

AXLE DESIGN AS A KEY FACTOR FOR GREENING ROAD FREIGHT TRANSPORT



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Abstract

Electric powered transport solutions offer the possibility to rethink vehicle architectures. Due to their high efficiency and compact geometry e- motors can be integrated in the axle itself. Axle-integrated, electric drives enable significantly lower cabs, that will help to improve the visibility of traffic situations and vulnerable road users, especially in cities, at intersections and when turning.

Electrification of trucks for different transport applications calls for different technical solutions. A key factor for electrification is the overall efficiency of the drive train. Inner-city trucks will be operated in low to medium speeds, long-haul trucks at high speeds. To achieve the best possible performance, drive systems should be matched to the specific conditions of use.

The potential of electric drive trains to harvest energy during operation leads to new innovative solutions for the transport industry, not only in truck- but also in trailer- applications. The energy can be used as a constant, sustainable source of electricity for trailer refrigeration units, independently of the tractor unit.

Axle design and the integration of drive train components into axles will become more important with the oncoming electrification of road freight transport.

Finally, axle design will become a key factor for greening road freight transport.

Keywords

Electric transport solutions, Axle design, axle integrated electric drive, Vehicle architectures, drive train efficiency, trailer electrification, emission- free refrigerated trailer

AXLE DESIGN AS A KEY FACTOR FOR GREENING ROAD FREIGHT TRANSPORT

1. Electrification of road freight transport

Road freight transport of the future runs on electricity – starting in metropolitan areas. Be it Paris, Brussels, Amsterdam, London or Milan: Numerous European metropolises are already implementing stricter regulations for freight transport, access regulations and – depending on the time of day – zero-emission zones in the urban environment. (Schoenfeld, 2022) Restrictions are likely to increase in the coming years with the increasing level of environmental awareness worldwide. The requirements for low-emission and quiet transport, particularly in inner-city logistics, are becoming more stringent. For a logistics operator, it is becoming difficult to reach innercity transport destinations efficiently and on time. Electric vehicles are a real alternative for traffic and transport, especially in cities. They are highly efficient, consume less energy and therefore have got low CO₂- emissions. Locally, these vehicles are emission free and silent.

Given the enormous traffic congestion in cities during the day and the associated air pollutant and noise emissions, the idea of shifting some delivery traffic to nighttime hours makes perfect sense. In Germany Fraunhofer IML already carried out a project for low-noise nighttime logistics, in short: GeNaLog (German: “**Geräuscharme Nachtlogistik**”) from 2014 to 2017. This tested whether it is technologically possible to deliver to retail outlets during off-peak hours and at night. One of the partners involved was the REWE Group, with whom a five-week test phase was carried out at the end. The project has shown that this form of delivery is technically feasible. In Germany, the “Technical Instructions on Noise Protection” (German: “TA Lärm”) apply. It specifies guideline values for how loud deliveries may be at night.

A diesel vehicle cannot meet these strict specifications. It could only drive at night under the maxim “no plaintiff, no judge”, meaning only when residents complain do noise experts take measurements and check whether the specified limits are being complied with.

An electric vehicle, on the other hand, is the perfect basis for a silent night delivery vehicle. In the future, not everything will be able to be delivered at night. But if you can shift some of it and use the free capacity on the roads, everyone benefits. (Gringer, 2022)

»If you take a long-term view, there is a very, very strong case for electric drives. And you can say that now is the time for it.« (Gringer, 2020)

2. Electric powertrains offer the possibility to rethink vehicle architectures

In the last century, truck design was dominated by the internal combustion engine. Diesel engine, manual transmission, cardan shaft and differential axle form the heart of every truck.

