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Content

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▶ **Development processes and methods**

▶ Program Committee

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ZF E-Mobility Products and Software for Commercial Vehicles

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Abstract

E-Mobility has been one of the top-priority subjects for the past few years and will remain so in the future. OEM und suppliers have been struggling to find the ideal, yet equally commercial and technical solution. So far there seems to be not one solution, but many, ranging from Hybrid, Plug-in Hybrid, BEV and FCEV. It is vital to meet the needs of the respective segments with components that can be used in as many applications as possible. This article describes one element of the ZF commercial technology approach: A kit that consists of electrical, mechanical and software components. One major problem with electrified powertrains is the lack of electric range. ZF tackles the challenge by developing energy saving strategies that are tailored to the degree of electrification. They cover aspects comprising intelligent control of auxiliary units, thermal management, as well as charge control. Together with functionalities like prevision, it is possible to push energy efficiency even further. The development of an energy management system relies strongly on the use of their ZF owned development vehicles. Integrated in the series software ZF provides a portfolio which covers all important aspects of E-Mobility software.

Introduction

Since the market development of the various E-Mobility solutions for commercial vehicles (CV) is still unclear, a flexible approach is necessary. To be able to fulfil both the commercial demands as well as technical demands for E-Mobility driveline for CV, it is important to supply the respective segments with components that can be used in as many applications as possible. In the sections below a compilation of current ZF E-Mobility solutions are presented with special focus on software.

It is now understood that for low daily mileage applications, the electrification of BEV will become ubiquitous in almost all vehicle segments, from LCV up to HCV. For high daily mileages exceeding 400 km/day, however, it would not be possible to install the battery

capacity needed for BEV in the vehicle due to installation space and weight limitations. In this area of application fuel cell technology offers promising solutions.

Regardless of the energy storage capacity the importance of the factor range is evident in all segments. To increase the mileage of a vehicle with a fixed amount energy installed it is necessary to have an overall view on the vehicle. Only in that way energy saving potentials could be identified and utilised. ZF tackles the challenge with the development of an energy management that implements strategies to save valuable energy to increase the range of commercial vehicles.

ZF E-Mobility Solutions

Table 1 introduces the first generation of ZF CV E-Mobility products. They have been released over the last few years and are already in volume production or are in various stages of development. Beyond the depicted hardware, there are software products of various kinds complementing the hardware or extending the control to higher levels.

Table 1: ZF E-Mobility CV products, first generation.

	CeTrax	CeTrax lite	AxTrax AVE	eTrailer
CV segment	Bus, MCV 26 t	LCV < 7,5 t	Bus 26 t	Semi-Trailer 40t
Type	BEV Central drive	BEV Central drive	BEV Axle drive	e-Trailer Hybrid / Range-Extender
Electric motor type	Induction motor	Induction motor	Induction motor	PSM
Power peak	300 kW	125 kW	2 x 125 kW	~ 270 kW
Power continuous	200 kW S2 = 30 min	80 kW S2 = 30 min	2 x 87 kW S2 = 30 min	~ 180 kW S1
Nominal voltage level	650 V DC	420 V DC	650 V DC	650 V DC
Torque Peak	1,350 Nm	390 Nm	2 x 485 Nm	~ 600 Nm
Max. rpm	8,500 rpm	13,000 rpm	10,300 rpm	13,000 rpm

CeTrax is the ZF central drive solution for buses and HCV [1]. It consists of an induction motor with 200 kW continuous power and a one-stage planetary gear set. SOP has been in 2020. There are different models for the Chinese market that have the same design concept but are developed according to local requirements.

AxTrax AVE is the ZF electrical portal axle for low-floor buses [2] where the complete drivetrain is integrated into the wheel hubs. It consists of two 125 kW induction motors with two gear sets and a fixed gear ratio. AxTrax AVE is a volume-production product.

CeTrax lite is the ZF central drive for LCV. This product features an induction motor rated at 80 kW continuous power and a fixed ratio gear set. The electric components come from the ZF volume-produced product Electric Axle Drive of the ZF E-Mobility-Division for passenger car market.

ETrailer is a product of the former WABCO and now ZF company [3]. It consists of an electric drive system, a battery, and a cooling system attached to a trailer. There are several fields of

application. One is hybridizing the tractor and trailer combination to a cost efficient HEV variant. The fuel savings are estimated with 7 to 16 percent. Another opportunity lies in utilizing the electrified trailer as range extender for BEV tractor units. With an increased battery capacity and an additional charging system this amounts also to higher costs for the range extending trailer. Thinking of a PHEV variant, it could also be used in applications where there is another power consumer on the trailer like in reefers. Thus, the recuperation energy can be used to supply those auxiliary units.

ZF E-Mobility software products comprise among others, functions for the drive software, gearbox and, energy management. Especially the drive software has a high degree of maturity and is part of serial products. All software components are under constant development and are subject to quality processes.

ZF E-Mobility Hardware Kit
The following part describes in detail the key components for successful kit products. These include the electric machines, transmissions, cooling systems, shifting actuator and, power electronics. Wherever possible, synergy effects between the various E-Mobility products were used as well as synergy effects from already existing ZF volume-production products in the AT segment. The carry-over of components and parts as well as proven design features in hardware has a major impact on development time, robustness, quality, and predictability.

Electric motors
As key components, the used electric motors are described in greater detail. To meet various requirements regarding drivability, installation space and total costs of ownership (TCO), different induction motor (IM) sizes and types are used for the vehicle segments. All IM are developed by ZF in-house for optimum performance and durability and since its development is from one source, synergies
can be used in an ideal way.
For the LCV segment up to 7,5 t, the already existing induction motor used in the ZF passenger car series application represents a great opportunity because the 400 V level appears to be a good solution for those applications in terms of short-term availability and economic advantages. Lifetime requirements in this segment can be met without restrictions.
For MCV or even HCV, a higher voltage level of 650 V to 800 V is desirable due to the higher power levels required for up to 400 kW. ZF uses mainly induction motors for traction applications because they are robust, cost effective and their efficiency is very good even when

compared with PSM (permanent magnet synchronous machine) applications. ZF was even able to prove this in internal testing with an equivalent competitor product.

Since these systems will be continually developed and the requirements regarding full integration (weight, space) and efficiency will constantly evolve, PSM technology, which was already included in different ZF projects, will be considered in future developments. PSM technology allows for various technical design approaches like wave winding or hair-pin systems.

The CeTrax induction motor is rated 300 kW peak power @ 650 V and 8,500 rpm. Since space restrictions are not an issue for state-of-the-art central drive bus applications, the CeTrax installation space meets the ZF AT Ecolife series while remaining compact. AxTrax AVE is a volume-produced product for buses and also uses induction motor technology. Peak power is 2 x 125 kW @ 650 V / 10.300 rpm.

Power Electronics

For power electronics, ZF uses products supplied by its cooperation partner Zapi / InMotion for drives with a DC nominal voltage of 650 V. The power electronics are also designed according to a modular principle which enables the expensive power semiconductor components to be variably adjusted. This makes it possible to match the power electronics precisely to the requirements of the electric motor.

Software functions can be split between the inverter control and a central electronic control unit, i.e. the ZF drive control unit. The split can be flexibly represented. Functions with high demand torque dynamics can be performed on the inverter control unit. In contrast, low dynamic functions such as temperature calculations can be moved from the inverter to the ZF control unit. The ratio may vary depending on the project and ECU resources.

When it comes to power electronics, numerous projects show that two inverter variants enable most projects to be optimally operated in terms of cost, installation space and weight. The two variants feature identical customer interfaces for high-voltage, low-voltage, and cooling connections. This also makes it easier to integrate the different drive variants from the modular system.

The interface between the ZF control unit and the inverter is also identical for all inverter power classes. Therefore, the vehicle control unit can be combined with different inverters without additional effort. This makes it very easy to build single- and multi-motor drives. The inverters and functions are designed so that induction and PSM motors can be operated. Fig. 1 shows the characteristic data of the two inverter variants, which have proven to exhibit low installation space and weight costs. Both power electronic systems allow a DC voltage up to 750 V without

derating and without loss of lifetime. At higher DC voltages, these factors entirely depend on the driving profile and other customer requirements as to whether the lifetime is affected or not. The smaller of the two inverters has a 20 second peak current of 340 A (RMS). The larger version can hold up to 530 A (RMS). The S1 continuous current is 225 A (RMS) or 375 A (RMS).

