Days of future past…
Electrified heavy-duty vehicles
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1 Introduction

Noiselessly and without exhaust, the bus approaches the bus stop. Neither sound nor exhaust, because the vehicle has an electric drivetrain that takes the energy from batteries.

While the doors open to allow passengers to leave and enter the bus, a pantograph on the bus’s roof automatically lifts up and attaches to the electric contacts of the local charging infrastructure. For the short time that it takes the passengers to leave, enter and take a seat, the vehicle’s batteries recharge. With this so-called opportunity charging, the bus can continue its tour around the city without the need of longer breaks or pauses. This setup allows for continuous operation even around the clock despite the fact that the battery’s capacity alone would not be enough to do a one-day shift.

Scenarios like this one became very common in the recent discussion about reducing the emissions in public transportation - but the idea is far from being brilliantly new.

The scene described dates back about 45 years to the mid-70s of the last century. The photo in Figure 1, taken 1980, pictures the scene.
From 1975 to 1988, Rheinbahn in the German city of Düsseldorf operated a fleet of all-electric MAN buses. From the 21 buses in service, only the bus number 9063 remained and serves as exhibition example in a museum today [1].

Back in the 70s, the oil crisis pushed the development of electric transportation but even back then, improving the air quality in the cities was part of the project. Estimations indicate, that heavy-duty vehicle are responsible for about 25% of all emissions in traffic [2].

50 years later, climate change, governmental CO2-reduction plans and even local regulations demand lower emissions [2,3,4]. This motivates manufacturers to develop heavy-duty vehicles that achieve close-to or even zero emission and massively improved fuel efficiency. Better, call it energy efficiency, as using fossil fuel is already ruled out. Combustion engines, powered by fossil fuel, simply can no longer reach the demanding targets in future. The Power-to-X-discussion about the use of hydrogen or even liquid synthetic fuels, generated from renewable energy, is ongoing. Technically, the clear economical and efficiency advantage is with the electric vehicle.

Even the MAN bus from 1970, with a battery capacity of only 108 kWh and a range per charge of only 60-80 kilometers, was highly energy efficient. The 200 kWh per 100 km represent a Diesel-equivalent of only 20 L/100 km. This is remarkable, as even a most recent Euro6-rated in-city bus today easily consumes as much as 35 L/100 km.

Purely focusing on range, with only 2 kWh/km, the old-timer could easily compete with the best modern vehicles that consume similar or even higher amounts of energy. To say the least, modern electric busses offer far higher safety levels and driving comfort for both, passengers and drivers. The comparison thus is slightly misleading, as so many things have evolved over time.
2  From a battery's point of view

With the introduction of Lithium-Ion batteries in hand-held devices like mobile phones, camcorders, tablets and power tools, a new era in battery technology rose in the early 1990s. Gravimetric energy density grew from less than 50 Wh/kg to about 200 Wh/kg while the volumetric energy density achieves 300 Wh/L, compared to the 50 Wh/L in former lead-acid batteries. This improvement was one of the breakthroughs needed to make e-mobility a viable option, even for heavy-duty applications.

In the MAN-bus, the trailer carried about 6 tons of lead-based batteries. A modern battery pack of the same energy is about 600–700 kg only.

While passenger cars today mostly carry less than 100 kWh and achieve 400 km range easily, heavy-duty vehicles demand far higher capacities. Some modern busses feature battery capacities in excess of 600 kWh [5]. This also represents the capacity needed to allow long-haul trucks to go the necessary distance.

In turn, charging the battery in an acceptable time becomes a technological challenge. For private use and depending on battery capacity, a 10 kW wall-box can conveniently charge a passenger car overnight. In commercial scenarios, even a charger with 100 kW output power would need hours to refill the battery of a larger bus or truck. In so-called harbor charging, this poses as a viable option for buses that are idle at night. For long-distance logistics, downtime of hours to recharge a truck remains intolerable.