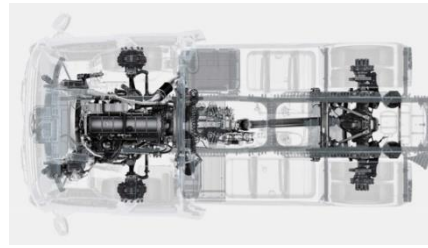


Figure 1 – ICE- powertrain (MAN, 2020) Figure 2 – ICE- powertrain (Mercedes-Benz)

All other systems, even driver position and cab, have been arranged around this central drive train.

Depending on the legal constraints, either the conventional- or the cab over engine- truck design emerged.

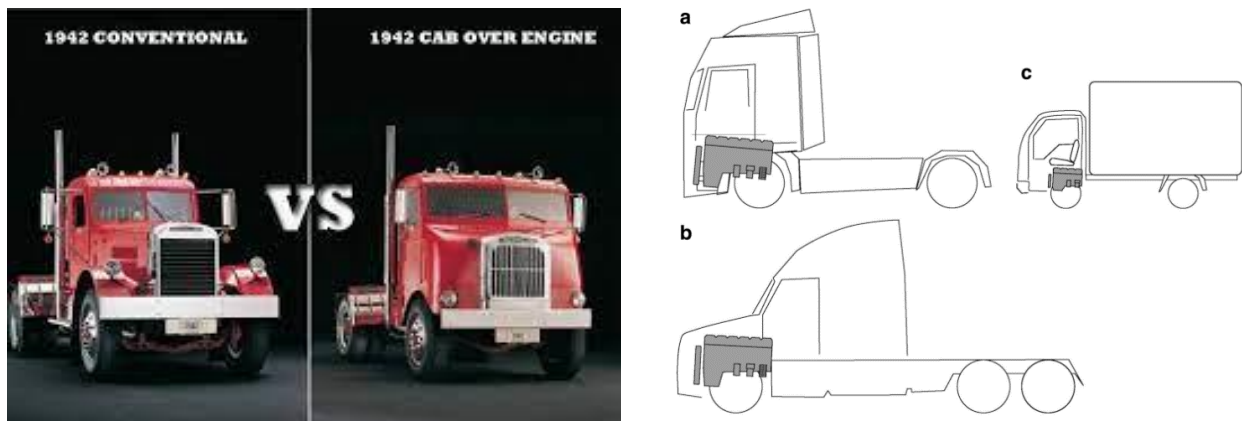


Figure 3 – conventional vs cab over engine design (Freightliner) (Hilgers, 2022)

In a conventional truck, the diesel engine is located under a long hood in front of the cab. This is the preferred design in countries without length restrictions, such as the United States. In a cab over engine design, the cab is located above the engine. This is the preferred design in areas with strict length limitations, such as Europe.

Electric drives are no longer bound by these constraints. Electric motors are smaller and lighter than conventional combustion engines and can be arranged more decentral. Even installation of e-motors in the unsprung masses (axles) is no longer out of the question.

The first electrically driven trucks often adhered to the familiar design of the conventional diesel powertrain. With a central drive, the differential axle and cardan shaft of the ICE- powertrain are adopted and 'only' the diesel engine and multi-gear-transmission are replaced by an electric motor, often with single speed- transmission.

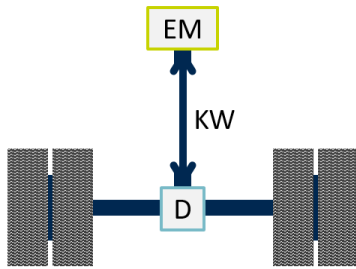


Figure 4- Central drive (EM=electric motor; KW=cardan shaft; D=differential gearbox) (Rhein, 2020)

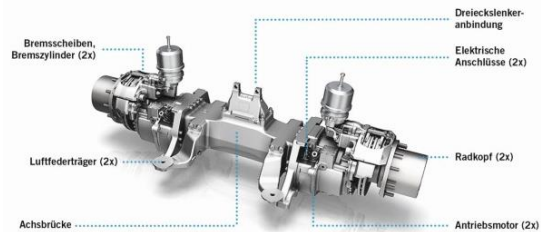
This design is likely to be predefined by the manufacturers model kit, as diesel and electric drives have to share the existing diesel platform.