	ACH65M30	ACH65L50
Manufacturer	InMotion	
Type	3-phase drive inverter	
Performance data		
Nominal DC voltage	650 V	
Maximum DC voltage	750 V (without derating)	
Current (peak, 20 s)	Up to 340 A$_{rms}$	Up to 530 A$_{rms}$
Current (duration, S1)	225 A$_{rms}$	375 A$_{rms}$
Insulation resistance	> 20 MΩ (new hardware)	
Dimensions, weight		
L x W x H (mm)	421 x 362 x 122	583 x 362 x 122
Weight (kg)	20	25
Highlights	• Efficiency > 98 % (nominal value) • Robust design with IP6K9K • Liquid cooling	

Fig. 1: Inverters.

Mechanical components: transmission and cooling systems

The ratio between the reuse of components from already existing products and new components was a key point in different E-Mobility systems. ZF, as a driveline specialist [3], views the gear set and, especially, planetary gear sets, as key E-Mobility components in terms of power density and the required lifetime in the CV sector with strict requirements. Another important component is the oil used, which is what ZF is focusing on together with established suppliers. The oil types used are familiar from other ZF products, impacting durability and serviceability.

Fig. 2: Transmission and cooling.

	CeTrax	CeTrax lite	AxTrax AVE
Transmission type, ratio	Planetary gear set, i = 3,4	Two-stage spur gear set, i = 5,9	Two-stage ratio i = 22,7
Cooling / lubrication system	Stator: water cooled T/M: oil injection	Stator: water cooled T/M: oil injection	Stator:water and air cooled T/M: splash
Pump type	electric	electric	-

Since CeTrax is ZF's forerunner central drive for BEVs, as many carry-over parts from the ZF AT Ecolife were used as possible. These parts include one planetary gear set to reduce the input speed of 8,500 rpm as well as both the complete output bearing concept and the output shaft. Since city bus applications have extremely high requirements regarding lifetime and reliability in general, the possibility of having well-proven carry-over components from volume-produced AT products can be regarded as a big advantage. For optimized performance and overall efficiency, ZF decided to use a normal water-cooled stator system combined with an oil circuit for transmission cooling, including an electrical oil pump. Furthermore, some induction motor applications require, under certain conditions like a standstill after high power passages, thorough cooling of the rotor, the corresponding bearing and the sealing components. CeTrax lite is the perfect example of an effective carry-over from the existing ZF passenger car volume-produced product, the Electric Axle Drive. This creates high confidence levels right at the development start because off-the-shelf components can be used, thus ensuring cost effective engineering. CeTrax lite features a two-stage spur gear set to reduce the electric machine speed of 13,000 rpm and uses two ratios currently taking into account the same design space. Also, the transfer of the power electronic and parking lock concept from the passenger car product and integration into new packaging variants can be achieved. The stator remains water cooled, whereas the rotor shaft, stator windings as well as the transmission are additionally cooled by an electric oil pump, combined with an extra oil cooler. Thus, the continuous power of CeTrax lite can be considerably increased by some 10 kW.

Mechanical component: electric actuators

ZF considers electric actuators as a strategic component for the next generation of E-Mobility products since they are easily adaptable for different applications and allow precise and smooth gear shifting without the need of a pneumatic or hydraulic system supply. The actuators feature one BLDC motor with an integrated planetary gear set and position sensors. Kits with

various motor sizes and additional components such as an actuator brake are considered to cover every aspect of future product development.

E-Mobility Software Functions

In conventional vehicles, many driving and assistance functions are implemented in the combustion engine control unit. For electric vehicles, these functions must be executed elsewhere. The ZF control unit can take over the functions as a central vehicle / drive control unit. As there are numerous different application variants in commercial vehicles this poses challenges not only to the hardware but also to the software. To meet these demands and yet supporting a common base a platform software is used that is adapted and applied accordingly. Moreover, the opportunity is offered to provide customers a custom interface which suits their specific needs. The communication interface between the central ZF control unit and the vehicle is identical for all drive variants. This also applies to variants with and without multispeed transmission. This makes it very easy for customers to integrate different electric drive systems into their vehicles. The software is split into four major components. The EV-Drive functions are controlling the drive system, the EV-Control is managing start up and shut down of all delegated ECUs, the EV-Energy is controlling the power distribution of all high voltage components and the EV-Gearbox controls the transmission. All components are functional software and share the same abstraction layer and the same basic software (see Fig. 3).
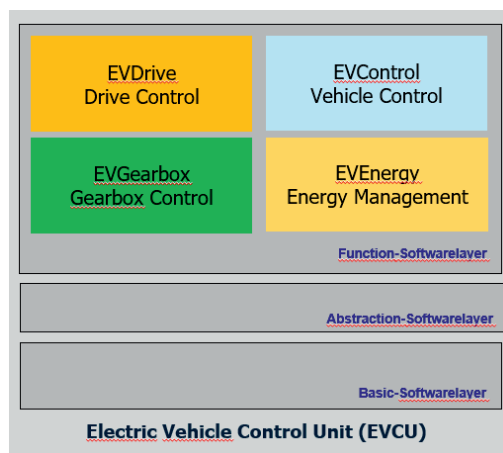
Fig. 3: Architecture of e-mobility software.

Depending on customer wishes individual software components can be switched on or off. The development of the four functional parts is highly quality oriented with project management, supplier monitoring, configuration management, change request management, quality assurance, problem resolution management, functional safety and thorough testing. In the following the EV-Drive and the EV-Energy software components are depicted in more detail. Both components are running at the same ECU.

EV-Drive Software Component

The drive software controls the electric drive. It handles, verifies, and brings together various torque demands. On one hand it provides a unified interface to the inverter whereas on the other hand it supports numerous variants and several interfaces to the customer. The EV-Drive software has a high degree of maturity and proofed itself in various volume-production projects.

The job of the drive software comprises interpreting the accelerator pedal, determining the driving conditions, and distributing torque and power including recuperation. The software platform can handle central drive architecture or axle drive architecture with multiple axles.

Standard Functions	Optional Functions	
Driving functions • Driving direction • Launch, driving • Recuperation	**Start-up comfort** • EasyStart function • Creeping function	**Other Functions** • Retarder Functionality • Multiple driven axles • Performance Switching • Customizable Function Adjustment • Coasting/Sailing

Traction control
• Response to ABS signal
• Traction Control System
• Drag Torque Control
• Brake-blending ready
	Driving comfort
	• Cruise control
	  • TempoSet
	  • Cruise control
	• Acceleration limiter	

Component protection (torque, speed, temperature)	**OPENMATICS/Telematic interface**	
Safety functions (ISO26262) **Diagnosis**		

Fig. 4: Function of EV-Drive.

The drive control functions are separated into standard and optional functions. Basic functions essentially include the basic driving and driving dynamics functions, the component protection functions, and the safety functions developed according to ISO26262. Fig. 4 lists the driving functions for a single-axle drive. The software modules are divided into operational and strategic functions. The strategic functions aim to essentially determine the driving torque, the torque distribution and recognize the driving condition. The operative functions process the desired torques and convert these into the drive torques considering the component protection.

In that way recuperation is handled as negative torque request which can be controlled either by the retarder lever or is part of a one pedal drive strategy and is controlled by the acceleration pedal. One example for standard functions is the electronic traction control. It not only supports traction on slippery surfaces it also prevents the axle gear stage from being exposed to so-called ice plate impacts. These heavy torque impacts occur abruptly when the driven wheels are spinning and then return to a high friction surface like asphalt. The resulting torque peaks can damage the mechanical drive components so that they fail prematurely. In that sense electronic traction control also comprises component protection. It is essentially the duty of the drive software to assure that the hardware runs in its operational boundaries. That is torque, voltage, current, and temperature limits are not violated. Especially monitoring the temperature means to provide a temperature model for mechanical parts that cannot be measured directly.

An example for optional functions of the drive software is the easy start capability. It ensures at start up that a vehicle does not unintentionally roll back down a slope when the driver switches from brake to accelerator pedal. Other functions like cruise control and tempo-set functions assist the driver. For city buses, limiting the acceleration is important so that standing passengers are not injured during a high-start acceleration. When combined with a telematics system (i.e. ZF Openmatics), additional functions, such as power or acceleration limits that depend on vehicle position can be used. The GPS-based power limitation, for example, is usually used in city buses. On one hand, the power is limited to save energy in inner city traffic and on the other hand, full power is released when the bus is traveling on a city highway.

EV-Energy Software Component

It is a well-known fact that with E-Mobility arises the problem of driving range. Especially BEV based commercial vehicle lack the necessary energy storage capacity to prove themselves in every long-haul scenario. Moreover, the total costs of ownership increase tremendously with the installed battery capacity. Also, the construction space for battery packs in semitrailer tractors is an issue. Hence, there are strong arguments that necessitate a high-power consumption efficiency to gain the maximum range with the installed amount of energy.

