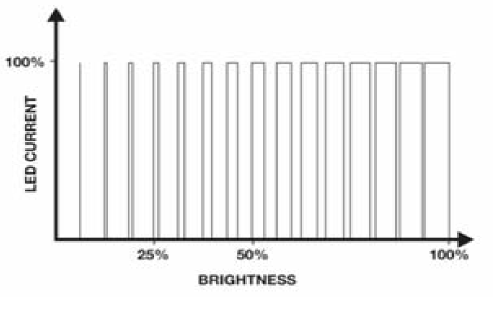


Fig. 6 – PWM dimming [13].

The dc/dc drivers used in the automotive industry for exterior lighting applications are buck, boost and buck-boost, one of them is chosen by topology dependencies and load power requirements, buck-boost drivers are the desired choice for headlights and linked with EMI performance and cost constraints. Performance and efficiency of the drivers from an electrical perspective, for exterior lighting applications, is affected by other electronics like microcontroller, analogue inputs, transceivers for communication and switching phenomena for PWM control of LED’s as well for the internal dc/dc regulators, in Fig. 7. Output luminous flux is dimmed by variating the output current and voltage in PWM, usually higher than 300 Hz to avoid stroboscopic phenomena, not linked with the internal frequency switching of the regulator which can vary in the range of kHz to MHz [14].

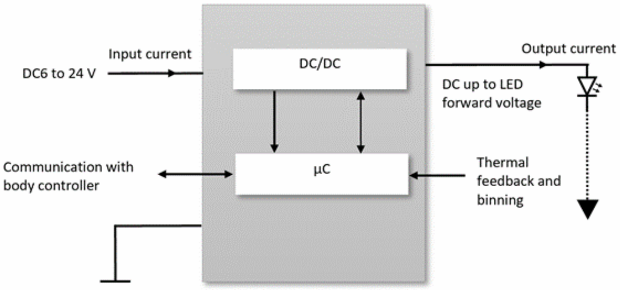


Fig. 7 – Illustration of dc/dc driver.

Adoption of 48 V network provides the opportunity to remove the costly structures due to similar levels between the power network voltage and required forward voltage for the LED’s to be turned on, hence the driving strategy with the dc/dc can be replaced with other driving structures, more cost-oriented and with less electromagnetic interference/susceptibility overall, whereas this paper is providing the overall concept for the optimization of power requirements and system needs to control the marginal design-to-cost approach by 48 V use for the lighting systems and product development.

3. ELECTRICAL AND ELECTRONIC ARCHITECTURE

3.1. MIXT ARCHITECTURE

The application of the 48 V network used alongside the 12 V network, in many approaches gave birth to the hybrid power network, the segregation between the highest consumers and the lowest consumers are achieved and the dc/dc converter oversees the balance of power between the two networks in different life phases like awake, asleep, wake-up and go-to-sleep. Back-to-back networks with the dc/dc converter, keep alive with a balanced state of charge (SOC) on networks when one side of the power network source is in failure, depletion, or overcharge, the other will compensate it [4, 17, 18]. The 48 V network is used for the highest consumers, inductive loads and high starting currents and make it susceptible to architecture design constraints and contains in most cases an integrated starter generator (ISG) and a bi-directional dc/dc converter to deliver up to 10 kW of available energy from the 48 V to the 12 V network [2, 4, 5] and the additional loads. On ICE vehicles, the 48 V power architecture is used mainly for trucks and vans due to the additional loads which like the second HVAC (heating, ventilation and air-conditioning) unit, second compressor, additional alternator, etc. This technology is targeted at conventional ICE vehicles, HEV and BEV, as auto manufacturers strive to meet increasingly stringent CO_2 emissions targets [2, 3, 19, 20]. Mixt electrical architectures are using today the 12 V network for comfort types of equipment like lighting, infotainment, audio systems, seats and ignition status for critical safety-related needs, the 48 V network manages active chassis systems, power steering, HVAC compressors, active dampers for suspension, superchargers and regenerative braking [2], the engine start is as well managed ease and achieves more dynamically the stop and start phases or cranking [15].

3.2. FULL 48 V ARCHITECTURE CONSTRAINTS

The automotive market is ready for the full switch towards the 48 V network, the technology is available but the architecture maturity with associated costs to redesign all the electronic control units with the new features and strategies as the communication bus, electromagnetic interferences or the strategy for safety applications and other regulatory constraints, are holding back the adoption [2, 3, 4, 15].