Actually, electric drive technology is changing fundamentally. The trend is to bring the electric drive to the axle.

Axle-integrated electric drives from BPW were already displayed on the IAA in 2016, two years later followed by Mercedes-Benz.



Figure 5 - eTransport- axle (BPW, 2017)

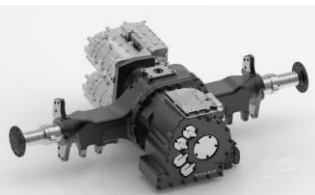


eActros- axle (Mercedes, 2018)

Since 2016 it has taken a couple of years till axle-integrated drives are being seen more and more frequently in new electric trucks. On the latest IAA- show in 2022 the number of axle integrated electric drives increased fundamentally.



Figure 6 - (Mercedes, 2022)



(Volvo, 2022)



(BPW, 2018)



Figure 7 – (Meritor, 2022)

(Allison, 2022)

(FPT, 2022)

As the exhibits have shown, axle-integrated drives with 1 or 2 e- motors, with and without differential gears, are preferred drive train solutions in oncoming trucks.

Wheel hub drives are still exotic, because they are comparatively large and heavy, due to low wheel speeds and high torque requirements.



Figure 8 – (Ziehl- Abegg, 2020)

However, it seems foreseeable that the axle-mounted electric drive will prevail in trucks.

Drivers for this trend are:

- Space-saving design with maximum installation space for batteries and other components.
- Low system weight due to compact arrangement on the axle
- High efficiency due to low number of parts
- Good traction control
- Potential for torque vectoring

A comparison of the characteristic curves of motor torques versus motor speed between an electric drive and a diesel drive of comparable rated power clearly reveals the different characteristics of the two drive types.

While the electric motor's maximum torque (the power at the wheel) is already available from zero speed, the internal combustion engine must first be engaged by the friction clutch or the converter. For its maximum torque, shown here using the example of a diesel drive, it requires a speed of approx. 1200 rpm, and from 2200 rpm it reaches its speed limit. (Rhein, 2020)



Figure 9 - Torque-speed diagram combustion engine (Mercedes, 2021)

Due to the narrow speed range of the combustion engine, a multi-stage transmission is necessary to achieve the desired drive train characteristic.

On the other hand, with the electric motor, often a single-gear transmission is sufficient because power and torque of the e-motor are available over the full speed range.

Single-gear transmissions are common solutions, especially in inner-city delivery applications. To optimise efficiency, or for particularly high tractive forces, it may make sense to provide a 2- or even 3-speed gearbox.

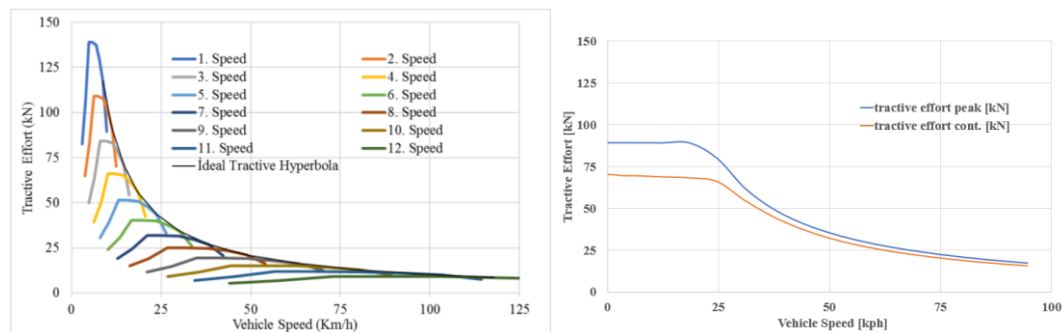


Figure 10 -Traction force diagram ICE (12-speed) (Yavuz, 2020) vs. BEV (1- speed) (BPW, 2022)

Since the drive is located directly on or in the axle, all other components can be arranged much more freely in the vehicle. The installation space in front of and behind the axle, as well as under the driver's cab, can be used to install the batteries, as well as any fuel cell and its hydrogen tanks. The driver's cab no longer has to be placed above or behind the diesel engine.