The most common scenario is a fast-charge from 10% to 90% of the battery’s capacity. In this range, energy transfer takes place by constant current charging. Though the charging voltage increases slightly, the output power in this mode of operation remains almost constant as well. Simplifying, recharging 480 kWh in one hour demands 480 kW of charging power, while even the most powerful public DC-charging stations today can provide a maximum of “only” 350 kW. The change in battery chemistry also brought electrical challenges. While former lead-acid or lead-gel batteries were partially resistant to overcharging, lithium-based chemistry needs protection from such events. Both, overcharging and deep discharging can potentially damage the cells beyond repair.
3 From charging infrastructure’s point of view

The power electronic sections of high-power chargers are typically not monolithically integrated. Instead, units with lower output power in parallel operation form one high-power charger. Widely used are units with individual power levels up to 60 kW. In high-power charging applications, the charger’s efficiency is in focus. Legislation demands the operator to pay for the energy taken from the grid and bill the customer the energy delivered. Losses due to inefficient energy conversion remain with the owner of the infrastructure. Recent developments in chargers therefore target new topologies as well as new power semiconductor technologies. Figure 2 depicts a schematic of a 60 kW unit. In sum, six of these units operate in parallel to provide 350 kW charging power.

These days, silicon carbide (SiC) MOSFETs more often replace IGBTs in this area. Their inherent properties allow achieving unprecedented efficiencies, especially in times of partial load operation. For designers of charging hardware, this minimizes the cooling effort while the operators benefit economically. Power semiconductor devices, supporting the design of systems from a few kilowatts to several hundred kilowatts are available to the market today [6].

Current plans for charging infrastructure include 400 high-power charging parks throughout Europe that feature 6–8 charging spots with 350 kW each [7]. In a near-future scenario, where these stations provide their service for 5 hours per day, the energy throughput sums up to 5 million kWh per day. Increasing the efficiency from grid to battery by only 1% saves 50.000 kWh on a daily base – additional 2 billion kWh sold per year.
4 From drive-train’s point of view

In the beginning of electric mobility, DC-motors were the electric machine of choice. As the power supply is a DC-source, a rather simple, thyristor-based DC-DC-converter was enough to control the DC-motor. As a single semiconductor in buck-converter mode did the work, this setup achieved outstanding efficiency regarding the electrical energy conversion. Thyristors also pose as a very robust and durable technology that has proven its reliability and long-term stability in locomotive applications and high-voltage DC-transmission lines before. Detrimental from today’s point of view were the inconvenient control method to turn off the thyristor, the low switching frequency and the sparking at the DC-motor’s brushes that lead to poor EMI-behavior and the need for regular maintenance.

With the development of IGBTs, beginning in the early 1990s, using DC-AC-conversion to drive three-phase machines from a DC-source became feasible. As permanent magnet synchronous machines (PMSM) achieve the highest torque density, they became the dominant technology in commercial vehicles related to transportation of goods and people. Particularly in applications that demand higher driving comfort, their smooth and low noise operation is beneficial.

Figure 3 holds a block-diagram of a typical drive train and a selection of electronic components used in commercial vehicles.

Figure 3 Typical block diagram for drive trains in electric heavy-duty vehicles.

Technically, the power conversion stage in this application is highly similar to inverters that drive rotating machines in industrial applications. However, lifetime demands in commercial vehicles regularly grows to exceed 100,000 operating hours in a service period of 20 years. Within these boundary conditions, the lifetime expectation in construction, commercial and agricultural vehicles (CAV) is closer to those from locomotive and traction applications, rather than passenger cars.
Additionally, the use-cases and operation modes are less random. For buses, trucks, wheel-loaders and similar vehicles, load profiles exist that act as a basis to calculate the stress, applied to the semiconductors during operation. This allows an accurate estimation of the lifetime and an optimization of the inverter system in regards of cost and performance.

Performance, in particular efficiency, also increases when wide band gap devices like silicon carbide (SiC) MOSFETs or gallium nitride (GaN) HEMTs replace the silicon-based IGBTs. The gain in efficiency leads to either higher mileage per charge or to smaller battery capacity to achieve the same range. However, reducing the battery capacity leads to higher stress in case the application’s power requirements remain the same. A careful and holistic approach is advised, taking all systematic synergies and potential disadvantages into account.

In vehicles used in mining, construction sites or similar off-road applications, switched reluctance machines offer a potential financial advantage. They also relieve the manufacturers of the dependency on rare-earth magnetic materials. On the downside, the driving power section is different, and the operating mode is less comfortable in regards of noise and vibrations, which is of lower importance in this class of vehicles.

The necessary inverter needs choppers in high- and low-side configuration as sketched in Figure 4.