In conventional commercial vehicles the internal combustion engine is the heart of the vehicle. Aside from delivering the drive power it also provides power to several other auxiliary units like air compressor, alternator, air condition, etc. In a BEV those units must be electrified. It is favourable to connect the great power consuming units directly to the high voltage electrical system. This results in higher efficiency and the stability of the low voltage electrical system is sustained.
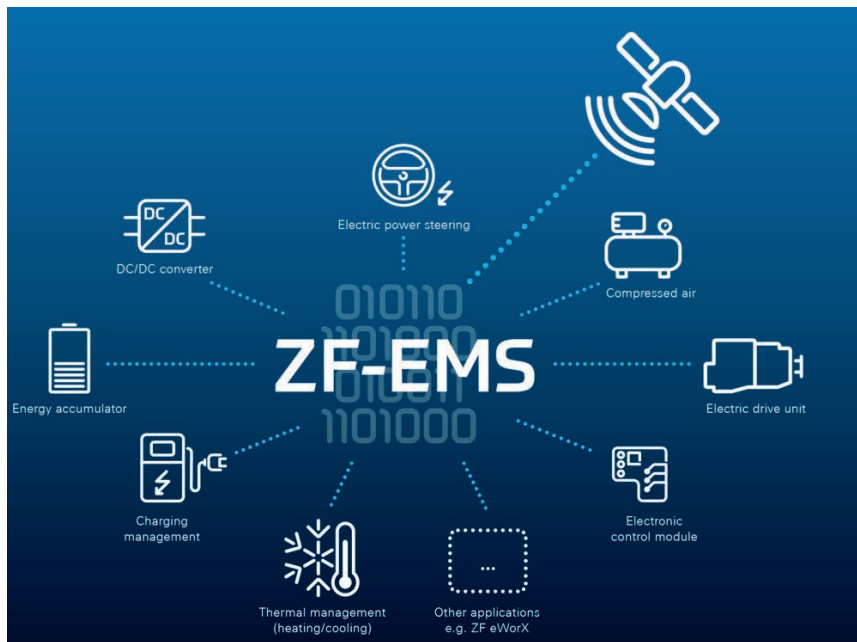
Fig. 5: Energy management software and controlled HV components.

Both aspects energy efficiency and the management of other ECUs are covered by the ZF energy management system so called ZF-EMS. ZF-EMS is essentially a standalone software that controls and coordinates all units connected to the high voltage circuit (Fig. 5). It currently manages the high voltage battery with the battery management system as control unit. Furthermore, auxiliary units like electric power steering, air compressor and air condition are managed by EV-Energy Software. In a BEV the low voltage electrical system is supplied with energy from the high voltage circuit via a DCDC converter that is itself supervised by the energy management. Of course, the EMS is also responsible for limiting the consumed power and the delivered power of the drive system. ZF-EMS distributes the available power to all high voltage components. It monitors that the current limits of the battery are maintained. Furthermore, the EV-Energy software incorporates the thermal management. The cooling system of BEVs is typically divided into separate cooling circuits. For the thermal management of the battery active cooling and heating is mandatory which is done in a low temperature circuit. Other components like electric motors and inverters are normally passively cooled. However, in situations of extensive power demand also active cooling is used. It is a matter of the cooling

system's layout how much the different circuits can interchange heat with each other. Having energy efficiency in mind it offers a great potential to use for example the waste heat of the drive system to heat up the battery or the cabin. That holds especially true in the winter season. Another part of the EV-Energy software comprises charge management. ZF-EMS supports both AC charging and DC charging. AC charging uses an on-board charging unit which converts AC current of lower voltage to DC current of the vehicle's high voltage. In contrast to that, DC charging does not need any power conversion. The charge plug is directly connected to the vehicle's high voltage circuit. However, the process must comply the safety regulations of ISO 15118 / DIN 70121 due to the high charging power. A sequence of checks and prerequisites is run through before power delivery can start. As ZF-EMS is on top of several other control units it extensively uses CAN communication to manage the different components. Therefore, extra CAN networks are setup besides the vehicle's conventional ones that are exclusively used by the additional units. As supervising ECU, the energy management also handles errors of other components. It is in the responsibility of the energy management to assess the impact of a failure of a single unit to the operating conditions of the overall system. For example, considering a defect of the DCDC converter if it occurs during start-up it is appropriate to shut down the vehicle again and warn the driver whereas if it occurs in driving situations a shutdown could be dangerous and thus the driver is only warned.

Efficiency Functions

The heart of energy management is dedicated to energy saving strategies which increase the driving range of the vehicle. There are several possibilities to do that. Some of them are easy to implement because only a single component is involved others have greater potential but incorporate the interaction between different components. An easy to implement efficiency function is the speed dependent support of the steering pump. At standstill the steering pump is switched off, at low speed the support is maximised, and with increasing vehicle speed it is decreased again. In contrast to that a smart thermal management offers greater potential. However, it concerns not only the interaction of different components but also the design of the cooling system. Exploiting the full operational temperature range of the components leads to less cooling and heating and the pump speed can be reduced, too. With that, a fair amount of energy can be saved. Moreover, if the design of the cooling system enables to interchange heat between different circuits waste heat from the passive circuit could be used to heat the cabin and the battery. Another important issue of energy management is the prioritisation of components concerning the power distribution. This becomes important if the high voltage battery is low on energy. In that situation the assignment of power to the drive system and

cabin air condition is reduced. Further on, if the energy level drops below a lower threshold the drive system will not gain any power and the cabin air condition is switched off.

The above-given energy management functions represent only a few examples. There are a lot more worth of mentioning but this would take far too long. Energy efficiency is not only restricted to the state of driving but also parking and charging benefit from smart strategies.
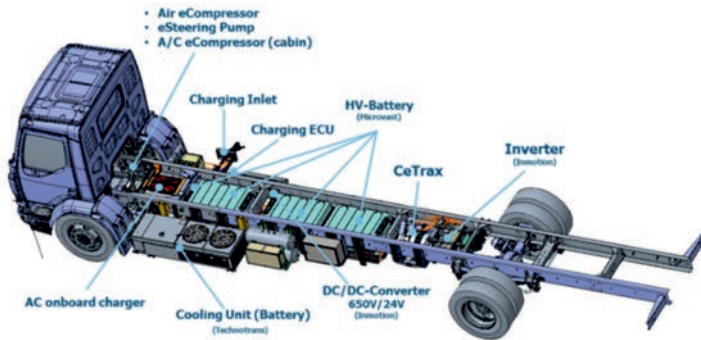
ZF Test and development facilities

The development of an energy management functions relies on an overall view on the vehicle in various situations. The complex interaction between the different components and their energy saving potential is analysed best under real test conditions. Therefore, ZF has built up a test truck which serves as platform to develop the energy management system. Fig. 6 shows a schematic overview of the vehicle. The positions of the aforementioned high voltage components are marked. Furthermore, MiL, SiL and, HiL simulations are utilised to support the development. There are several reasons why simulations are considered in the development
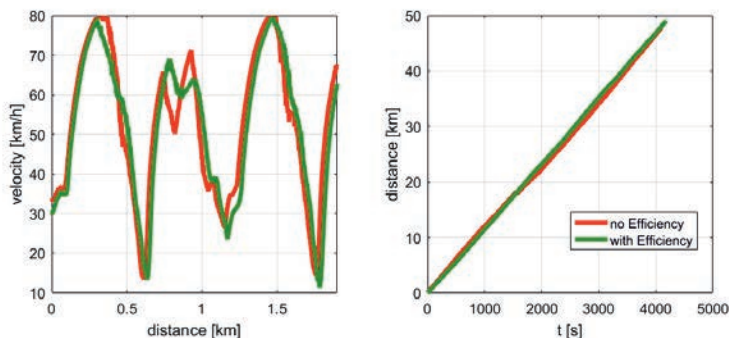
Fig. 7: Velocity and distances of test drives with and without energy management.

process. One is to ensure the software has reached the necessary degree of maturity before it is used in the truck. Another one lies in the possibility to conduct various automated tests that cannot simply be done in a vehicle.