This allows us to envisage new truck configurations in the future. Especially in inner-city transport applications, it would be advantageous to have the driver's cab at a lower level. This makes it easier for the driver to recognise vulnerable road users, such as pedestrians or cyclists. The better visibility can help to avoid serious and sometimes fatal accidents, especially at intersections and when turning.

Another advantage that should not be overlooked is the flat entrance to the vehicle. For transport tasks with more or less frequent loading and unloading operations, the flat entry represents a significant relief for the driver.



Figure 11 - Inncity- truck (VoltaTrucks) Figure 12 - Inncity- truck (MAN, 2020)

It is to be expected that trucks for inner-city transport will look different in the future than they have in the past.

3. Different drive train solutions for different transport applications

In the transport world, the diesel or energy consumption of trucks is one of the most important business factors. In case of a change to electric drives, energy consumption becomes even more important, because energy storage capacities will be limited by battery, or H₂- tank sizes.

Energy storage systems for vehicle drives are compared in the so-called Ragone diagram (Figure 13). It shows the dependence of the weight-specific energy (energy density) on the weight-specific power (power density). The energy density is an indicator for the range of the vehicle, the power density is important for power output and acceleration processes.

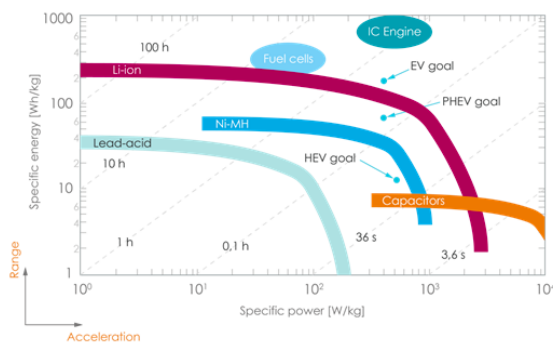


Figure 13 - Specific energy vs. specific power for different vehicle drive systems

In vehicle applications, interconnecting larger packs of Li-ion batteries increases the driving range and performance. Nevertheless, a large difference remains in terms of range, compared to a diesel or gasoline engine. The main reason is the much lower energy density of a battery compared to a fuel tank. As a guideline, about 11 kWh are chemically stored in one kilogram of gasoline, whereas only about 0.14 kWh are stored in a Li-ion battery of the same weight (Karle, 2018). During vehicle operation this ratio is put into perspective because energy consumption of electric vehicles is only one third of that of ICE- vehicles. In addition, braking energy can be recovered. Nevertheless, to achieve an acceptable range, a significantly heavier battery must be installed compared to the weight of a fuel tank.

The efficiency of electric motors for automotive drives, i.e. the ratio of the electrical energy input to the usable mechanical energy, is over 90 % across nearly the entire operating range. Internal combustion engines achieve a maximum of 40 % , but only in the favourable torque-speed range, which requires optimum shifting behavior of the driver or an automatic gearshift. However, overall efficiency comparisons are much more complicated and strongly dependent on the cycle under consideration.

Electric motors can become wheel-drive generators when the vehicle brakes. The released kinetic energy can be used to charge the battery. This process is known as recuperation. In case of the ICE, braking torques can be generated, but the energy will be released into the environment via heat and is therefore not made usable. (Rhein, 2020)

To optimize installation space and weight, permanently excited synchronous motors are predominantly used in truck applications. A permanently excited electric motor usually has the range of optimum efficiency at medium speeds. At high and low speeds the efficiency drops.