![Figure 4 Overview on switched reluctance motor drive](used with permission of Nidec SR Drives Ltd)

In addition to the topology, demands in regards of mechanical robustness and the power levels of the application in focus are considered. To serve this market, dedicated power modules that hold one phase, consisting of two choppers, are now available.
A final consideration targets the energy storage in place and its correlation to use-cases. Batteries went through an enormous development in the last decades and are the dominant storage technology today. Their technical potentials in energy and power density is still not exhausted. In short-term, improvements by factor 2–4 are expected [8] while the long-term prognosis hints to a factor 8-10 [9].

In parallel, hydrogen-powered fuel cells could potentially act as energy storage as well. The fuel cell stack’s output voltage changes with the power taken from the stack. Therefore, and to recover braking energy by recuperation, fuel cell based drive-trains still carry batteries that also support the peak power demand. To interact properly, a further DC-DC-converter between those components is mandatory, that channels the energy from the fuel cell to the battery. Here too, wide band-gap materials like SiC-MOSFETs play an important role as efficiency is of utmost importance.
5 From power semiconductor’s point of view

Within the last three decades, optimization of the IGBT-technology lead to continuous improvements in efficiency, robustness and power density. Figure 5 gives a summary about this development.

![Figure 5 Overview on chip technology improvement](image)

As a consequence of this development, power electronic equipment today demands less space and lower cooling effort for the same levels of output power. Vice versa, equipment with the same volume as a drop-in replacement or drop-in upgrade offers higher output power.

The most prominent member of this development is the well-established EconoDUAL™ 3. This half-bridge module became the most widely used power device in electric buses and trucks. Part of the success is the wide range of current and voltage levels this family supports. Along with the development in chip and packaging technology, the half-bridge in EconoDUAL™ 3 evolved as depicted in Figure 6.

![Figure 6 EconoDUAL™ 3 development from IGBT3 to IGBT7](image)
Despite offering twice the current rating, the mechanical dimensions of the device remain unchanged; the same is true for the positions of pins and terminals. As part of the development, the maximum operating temperatures for the chips grew from 125°C in IGBT3 to 150°C for IGBT4 and even 175°C for IGBT7 [10/11/12].

Still the designers are facing a thermal challenge. As the current density on chip-level [A/cm²] grew faster than the efficiency, the power loss density [W/cm²] also rose. With half the losses on a fifth of the area, power loss density on chip-level grows by 250%. Even on power module level, power loss density almost doubled. Transferring heat from these local hot spots makes thermal management a more demanding task. Choice and design of heat sinks as well as thermal interface materials have to consider these circumstances.

In vehicles, traction inverters are traditionally equipped with liquid cooling systems. This allows transferring the heat from the source to a radiator that can dissipate the thermal energy to ambient. To cope with the ongoing increase in cooling demand, highly efficient integrated cooling systems replace the classical cold plates. In these systems, the power semiconductor gets in direct connection to the coolant; therefore, they are also referred to as direct liquid cooling systems. This shortens the chain of thermal resistances and eliminates the need for thermal interface materials.

The plane base plate of a semiconductor does not offer the best heat transfer capabilities. A film of coolant that builds across the area in laminar flow hinders the exchange of heat. An additional structure that enforces turbulences in the coolant to enhance the thermal transfer improves the situation. These so-called pin-fin base plates have already entered the passenger car segment.
The comparison in Figure 7 gives an overview on the level of improvement. The HybridPACK™ Family [13] had the first modules that became available with both base plates, plane and pin-fin.

![Figure 7](image)

**Figure 7**  Overview on the thermal performance of different cooling systems

The diagram in Figure 7 reveals that the change from liquid cooling to direct liquid cooling improves the thermal performance by about 30%. The major reduction of the thermal resistance from case to ambient $R_{\text{THCA}}$ is the result from eliminating the thermal interface material between the module and the heat sink.

A further version of structured base plate exists, the so-called wave design. Here, a patented technology allows creating the turbulences with aluminum ribbons. The shape of the ribbons, attached in a technique similar to the one used to connect bond-wires, resembles a wave-structure. The lineup of HybridPACK™ Drive modules in Figure 8 allows a detailed view to similarities and differences within the designs.