Table 2

Electrification outlook [16]

Powertrain type	12 V	48 V	Full Hybrid	Plug-in Hybrid	Electric Vehicle
CO_2 potential savings	< 5 %	7 %-10 %	20 %-30 %	50 %-75 %	100 %
Fuel Saving by	Start-Stop	Eco-Drive	Electric Driving	100 % Electric driving	100 % Electric driving
PWT installed power	< 5 kW	6-20 kW	20-40 kW	50-90 kW	50-90 kW
Architecture type	12 V	Mixt 12 V and 48 V	HV PWT, 48 V body electronics	HV PWT, 48 V body electronics	HV PWT, 48 V body electronics

Electrical and electronic architectures changes are imposing new mechanical or mechatronic systems design, due to the many 48 V types of equipment dedicated for energy saving and reduction of power losses, the belt starter used on ICE vehicles is replaced by the ISG. As a steppingstone, the mixt architecture is the solution, for the design-to-cost approach and the time-to-market, on the long run, the 48 V network provides the backbone for upgrades and savings of fuel along with emission gases reduction. [15, 16]. Traction and stability systems used on internal combustion engines are merged and used along with electrical motors on 48 V network, to achieve high electrification targets (Table 2), switching towards this network provides the backbone for full-electric vehicles adoption and optimal power trains [15,16].

4. **LIGHTING SYSTEM PROPOSAL**

The model-based design approach for the lighting system proposed is carried with Matlab/Simulink, we use generic dc/dc control blocks and LED loads based on real usage scenarios in vehicle manufacturers architecture, whereas the EMI input filters, CAN line communication and microcontroller interfaces are not considered and focus is on the power distribution lines and levels.

4.1. LINE RESISTANCE EVALUATION FOR 12 V NETWORK

The vehicle harness is the most expensive and difficult to manage and the line resistance requirements are impacting the performance behaviour, for the 12 V network we do the modelling of the step-up stage with a voltage target of 60 V and the step-down stage to the LED string voltage, in Fig. 8, the efficiency of the system linked to the line resistance between the system supply and the boost is assessed for the given loads.