38400	81,0	89,1	92,1							
31000	85,4	91,7	94,0	92,9						
25600	87,2	92,8	94,7	95,2						
18000	90,4	94,4	95,8	96,7	96,3	93,9				
12800	91,8	95,1	96,3	97,0	96,7	95,9	94,1			
9400	93,3	95,7	96,5	97,1	97,0	96,1	95,3	94,8	94,4	93,1
6000	93,9	95,9	96,5	97,0	96,9	96,0	94,9	94,5	94,0	93,2
3600	94,4	95,7	96,1	96,5	96,5	95,3	93,9	93,2	92,6	91,5
2400	93,6	94,2	94,3	94,4	94,3	92,7	90,3	89,2	88,2	86,4
1300	91,4	91,6	91,4	91,2	91,1	88,5	84,8	83,2	81,8	79,2
Torque at wheels [Nm]	6	12	20	30	40	50	60	70	80	88
	speed [kph]									

Figure 14 - Efficiency map of a permanently excited electric motor PSMS (BPW, 2022)

Main operating points for the motor differ depending on the use- cases of the vehicle.

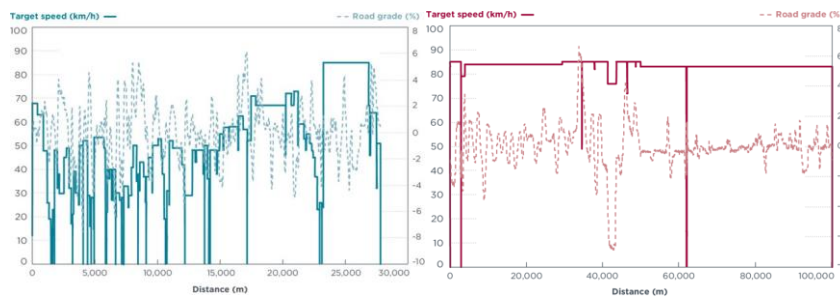


Figure 15 – Truck use cases: Urban delivery- vs. Long haul- Vecto cycle (European Commission, 2018)

In urban delivery applications, the main operating points are in the medium speed range and thus in the optimum efficiency range.

In long haul applications, on the other hand, the main operating points are in the high speed range and thus in a range with significantly lower efficiencies.

A truck for inner-city transport in the 7.5 to 26 ton class is optimally equipped with an axle-integrated electric drive with a single gear transmission. The torque curve of the electric motor provides good gradeability and acceleration, while the high efficiency at medium speeds ensures a low energy consumption.

At highway speed, the engine runs at high speeds for a long period of time. From the point of efficiency, it would be advantageous to reduce the speed permanently with a longer gear ratio. By using a 2- speed transmission and changing the gear ratio in 2nd gear, the engine speed can be reduced, bringing the engines into a more favourable efficiency range. Efficiency improves by up to 10% at highway speeds, depending on power requirements.

Vdc:650V	L= 160	i= 15								
38400	81,0	89,1	92,1							
31000	85,4	91,7	94,0	92,9						
25600	87,2	92,8	94,7	95,2						
18000	90,4	94,4	95,8	96,7	96,3	93,9				
12800	91,8	95,1	96,3	97,0	96,7	95,9	94,1			
9400	93,3	95,7	96,5	97,1	97,0	96,1	95,3	94,8	94,4	93,1
6000	93,9	95,9	96,5	97,0	96,9	96,0	94,9	94,5	94,0	93,2
3600	94,4	95,7	96,1	96,5	96,5	95,3	93,9	93,2	92,6	91,5
2400	93,6	94,2	94,3	94,4	94,3	92,7	90,3	89,2	88,2	86,4
1300	91,4	91,6	91,4	91,2	91,1	88,5	84,8	83,2	81,8	79,2
Torque at wheels [Nm]	6	12	20	30	40	50	60	70	80	88
	speed [kph]									