Having the ability to test energy management right on the track offers the opportunity to assess the potential of various functions. Below, a test-driven survey is presented and the conclusions that are derived from it. The left diagram of Fig. 7 shows the velocity profiles of some test drives. It illustrates quite aggressive driving sequences those consist of cycles of strong acceleration and deaccelerations. The test drives were carried out on ZF's own test track. They
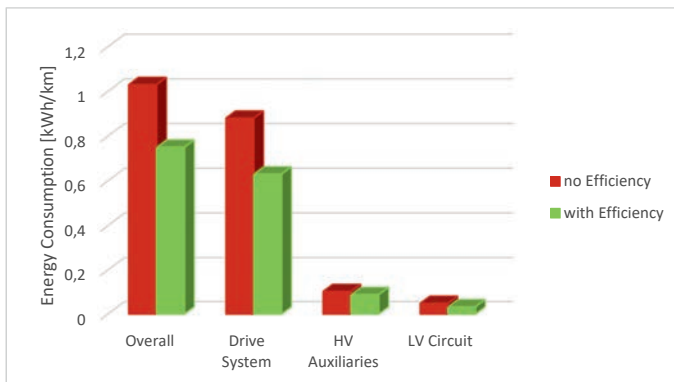
Fig. 8:   Energy consumption of test drives with and without efficiency functions.

were done with non-active and active energy efficiency functions. As Fig. 8 shows ZF-EMS clearly has an impact. The test drive carried out without efficiency functions active has an average energy consumption of about 1 kWh/km whereas with efficiency functions it reduces to 0.78 kWh/km. The major portion of the savings is achieved by limiting the maximum available power of the drive system and enforce strong recuperation. This could be also recognised in the velocity profile (left diagram of Fig. 7). The maximum velocity is hardly achieved in the case of active efficiency functions. However, this does not lead to a slower average speed as it could be deduced from the right diagram of Fig. 7. The 45 km mark is reached almost within the same amount of time. Fig. 8 also shows the energy savings from the other high voltage auxiliary units which is about 0.015 kWh/km. This is mainly achieved by adapting the power to the driving conditions and allowing the temperature of the battery to vary in a wider range. Also, the low voltage circuit benefits from these measures. Its savings amounts to approximately 0.01 kWh/km. Although, the results can only be evaluated in the

context of route and velocity profile the difference between an active, well-adapted energy management and the absence of any energy management becomes very clear.

Further development in EV software

ZF-PreVision was already applied in conventional vehicles for adapting the gearshift strategy [3] which led to a reduction of fuel consumption. Future efforts aim for the usage in connection with ZF-EMS. This further increases the ability to save energy. Knowing parameters from the route and topology ahead enables the energy management to precondition the vehicle in advance. For example, storage systems (like compressed air tank) could be driven to low before the vehicle enters a long downhill passage where recuperation refills them. Furthermore, improvements concerning the component protection of the drive system are possible if the derating strategy also accounts for temperature prediction on the base of topological information. There are a lot more opportunities one can think of if prevision is available. Common to all of them is the usage of prediction models that must be developed and linked to route information.

Summary and Outlook

The ZF E-Mobility kit represents one approach that will meet customer cost, efficiency, robustness, and versatility requirements for all products in almost all CV segments. For customers as well as for ZF, the modular ZF E-Mobility kit approach will result in significantly shorter development times, more robust products, improved serviceability, and a broader field of applications to cover. Also, modifications based on specific customer requirements can be implemented comparatively easily.

Nowadays, the increasing importance of software products becomes even more evident. This holds true for software functions related to specific hardware like the drive software and the gearbox software as well as for software focusing on the overall vehicle like the energy management. Especially, the later one plays an underestimated role in the electrification process of the drive system. But however, it is a matter of energy management that with a certain amount of installed battery capacity a maximum amount of electrical range can be achieved.

Next generation ZF E-Mobility products are already undergoing further development since costs, compactness and efficiency requirements will increase drastically when volumes rise starting in 2025. For the next generation, even more elaborate electric motors, power electronics and a higher level of sophisticated transmission knowledge will be required,

nevertheless, first-generation E-Mobility products will be needed. To achieve ZF's goal as a market leader, we are introducing two completely new products/ product lines.

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Thermoelectric Generators for Heavy-Duty Vehicles as an Economical Waste Heat Recovery System

Holistic design and evaluation with the use of modern simulation methods

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Abstract

Fuel consumption and emissions from heavy-duty vehicles account for a large proportion of emissions of road transport and without further innovation, significant reductions are unlikely. Part of this problem is that about 2/3 of the chemical energy of the fuel is lost in the form of waste heat via the engine coolant and exhaust system.

Thermoelectric generators offer a solution with low complexity and a competitive cost-benefit ratio. In this research study, a holistic modelling approach including all vehicle interactions is used for analysis and optimisation. Conventional heavy-duty commercial vehicles with diesel and innovative natural gas vehicles will be investigated. The holistic design with modern simulation methods allows the evaluation of the technology based on fuel and emission reduction and payback period for future commercial vehicles.

The results of the system are highly dependent on the load point and the application profile of the vehicle. For the diesel heavy-duty vehicle, the fuel reduction is in a range of 0.5–1.5 % and the amortisation period varies between 1.4 and >10 years at maximum electrical output of the generator under different dynamic driving conditions in the range of 180–1900 W. For the natural gas vehicle, the fuel reduction is in the range of 1.8–2.6 % and the amortisation period is between 0.7–2.5 years with output powers in the range of 1950–3150 W. In addition, the power density of the systems was determined to be 241 W/dm^3 in diesel and 568 W/dm^3 in natural gas vehicles, which represents a significant increase compared to the state-of-the-art. The lowest cost-benefit ratio is achieved by 85 EUR/(g km) for the diesel and 32 EUR/(g km) for the natural gas heavy-duty vehicle.

Thermoelectric waste heat recovery technology can be interesting for vehicle applications with gasoline, diesel, natural gas, hydrogen combustion engines and fuel cells, among others.

Introduction

Emissions from heavy-duty vehicles (HDV) need to be reduced to mitigate climate change and meet future regulatory requirements. [1] As HDV are expected to continue using internal combustion engines, due to a lack of techno-economic alternatives, a waste heat recovery system offers future potential for reducing fuel consumption and emissions. In this context, natural gas engines offer a promising alternative drive solution to the dominant diesel units for HDV in long-haul operations. [2] They are economically viable and have a lower environmental impact than diesel engines. Natural gas engine based on the Otto engine principle offer greater potential for waste heat recovery systems in the form of Thermoelectric Generators (TEG), caused by higher exhaust enthalpies, to further improve their overall efficiency.

TEG offer a low-complexity solution. Based on the Seebeck effect, TEG convert thermal energy directly into higher-value electrical energy. Installed in the exhaust system of an internal combustion engine, TEG can convert a part of the unused energy to supply the on-board network or charge the battery. Their advantages are low maintenance costs, relatively low system weight, small installation volume, and a competitive cost-benefit ratio. The state-of-the-art can be considered for example from preliminary work [3][4][5].

A Thermoelectric module (TEM) can either be operated at maximum efficiency or at maximum power. The efficiency for maximum power η_{mp} can be described according to [6] as:

$$\eta_{mp} = \frac{P_{el}}{\dot{Q}_h} = \frac{T_h - T_c}{T_h} \frac{1}{2 - \frac{T_h - T_c}{2T_h} + \frac{4}{ZT_h}} \qquad (1)$$

where P_{el} is the output power of the TEM, $\dot{Q}_h$ is the hot-side heat flow and T_c and T_h are the temperatures on the cold side and hot side respectively. In a TEG, a number of TEMs are thermally and electrically interconnected in the architecture. The electrical generator power P_{TEG} is composed of the electrical power of the TEM from equation (1) and the efficiency of the power electronics η_{PE}, to:

$$P_{TEG} = \eta_{PE} \cdot P_{el} = (\eta_{DC/DC} \cdot \eta_{MPPT}) \cdot P_{el} \qquad (2)$$

This results from the selected circuitry of the TEM and the design of the electrical components and thus the efficiency of the DC/DC-converter $\eta_{DC/DC}$ and of the Maximum Power Point Tracker η_{MPPT}. The average power $\bar{P}_{TEG}$ expended with time-varying TEG power in the time interval $T = [t_1, t_2]$, such as a driving cycle, can be determined as:

$$\bar{P}_{TEG} = \frac{1}{T} \int_{t_1}^{t_2} P_{TEG}(t) \cdot dt = \frac{1}{T} \int_{t_1}^{t_2} (\eta_{PE}(t) \cdot U(t) \cdot I(t)) \cdot dt \qquad (3)$$

Where U represents the voltage and I the current of the TEG system.