![Figure 8](image)

**Figure 8**  HybridPACK™ Drive power module versions in direct comparison. Wave-structures to the left, pin-fins to the right

Though the thermal performance of the pin-fins is slightly higher, the ribbon-bonds pose a cost-optimized solution [14/15]. As it has proven to be a beneficial and reliable approach, it is safe to assume that this improvement appears on further power modules in the near future.
6 From the application’s point of view

Heavy-duty vehicles in all classes have seen massive changes since the all-electric MAN SL-E started operation in 1975. Common to most electrified heavy-duty vehicles, besides the obvious drive-train, is a cluster of subsystems that increases comfort as well as operational safety. The bus in Figure 9 acts as an example to highlight the changes that took place.

![Electric subsystems in heavy-duty vehicles](image)

The driver’s work is far less exhaustive than it was back in the 70s. Driver assist systems include electric power steering and braking. Comfort increases due to air conditioning and well-controlled ventilation systems. Among others, traction control, anti-locking brakes, electronic stabilization systems, lane-assist, cruise- and distance control combined with traffic sign detection all target to reduce the driver’s workload. Enhanced areal detection by Radar, Lidar and optic 2D/3D image capturing provides the information for automated safety features like pedestrian or bicyclist recognition. The sensors installed today, combined with massive calculating power and far-reaching connectivity allow fully autonomous driving in the near future.

Handing over safety relevant systems like steering or braking to electronics demands for an extra on safety measures including various levels of redundancy. ISO 26262, the core safety standard for vehicles, describes the requirements that safety relevant systems have to fulfill. Safe operation while driving the vehicle under usual conditions as well as critical situation is important. Even more challenging is, to maintain safe operation in case of failure. To ensure such fail-safe functionality, dedicated microcontrollers of the AURIX™-Family [16], gate drivers of the EiceDRIVER™ [17] portfolio and XENSIV™ [18] sensors are available, that support the designer in developing reliable safety-relevant subsystems.
7  A potential future perspective

Noiselessly and without exhaust, the futuristic looking vehicle approaches the station. Neither sound nor exhaust, because the vehicle has an electric drivetrain.

Futuristic, because the vehicle seems to resemble a transportation vessel. Its design is streamlined and aerodynamic and obviously lacks one important thing, which was always present in the past – there is no driver. It maneuvers accurately to its destination, reaching the targeted point with amazing precision. Massive contacts automatically attach to the vehicle in the robotic station. The humming sound from the nearby transformer reflects the massive power transferred into the vessel.

The scene could appear as the rendering in Figure 10.

![Figure 10 Recharging at 4.5 MW – 500 km in just minutes](image-url)

After just a few minutes, it detaches the connection and silently continues its journey.

Many times in the past, there were predictions about how future transportation may look like. No – we will most likely not see masses of warp-drive propelled, flying taxis transporting armies of hipsters around the metropolitan centers in five years from now, though pilot projects on autonomous drones already took place.

Considering financial aspects, the dominant cost-driving factors in transportation fleets, no matter if goods or people are transported, cover maintenance, energy and the driver. Therefore, it is safe to assume that highly reliable, autonomous, energy efficient vehicles will be part of our future. However, a vehicle without a driver does not need a lunch-break or any other interruption for the driver to recreate. As time is money, any pause turns into downtime and has to be as short as possible.
Electrification as a key to reduce emissions and improvements in energy storage technology along with developments in supplemental infrastructure enable the fully autonomous long-haul operation.

Charging standards for the heavy-duty vehicle sector currently extend to cut-off voltages of 1500 V and tolerable charging currents up to 3000 A [19]. This resembles a transfer of 500 kWh, respectively 400 to 500 km of highway driving, in merely 7 minutes, outperforming any fuel-based refilling system.

Without a driver, and the resulting human-induced downtime, the vehicle can operate a longer period and cover a larger distance in less time, even if it runs on lower top-speed. Inherently, the energy efficiency increases. Fully autonomous driving and digital high-speed connectivity also hold the key to forming road-trains that further increase efficiency and potentially shifting more transportation to the less crowded nighttime.

While none of this is absurd science fiction, further challenges remain, as cyber security will be a major concern with special focus on safe connectivity. Standardization for autonomous trucks, busses and in-city delivery vehicles needs to improve to support cross-border or even cross-continental interoperability. The technological bits and pieces to solve this global puzzle are all available.

The thrilling future in CAV is about putting all of them together.
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