Vdc:650V	i= 110	i= 22/9								
38400	88,0	92,3	94,1							
31000	90,1	93,7	95,1	93,8						
25600	91,8	94,7	95,9	96,1						
18000	93,3	95,6	96,5	96,9	96,2	94,0				
12800	94,6	96,2	96,9	97,1	96,9	96,3	95,5	93,8		
9400	95,1	96,4	96,9	97,1	96,9	96,4	96,4	96,1	95,0	94,8
6000	95,5	96,4	96,7	96,9	96,7	96,1	97,0	97,1	97,1	96,9
3600	95,1	95,4	95,5	95,5	95,5	94,6	97,1	97,1	97,1	96,9
2400	94,7	95,0	95,0	95,0	95,0	94,0	96,8	96,9	96,9	96,7
1300	92,0	91,9	91,6	91,4	91,4	89,6	95,5	95,5	95,5	95,5
Torque at wheels [Nm]	1st gear					2nd gear				
	6	12	20	30	40	50	60	70	80	88
	speed [kph]									

Figure 16 - Efficiency comparison of electric drives with 1- speed vs. 2- speed transmission (BPW, 2022)

Therefore a truck for long-distance transport in the 40-ton class should be equipped with a 2-speed transmission, so that the motor will be operated within the range of optimum efficiency even at highway speeds.

4. Innovative solutions for the transport industry - Trailer electrification

As mentioned before, a growing number of cities are implementing driving bans, special requirements, and restrictions on diesel-powered vehicles. Restrictions are likely to increase in the coming years. This will be a challenge for refrigeration logistics in particular, which is essential for daily provisions to the population.

There is demand for temperature-controlled transport solutions which allow for inner-city refrigeration logistics with the lowest possible noise and CO2 emissions.

A new innovative solution targets energy production: The energy generated during driving and braking is used as a constant, sustainable source of electricity for trailer refrigeration units. This functions independently of the tractor unit, so fleet operators can use the solution flexibly for their entire fleet. The fully integrated system combines hybrid or all-electric trailer refrigeration units with the energy-generating ePower axle to create an autonomously powered trailer refrigeration solution.

How it works: The energy generated when the vehicle is rolling, going downhill or braking is stored in a high-voltage battery and then used to power the refrigeration unit and keep the cargo at an optimal temperature at all times.

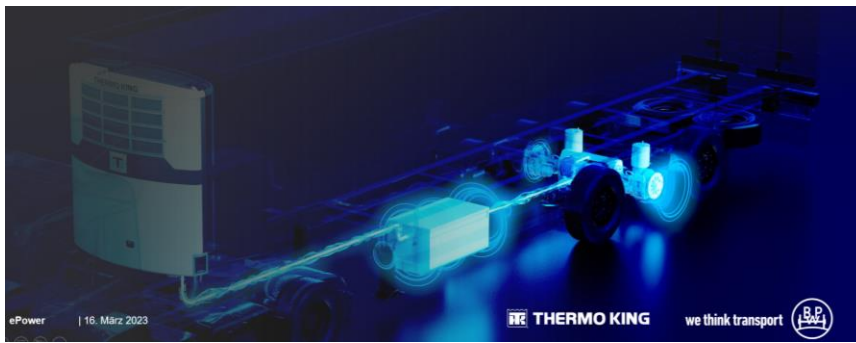


Figure 17 - Energy recuperation system in a refrigerated trailer (BPW, 2022)

With its quiet operation and lack of CO₂ emissions, this technology enables inner-city delivery operations even in environmental and low-emission zones. The sustainability balance includes both an ecological and an economic dimension: emissions and noise are reduced, and ongoing operational costs drop immediately – an important argument, especially in times of high energy prices. (Schoenfeld, 2022)

The all electric trailer system powers the cooling system solely with electrical energy generated in the trailer. The diesel consumption of up to 4000 l p.a., that occurs with conventional refrigerated trailers is eliminated, reducing the CO₂ emissions of the refrigerated trailer by up to 10 tons per year and trailer.