Methodology

As a methodological approach, the systems engineering and verification process is adapted to the TEG approach, as presented in Fig. 1. On the left-hand side of the development method, the modelling and analysis is carried out and on the right-hand side the verification and validation are accomplished. Based on the property assurances and the change management, the iteration process is processed or interrupted and restarted from the affected location. For the TEG system development, the overall vehicle level, the vehicle interactions with the TEG, the system and its subsystems and components are developed and implemented.
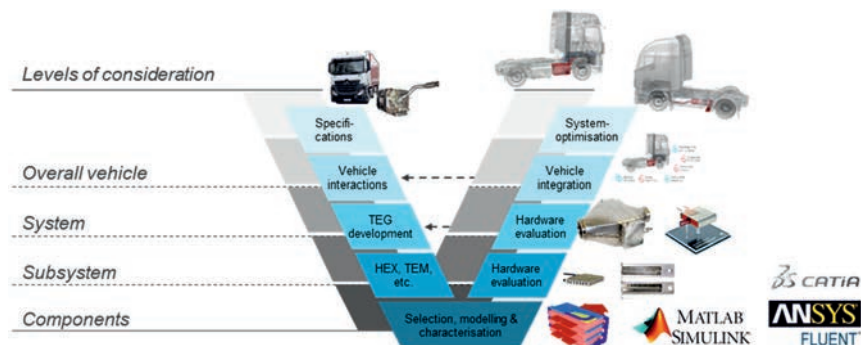
Fig. 1: Methodical approach based on the systems engineering and verification process according to [7] for the targeted design of TEG systems

The input parameters as specifications for the development process are, among others, the vehicle boundary conditions, determined on the basis of experimental real driving and simulations. Since preliminary work [3][4][5] has shown that exhaust gas aftertreatment (ATS) is most suitable for cost-benefit optimised TEG systems and long-term operation in HDVs, only the available exhaust gas enthalpies at the outlet from the ATS are considered. Since the low-temperature coolant circuit (LT-COC) offers the highest temperature differences and sufficiently high cooling capacity for the TEG, only this circuit is considered in this work. Table 1 shows as example the determined vehicle boundary conditions of the diesel and natural gas HDV. The driving scenarios selected are the World Harmonized Vehicle Cycle (WHVC) and the real driving route Stuttgart-Hamburg-Stuttgart (SHHS) in Germany. While the driving cycle is divided into typical urban, rural and motorway sections without gradients and a length of 1800 seconds, the real driving route represents a typical two-day long haul HDV operation scenario with all topographies of motorway driving. The total driving time is > 70,000 seconds. The values are given as mean and maximum values. The data for the driving cycle are

specified as an empty drive (15 t total weight) and under full load (40 t total weight). In addition to the determined temperature of the exhaust gas ϑ_{ATS} and coolant ϑ_{co} of the position for TEG integration, the respective mass $\dot{m}_{ex}$ or volume flows $\dot{v}_{co}$ as well as the available exhaust gas enthalpy $\dot{H}_{ex}$ with reference to the ambient temperature (ϑ_{amb} =20 °C) are indicated. The available enthalpy can be determined using the mass flow, the specific isobaric heat capacity c_p and the prevailing temperature difference $\Delta T = T_2 - T_1$ as:

$$\dot{H}_{ex} = \dot{m} \cdot c_p |_{T_1}^{T_2} \cdot \Delta T \tag{4}$$

The simulations are carried out with typical vehicle coolant and a glycol-to-water ratio of 50:50.

Table 1: Overview of the defined operating points (OP) and vehicle boundary conditions

Vehicle	OP	$BSFC$ [kg/100 km]	ϑ_{ATS} [°C]	$\dot{m}_{ex}$ [kg/s]	$\dot{H}_{ex}$ [kW]	ϑ_{co} [°C]	$\dot{v}_{co}$ [dm³/s]
Diesel HDV	WHVC$_{15\ t,mean}$	21.2	189	0.12	21.7	48	0.3
	WHVC$_{15\ t,max}$	45.2	238	0.29	67.9	41	0.4
	WHVC$_{40\ t,mean}$	36.5	243	0.17	40.9	51	0.3
	WHVC$_{40\ t,max}$	52.3	286	0.38	108.5	46	0.4
	SHHS$_{40\ t,mean}$	29.2	297	0.2	60	51	0.4
	SHHS$_{40\ t,max}$	85.1	341	0.58	187.4	57	0.6
Natural gas HDV	WHVC$_{15\ t,mean}$	25	609	0.06	33.4	50	0.3
	WHVC$_{15\ t,max}$	46.1	659	0.16	96.2	43	0.4
	WHVC$_{40\ t,mean}$	42.7	652	0.1	64.5	52	0.3
	WHVC$_{40\ t,max}$	55.6	710	0.22	169.4	46	0.4
	SHHS$_{40\ t,mean}$	35.5	676	0.14	94.5	54	0.4
	SHHS$_{40\ t,max}$	88.9	743	0.36	275.3	58	0.6

A holistic approach is chosen that is developed and used for analysis and optimisation, as shown in Fig. 2. The model environment, suitable for static and dynamic investigations, considers all relevant positive and negative vehicle interactions and their influence on the efficiency of the overall system. The vehicle interactions considered, include the additional weight, the exhaust back pressure, the additional coolant pumping capacity, and the energy consumption of the on-board electrical system. Simultaneous optimisation, especially of heat exchangers (HEX) and TEM, has proven to be a key to efficient and cost-benefit-optimised TEG. The physical properties of the HEX, for example, are modelled numerically. They are combined with empirical macroscopic equations of the TEM, among others. The selection of a

TEG output design is achieved on the principle of a multi-criteria optimisation, which is especially dependent on the main objective to minimise the Total Cost of Ownership (TCO), as specific for HDV.
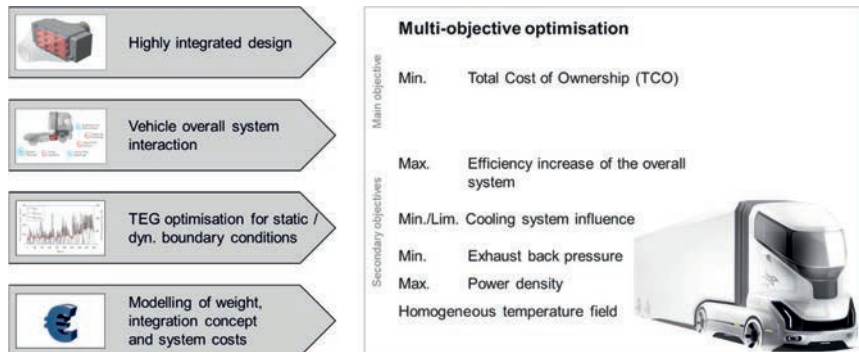
Fig. 2:   Development approach for TEG systems based on multi-objective optimisation and consideration of the overall vehicle interaction as well as holistic design criteria

The resulting fuel reduction is determined on the basis of the vehicle differential work as a result of the change in the shaft power of the vehicle. The individual positive and negative TEG interactions add up to the differential work and change in net fuel consumption and thus emissions. Using the example of the natural gas HDV under motorway constant driving, the individual effects on the fuel consumption reduction of the vehicle are summarised in Fig. 3 at the overall vehicle level. According to simulations from preliminary work (see [3]), the coolant capacity in the range of 40–90 kW can be introduced as heat flow of the TEG, depending on the driving profile of the vehicle, without fan operation starting and negating the net fuel saving.

Impact on the Internal Combustion Engine

    ↗ Additional mass m_{TEG} $+ 0.1\% \, \Delta BSFC^*$

    ↗ Additional back pressure p_{TEG} $+ 0.05\text{–}0.3\% \, \Delta BSFC^*$

+ Impact on the Cooling System

    ↗ Additional cooling load $\dot{Q}_{TEG}$ $0\% \, \Delta BSFC^* \, (\sim 40\text{–}90 \, kW)$

    ↗ Additional pumping power $\mathrm{P_{cp}}$ $< +0.05\% \, \Delta BSFC^*$

– Impact on the Electrical System

    ↗ Additional electrical power P_{TEG} $-(0.8\text{–}2.3)\% \, \Delta BSFC^*$

= Total: $-(0.35\text{–}2.1)\% \, \Delta BSFC^*$

                                              $(\Delta c = -(2.8\text{–}17.9) \, g/km)$

Fig. 3:   Exemplary evaluation of the TEG system for natural gas HDV in the form of the change in fuel consumption (*for typical load points of motorway driving; $BSFC = 32.2$ kg/100 km; specific CO_2 emissions $c = 813$ g/km; TEG supplies the electrical 24 V on-board network)