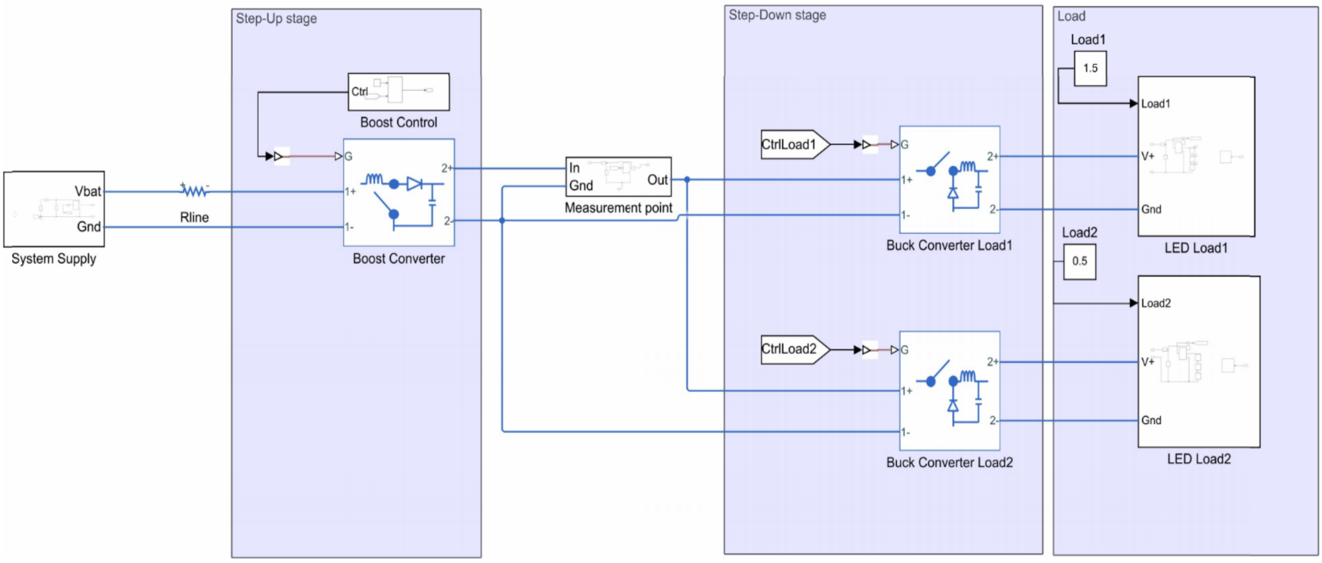


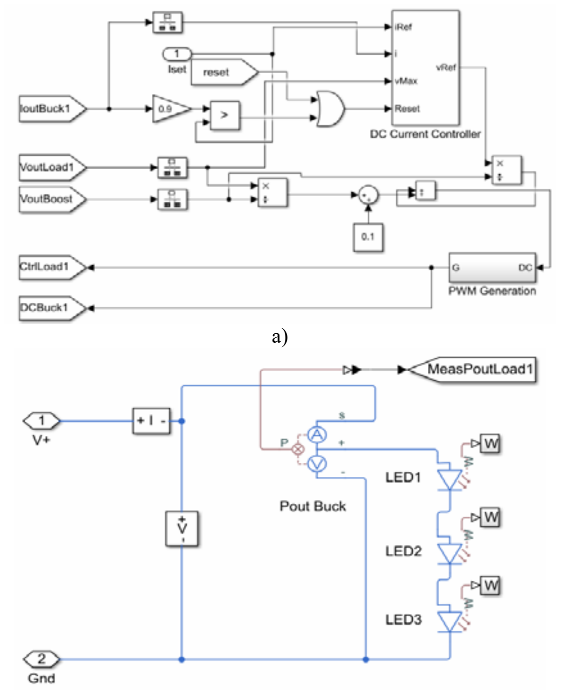
Fig. 8 – 12 V power network with step-up and step-down stages with LED loads.

The LED loads are chosen to have a gap in total LED voltage string, this will simulate the real case scenarios where we can assume the Load1 to be the low beams and the Load2 to be the daytime running lights, the buck converters for each load step-down the 60 V to each LED string voltage, the difference between the voltage drops across the LEDs will generate, from a system perspective, a worst-case scenario of overall efficiency, close to a real environment as we can meet in the modern-day vehicles, the simulated loads and associated representative values presented, in Table 3. Figure 9 is showing the current control loop model for the buck of Load1 in Fig. 9a and the LED topology with series loads used for the Load1 in Fig. 9b.

Table 3

LED loads values used for the simulation

Maximum values	Forward Voltage	Forward Current	Dynamic Resistance	Total installed power
LED load 1	48 V (3 LED in series)	1.5 A	1.2 Ω	72 W
LED load 2	19.7V (3 LED in series)	0.5 A	0.5 Ω	9.9 W



a)

b)

Fig. 9 – Control loop of the step-down in a); LED Load1 model in b).

The step-up and step-down stages, used on 12 V networks is rendering the system to be inefficient, each buck must dissipate the extra energy and voltage from the boost output. The internal frequency of the switching regulators was at 20 kHz, usually higher frequencies are used when small coils are needed, the control of the step-up or step-down was continuous conduction mode (CCM) to achieve constant current through the LEDs with a small current variation of +/-5 % around the required current for normal operation.

The system efficiency is measured for 3 different line resistance values with a load of 81.9 W, we assume an overall efficiency of 80 % for the dc/dc converter. In one scenario, ideal values for the line resistance of 0 Ω was assessed as a reference point, two voltage drops across power lines represented required, they are imposing the line resistance values and shown in table 4, the system efficiency was found for each scenario.

Table 4

Line resistance on 12 V power network

	Rline 1	Rline 2	Rline 3
Rline	0 Ω	0.0467 Ω	0.07 Ω
Voltage drop	0 V	0.4 V	0.6 V
Length of harness	6 m	6 m	6 m
Efficiency	Fig. 10	Fig. 11	Fig. 12
Average Efficiency	72 %	63 %	60 %

Fig. 10 – Average system efficiency for Rline 1 on 12 V network.

Fig. 11 – Average system efficiency for Rline 2 on 12 V network.

Fig. 12 – Average system efficiency for Rline 3 on 12 V network.

4.2. LINE RESISTANCE EVALUATION FOR 48 V NETWORK

With the 48 V network, we removed the step-up stage with the boost, the model represented in Fig. 13, the system efficiency by variating the line resistance is assessed.

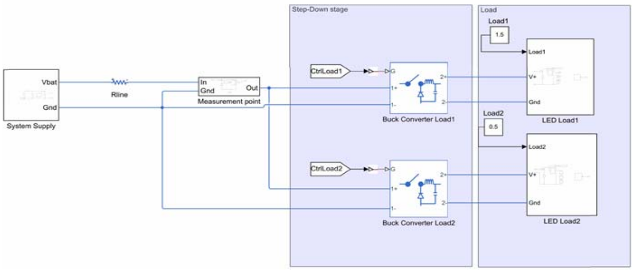


Fig. 13 – 48 V network with step-up and step-down stages with LED loads.