FUEL SAVINGS

Up to 4,000 l per year and trailer, depending on use and equipment.



REDUCTION IN CO₂ EMISSIONS

Up to 10 t per year and trailer, depending on use and equipment.

Figure 18 – Fuel savings and reduction in CO₂- emissions (BPW, 2022)

Heart of the system is the ePower- trailer axle. Similar to a bike dynamo, ePower converts wheel rotation into energy and temporarily stores it in a backup battery before feeding it into the system as needed. Recuperation (i.e. energy recovery during braking) also recovers lost energy and feeds it back into the system too.

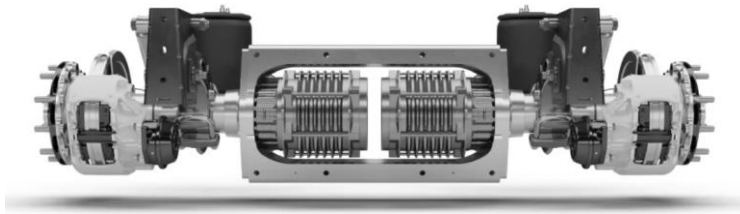


Figure 18 - electrified 'ePower' trailer axle (BPW, 2022)

Two asynchronous- generators, each with a max. Power of 8kW, are used to provide double the power and reliability. The recuperation unit is fully integrated into a standard 9to- trailer

axle. Therefore, the ePower- solution can easily be integrated in nearly every refrigeration trailer.

Before going into real operation, ePower was subjected to the endurance test during test drives in Spain and Sweden under extreme temperature conditions.

Tests in the south of Spain at daytime temperatures of over 35°C demonstrate the reliable supply of the cooling units even under difficult boundary conditions.

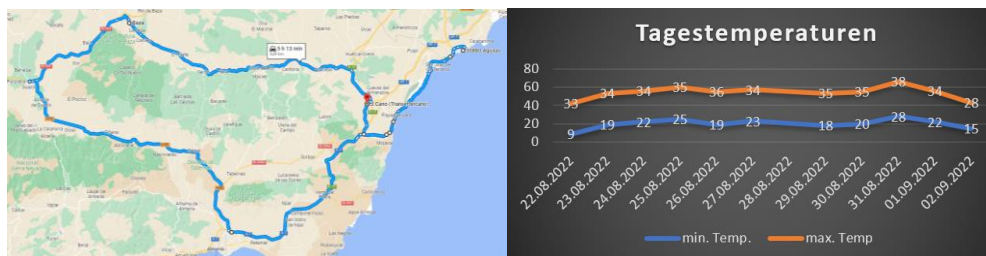


Figure 19 – Spain: Test vehicle, test area and daily temperatures (BPW, 2022)



Figure 20 – Scandinavian winter: Test vehicle and running gear (BPW, 2022)

In Sweden, in addition to the very low temperatures of down to minus 20 degree Celsius at night, there is also snow and ice in the Arctic Circle. There, grit is also used rather than salt. (Gringer, 2023) The tests demonstrate the reliability of the system under these extreme conditions.

The development phase is almost complete and extensive field trials with selected customers are underway. With stops in Germany, the BeNeLux countries, Scandinavia and Spain, the tour covers a wide range of climatic conditions.

The two available battery packages with capacities of 19 and 38 kWh cover a wide variety of application situations. Extensive simulations have shown an optimal cost-benefit ratio and an attractive return on investment for driving distances of up to 300 kilometres per shift. Due to the energy production during driving, however, even longer distances are possible with reliable refrigeration. (Schoenfeld, 2022)

“The technology is a significant advancement – both for operational flexibility and for the long-term sustainability of fleets using refrigerated trailers.” (Schoenfeld, 2022)

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