Results of the Holistic Optimisation

The TEG system in stacked design, with planar TEM and HEX in counterflow configuration, has proved to be the most effective. Fig. 4 illustrates this as an example of the output design for natural gas HDV and the objective of minimising the TCO. In the figure, the core consists of stacked coolant (COHEX) and hot gas heat exchangers (HGHEX) with intermediate TEM and thermal contacting. Fig. 5 also presents the enclosure for test bench investigations around the TEG core.
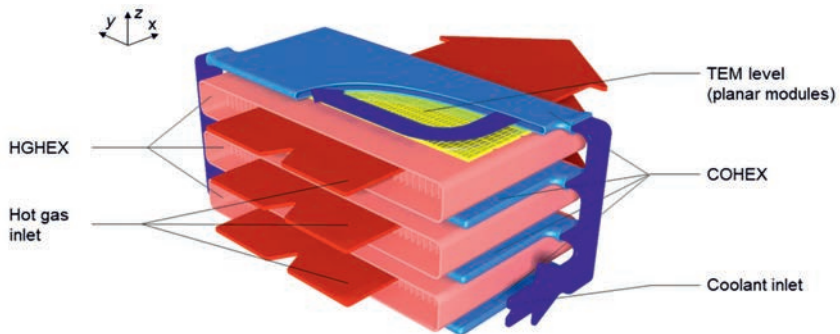
Fig. 4: Principle of the TEG stack design of the core using the example of the TEG experience design with objective TCO_{min} for the natural gas HDV

As can be seen in the Table 1, the two applications in diesel exhaust gas and natural gas exhaust gas differ significantly from each other in terms of the available exhaust gas enthalpies and especially the temperatures. Therefore, low-temperature modules of the material class bismuth telluride are used for the diesel and high-temperature modules of the material classes bismuth telluride (BiTe, cold side) and skutterudite (SKD, hot side) are used for natural gas HDV as currently efficient solutions. The performance characteristics of the selected modules are shown in Table 2.

Table 2: Thermoelectric module characteristics related to this work

Vehicle	ATS temperatures [°C]	TEM material	η_{max} [%]	p_{max} [W/cm²]	Reference
Diesel HDV	150–400	BiTe	5	1.1	[8]
Natural gas HDV	500–800	segmented BiTe & SKD	9	3	[3][4]

Possible main objectives of the multi-criteria TEG-simulation environment could be:

- Minimum cost-benefit ratio or total cost of ownership (TCO_{min})
- Minimum fuel consumption ($BSFC_{min}$)
- Maximum power output (P_{max})
- Maximum power density (PD_{max})
- Maximum efficiency (η_{max})
- Minimal long-term loss of stability or power (LoS / LoP)
- Further…

Fig. 5 illustrates the TEG variants, as test bench functional models, as results of the first two main objectives for both vehicles and the selection process from the generator design to the specific vehicle integration concept in the HDV tractor.
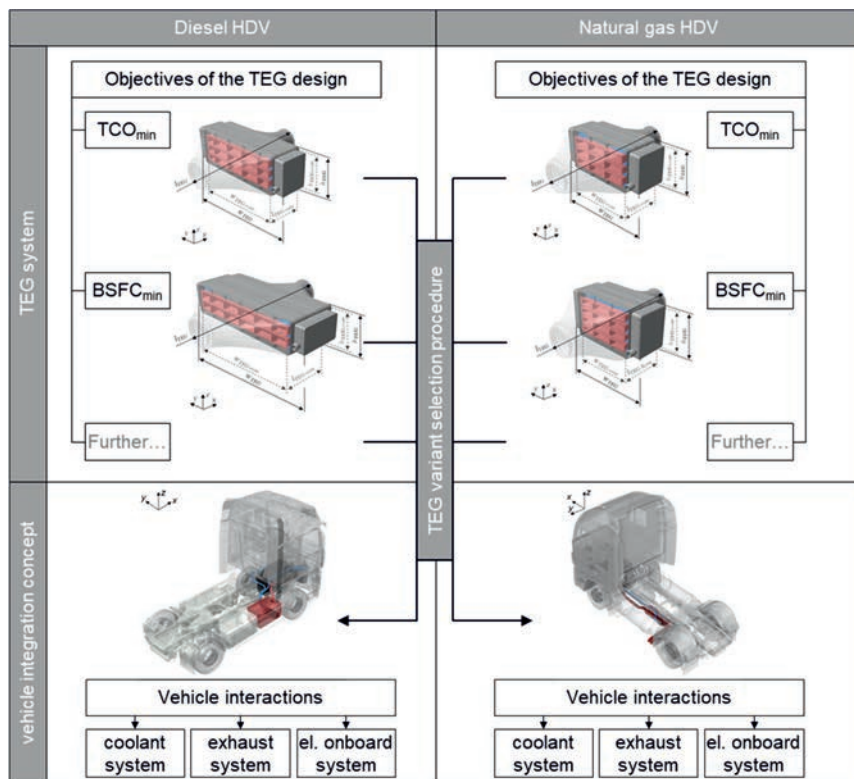
Fig. 5:   Selection process of the TEG variants based on the results of the multi-objective simulation method and development of the integration concepts considering the vehicle interactions in the long-haul tractor unit with diesel engine (left) and natural gas engine (right)

The design is determined using the weighted results of the driving scenarios and operating points. The mean values of the driving cycles and the real driving route as well as the median, nominal speed, torque and power are considered with great weighting. Maximal load cases, such as the respective maxima, are included with little relevance. Fig. 6 presents the Pareto

fronts for exemplary operating points for the cost-benefit ratio and the electrical power. Each point in the diagrams represents a geometrically different TEG design. For each operating point, the evolutionary algorithm used, has calculated more than 10,000 designs. With the help of these Pareto fronts, a holistic optimum for the respective TEG variant can be determined based on the weightings mentioned.

(a) Cost-benefit ratio of diesel HDV

(b) Power output of diesel HDV

(c) Cost-benefit ratio of natural HDV

(d) Power output of natural HDV
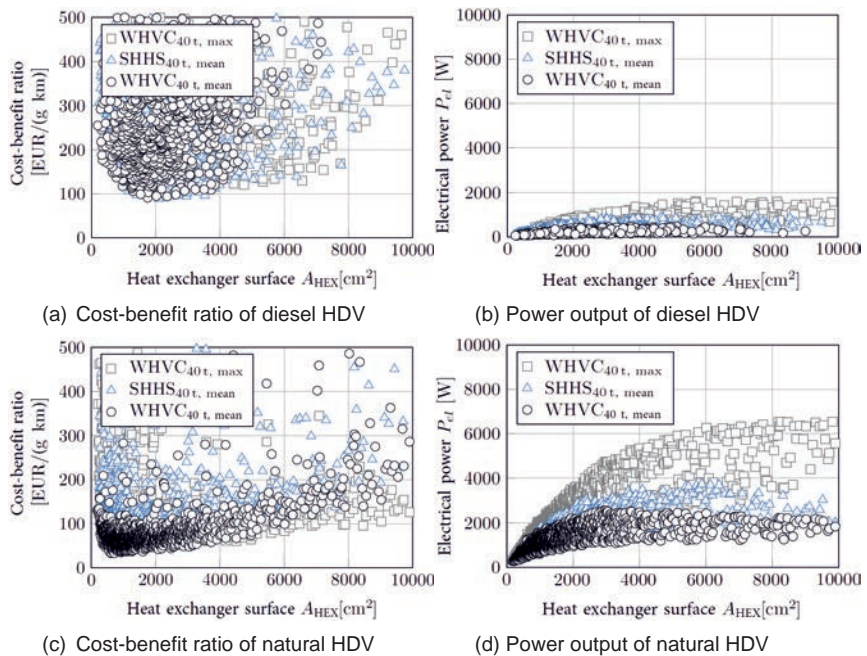
Fig. 6:   Results of the multi-objective optimisation in form of the cost-benefit-ratio and electrical power over the heat exchanger surface for both vehicles

Detailed results of the TEG variants TCO_{min} and $BSFC_{min}$ are shown in Table 3. For the diesel HDV, the optimum is determined for the TEG variant TCO_{min} with a unit cost of EUR 784, a weight of 24.5 kg, a HGHEX area of 1260 cm^2 and low-temperature material bismuth telluride. For the $BSFC_{min}$ variant, the unit costs increase to EUR 1254, the weight to 35.6 kg and also the HGHEX area to 3360 cm^2. For the natural gas HDV, a unit cost of EUR 1002, a weight of 27.4 kg, a HGHEX of 1420 cm^2 and segmented high-temperature capable TEM are determined for the variant TCO_{min}. For the $BSFC_{min}$ variant, the unit costs increased only

slightly to EUR 1053, as well as the weight only to 28.3 kg and the HGHEX area to 1655 cm^2, since the vehicle interactions, especially the coolant limitation, do not allow any further increase. In addition to detailed information for the three sections of the WHVC, typical light, medium and heavy sections of the SHHS route are also provided. Based on the average $\bar{P}_{TEG}$

Table 3: Overview of the results achieved by using TEG in HDV (ϑ_{amb} = 20 °C) with the objectives TCO$_{min}$ or BSFC$_{min}$ (Integration: after ATS & LT-COC)