For comparable results the LED loads, converter efficiency and voltage drop target across the lines are not changed and kept similar with the ones from the 12 V network, the efficiency is measured and shown in Table 5, for each value.

Table 5

Line resistance on 48 V network

	Rline 1	Rline 2
Rline	0.22 Ω	0.33 Ω
Voltage drop	0.4 V	0.6 V
Length of harness	6 m	6 m
Efficiency	Fig. 14	Fig. 15
Average Efficiency	97 %	96 %

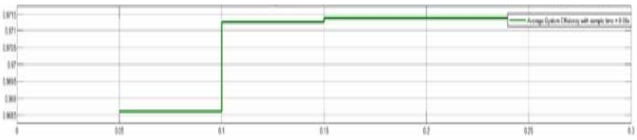


Fig. 14 – Average system efficiency for Rline1 on 48 V network.

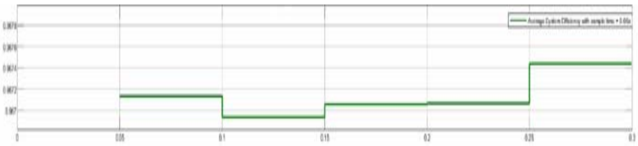


Fig. 15 – Average system efficiency for Rline2 on 48 V network.

4.3. LINE RESISTANCE PERFORMANCE

The imposed voltage drop target across the supply line reflects the impact against the total performance of the system, between the power supply (battery) and the loads. With the imposed maximum admissible voltage drops the weight of the harness changed hence the required wire section needed to attain these voltage drop based on IEC60228 for copper is shown in Table 6, the total weight reduction for the front lighting can be reduced by at least 70 %, with marginal calculation for safety the worst-case scenario would be the reduction with 50 %.

Harness weight is given by its length and section, the routing within the vehicle gives these lengths which usually are longer than the actual vehicle, the harness section is dimensioned based on nominal and peak currents over the line. When the section of the harness is badly designed and smaller than needed, the resistance is increased and the voltage drop is significant, usually can be a difference between 1.5 V or worst between the battery and the load.

Table 6

Wire harness weight

Network Voltage drop	12 V	48 V	Weight reduction
0.4 V	0.179 kg	0.028 kg	-85 %
0.6 V	0.108 kg	0.028 kg	-74 %

Whit high values of voltage drop, the performance is low, and the electrical efficiency as well, this phenomenon is mostly seen on vehicles with bulbs and LEDs, optical performance, power network fluctuations are real generators for flickering and even stroboscopic phenomena.

Lighter vehicles are more environmentally friendly, hence with the weight reduction of the harness, the CO_2 emission of the vehicle will be improved, according to the fact sheet from the ICCT [19], on average for each 100 kg reduction of the vehicle the CO_2 emissions are reduced by 6 g/100 km. Based on the improvement by going to 48 V network and by applying the same strategy for the rear lights which have a small power rating but the harness routing is very long, total cumulative harness weight reduction for external lighting will be reduced by a factor of 50 % for the 48 V network and the cumulative harness weight reduction, for a vehicle usage of 100 000 km, the total CO_2 emission reduction would be around 3 600 g.

5. **CONCLUSIONS**

The 48 V network and the lighting design approach for the electrical and electronics system architecture and the context for the overall approach, improve the vehicle weight, CO_2 footprint and overall cost. The simulation reflected the use case with a real headlight scenario, where the LED loads are in part the low beam with the high voltage drop, the second load is the daytime running lights with the least voltage drop, the OEMs are using the controller ECU for both functions, which is the most cost-effective solution with the least amount of issues like EMI and thermal behaviour.

Line resistance impact assessment, with the worst electrical efficiency of the cascaded switching regulators and the constant input voltage, not including transients or thermal impacts, showed the system impact on the 12 V network and the degradation of the overall performance or efficiency and reflected the advantages of moving towards the 48 V network. From the weight perspective, the harness is reduced by adopting the 48 V network, furthermore, the step-up stage is as well removed because the total voltage across the loads can be designed to be lower than the nominal power network and the efficiency in means of electrical power would be improved with 25 %.

Overall, the gains of the approach, are improving the CO_2 footprint of the ICE and HEV vehicles, on BEV is improving the SOC range and autonomy as well the cost mitigation of the OEM and end customer can see a marketable benefit.

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