Vehicle (TEG-Design)	Reference cycle / route	Overall Vehicle		TCO-Balance		TEG-System		
		$\Delta BSFC$ [%]	Δc [g/km]	C_{TEG} [EUR]	t_A [Year]	$P_{TEG,max}$ [W]	$\bar{P}_{TEG}$ [W]	m_{TEG} [kg]
Diesel HDV (TCO$_{min}$)	WHVC$_{15t}$ Overall	−0.6	−4.2	784	5.9	399	184	24.5
	WHVC$_{40t}$ Overall	−0.7	−8.5		1.8	656	339	
	WHVC$_{40t}$ Rural	−0.6	−7.8		2.3	318	237	
	WHVC$_{40t}$ Urban	−1	−12.4		1.4	491	339	
	WHVC$_{40t}$ Motorway	−0.6	−6.5		2	656	558	
	SHHS$_{40t}$ Overall	−1	−8.8		2	992	560	
	SHHS$_{40t}$ Light	−1.3	−7.6		2.7	663	475	
	SHHS$_{40t}$ Medium	−0.6	−6.1		4.1	868	614	
	SHHS$_{40t}$ Heavy	−0.8	−10.4		1.7	992	642	
Diesel HDV (BSFC$_{min}$)	WHVC$_{15t}$ Overall	−0.8	−5.7	1254	9.8	645	247	35.6
	WHVC$_{40t}$ Overall	−1	−12		2.9	1165	521	
	WHVC$_{40t}$ Rural	−0.8	−10.7		3.5	612	336	
	WHVC$_{40t}$ Urban	−1.1	−14.5		2.1	871	536	
	WHVC$_{40t}$ Motorway	−0.8	−9.5		4.5	1165	897	
	SHHS$_{40t}$ Overall	−1.2	−11.4		3.1	1891	925	
	SHHS$_{40t}$ Light	−1.5	−8.7		5.1	1144	699	
	SHHS$_{40t}$ Medium	−0.9	−8.5		5.7	804	1476	
	SHHS$_{40t}$ Heavy	−0.8	−11.2		3.2	1891	1607	
Natural gas (TCO$_{min}$)	WHVC$_{15t}$ Overall	−2.5	−15.7	1002	1.8	1954	1030	27.4
	WHVC$_{40t}$ Overall	−2.3	−24.6		1	2371	1424	
	WHVC$_{40t}$ Rural	−2.3	−34.1		0.7	1959	1100	
	WHVC$_{40t}$ Urban	−1.9	−22.4		1.1	2252	1518	
	WHVC$_{40t}$ Motorway	−2.4	−19.2		1.3	2371	2009	
	SHHS$_{40t}$ Overall	−2.1	−18.9		1.4	2688	1686	
	SHHS$_{40t}$ Light	−2.5	−15.9		1.8	2610	1741	
	SHHS$_{40t}$ Medium	−2	−19.8		1.3	2614	1850	
	SHHS$_{40t}$ Heavy	−2.1	−27.3		0.9	2688	1897	
Natural gas (BSFC$_{min}$)	WHVC$_{15t}$ Overall	−2.6	−16.4	1053	1.9	2170	1085	28.3
	WHVC$_{40t}$ Overall	−2.4	−25.6		1.1	2691	1506	
	WHVC$_{40t}$ Rural	−2.4	−34.9		0.8	2099	1127	
	WHVC$_{40t}$ Urban	−2	−23		1.2	2560	1585	
	WHVC$_{40t}$ Motorway	−2.6	−21.5		1.4	2691	2227	
	SHHS$_{40t}$ Overall	−2.1	−19		1.5	3150	1647	
	SHHS$_{40t}$ Light	−2.8	−17.4		1.9	2899	1367	
	SHHS$_{40t}$ Medium	−2.1	−20.3		1.3	2920	1685	
	SHHS$_{40t}$ Heavy	−1.8	−22.5		1.2	3150	1881	

and maximum TEG power output $P_{TEG,max}$ in the respective driving scenario, the resulting net fuel reduction $\Delta BSFC$ is determined as a result variable. This is equivalent to a kilometre-specific reduction $\Delta BSFC$ is determined as a result variable. This is equivalent to a kilometre-specific emission reduction Δc. Based on the fuel reduction and the underlying TCO base model (assumptions: annual mileage of 150,000 km, service life of 5 years, and high annual TEG unit numbers of ~30,000; for further details see [3]), the amortisation period t_A of the system can be calculated. As a result, the amortisation period varies between 1.4 and >10 years for the diesel and is between 0.7–2.5 years for the natural gas HDV.

The highly integrated TEG integration concepts developed for the outlet of the ATS and in the LT-COC are illustrated in the Fig. 7 for both vehicles.
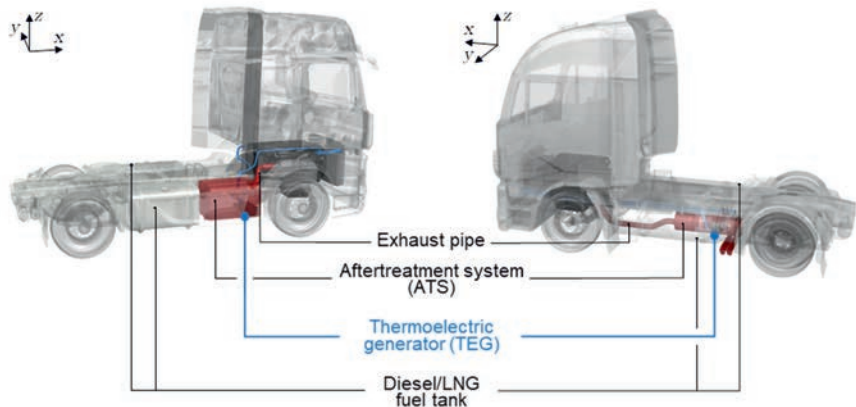
Fig. 7: TEG vehicle integration concepts – diesel tractor (left) and natural gas tractor (right)

An overview of the main TEG-simulation results is given in Table 4. The power density data was determined using the respective nominal power output of the TEG systems.

Table 4: Overall results of the TEG-simulation environment

Vehicle	Efficiency improvement (ΔBSFC) [|%|]	Cost-benefit-ratio		Power density		Amortisation period [Year]
		[EUR/%]	[EUR/(g km)]	[W/kg]	[W/dm³]	
Diesel HDV	0.5–1.5	805	85	157	241	< 2
Natural gas HDV	1.8–2.6	344	32	261	568	<< 2

Evaluation and Outlook

The results developed for both reference vehicles can be considered promising, as for the first time, the amortisation of the TEG system could be simulated in less than three or even less than two years, which is a decisive criterion for HDV. As an example, the evaluation of the results of this study in the context of the state-of-the-art is shown in Fig. 8 using the gravimetric and volumetric power density of various TEG systems. The improvement of the state-of-the-art is clearly recognisable.
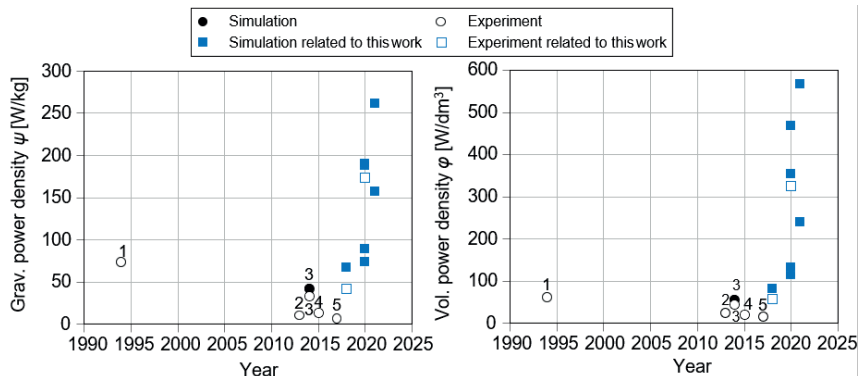
Fig. 8:   Comparison of gravimetric (left) and volumetric (right) power density of TEG systems for HDV applications (References: 1: [9], 2: [10], 3: [11][12], 4: [13][11], 5: [14])

In addition, a comparison of the two investigated powertrains, diesel and natural gas HDV, with other powertrains that might be of interest in the future, is presented in Fig. 9 on the basis of the average exhaust gas enthalpy and average electrical power. In addition, the potential for low- (LT-FC) and high-temperature fuel cells (HT-FC), as well as hydrogen combustion engines (H_2CE), is estimated.
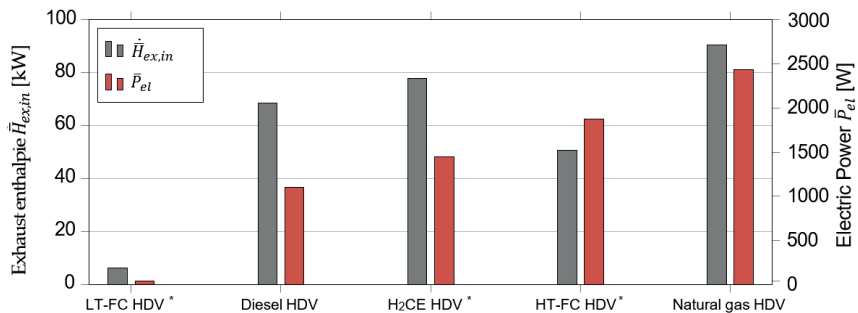
Fig. 9:   Comparison of the potential of TEG systems for different HDV powertrains based on the available exhaust enthalpy at constant speed of 80 km/h and the electrical power calculated with the TEG design $BSFC_{min}$ (* Estimation; boundary conditions among others: $\vartheta_{co,in}$=60 °C; own calculation with data from:[15][16][17][18][19][20][21])

Conclusion

A methodology for holistic thermoelectric generator optimisation for heavy-duty vehicles was presented, ranging from highly integrated generator design to whole-vehicle system interactions and multi-objective optimisation. The simulation environment was explained and exemplary results were presented for diesel and natural gas heavy-duty vehicles. As a result of the holistic optimisation, different generator variants could be presented that reduce fuel consumption and thus emissions. The variants for minimising the total cost of ownership of the respective vehicle, allow this for the first time under economic aspects for the thermoelectric waste heat recovery in heavy-duty vehicle in an amortisation period of less than two years in each case. In addition, the vehicle integration concepts were presented. The greatest benefit for the diesel application was achieved in the form of the cost-benefit ratio with 805 EUR/% or 85 EUR/(g km) and with 344 EUR/% or 32 EUR/(g km) in the natural gas application. Finally, a state-of-the-art assessment has been shown which demonstrates the achieved increases on the basis of the gravimetric and volumetric power density for heavy-duty vehicle applications. In addition the potential of the technology for future powertrains is estimated.

A commercially attractive thermoelectric generator system was presented and it is hoped that it will be used as a contribution to cost-effective greenhouse gas emission reduction of heavy-duty vehicles.

Acknowledgements

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Hybridization of Heavy Duty Trucks

Market Analysis and Technology for High Voltage as well as Low Voltage Solutions

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Abstract

The European CO2 targets of -15% in 2025 and -30% in 2030 in comparison to the 2019 figures pose a major challenge for truck manufacturers as well as drivetrain suppliers. Already today, it has become evident that fully electric vehicles will play a key role in order to meet these targets. However, the future of hybrid electric vehicles is much more complex to predict. Their potential unfolds in particular with regard to the heavy duty truck segment. Depending on future legislation, hybrid electric vehicles might become a necessity in this segment next to battery electric vehicles and fuel cell electric vehicles.

Two types of hybrids are in the focus of current discussions on hybridization of drivetrains. High voltage hybrids (hybrids, plug-in hybrids) and low voltage hybrids (mild hybrids). Apart from outlining different hybrid architectures, this article also provides insights into fuel efficiency simulations and cost levels for different sorts of hybrids. Additionally, an overview of ZF product solutions is presented for mild hybrids, hybrids as well as plug-in hybrids. For possible hybrid solutions, ZF strongly builds on its new Commercial Vehicle eDrive Platform: on the one hand to provide the latest e-mobility technologies to the customers with regard to various truck and bus applications and on the other hand to benefit from economies of scale.

Furthermore, legal aspects such as VECTO, Eurovignette and Euro VII are important factors serving as input when predicting the future market potential of hybrids. After taking into consideration all these aspects, a higher penetration rate of low voltage hybrids than high voltage hybrids seems to be likely, up to a scenario where low voltage hybrids might become new standard equipment for combustion engines.

Technology

In order to set up a hybrid driveline, an electric motor has to be added to the combustion engine driveline. There are several possibilities to place the electric motor in the driveline which leads to different hybrid architectures. There are parallel, serial and power-split hybrids whereas parallel hybrids are the only reasonable solution for heavy commercial vehicles in long-

distance applications. This is primarily due to the fact that these architectures allow for dimensioning the electric motor irrespective of the driving requirements of the vehicle.

Since parallel hybrids offer a broad range to dimension the electric motor, terms like "full hybrid" or "mild hybrid" are established to make a distinction among the various sizes of the electric motor. But the interpretation of these terms is quite vague and there are no generally applicable criteria in the industry. In general, a mild hybrid is associated with a lower voltage level such as e.g. 48V, whereas a full hybrid is associated with high voltage and provides electric driving feature to a certain level. In addition, there are plug-in hybrids where the battery can be charged on the grid. Consequently, plug-in hybrids can be considered a special case of full hybrids. Typically, plug-in hybrids offer considerably more electric range. The expectation is to provide a range of at least 50 km. Therefore, a plug-in hybrid is characterized to a larger extend by the capacity of the battery than by the electric motor dimension. Nevertheless, plug-in hybrids are more often associated with higher electric driving requirements, e.g. top speed and gradeability which in consequence leads also to a stronger electric motor. Hence, it is possible to deem the plug-in hybrid to be an alternative solution within the range of a normal high-voltage hybrid and a battery electric vehicle.
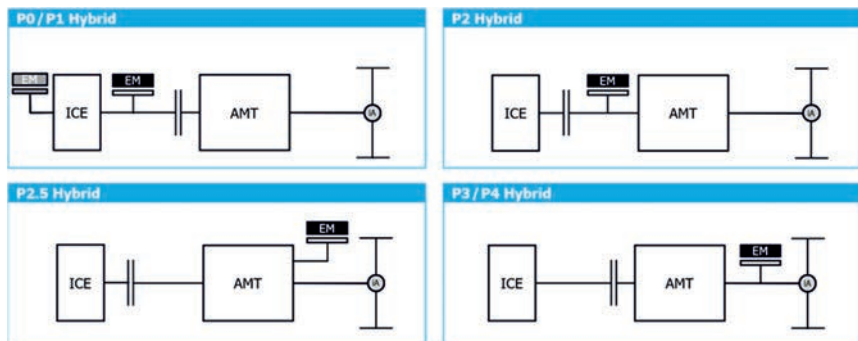
Fig. 1: Architectures for parallel hybrid

There are several architectures among parallel hybrids, each attributed with their advantages and disadvantages. Thus, it is crucial to make a decision for the right architecture. This depends on the application and customer needs. It has become common to designate parallel hybrid architectures with terms ranging from P0 to P4 as shown in fig. 1. The architecture with which the e-motor is placed at the PTO of the transmission is less commonly known. With regard to positioning the electric motor behind the transmission, this is similar to the P3

architecture, whereas from a functional point of view it resembles a P2. Therefore, this architecture type should be referred to as P2.5 in the following.

For high voltage hybrids, P0 and P1 architectures are not taken into consideration. One reason is that they do not offer the possibility to decouple the electric motor from the combustion engine, thus rendering electric driving impossible. From the remaining alternatives, ZF chose the P2 architecture when opting for high voltage hybrids.

ZF has been working on high voltage hybrids for heavy duty trucks for many years. A modular approach was pursued in connection with ZF' standard transmission TraXon (fig. 2) [1]. In this case, the selected solution benefits from the economies of scale of the conventional TraXon transmission. The most recently developed design features an electric motor of 130kW peak. One the one hand, this type enabled limited electric driving, which means driving requirements way below the one combustion engines offer. On the other hand, the electric motor size strikes a balance between functionality and costs, considering that fuel savings are paramount and limited electric driving an acceptable compromise.
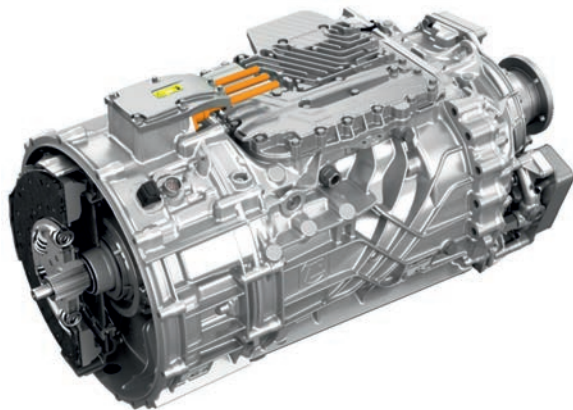
Fig. 2: TraXon Hybrid

The electric motor is of high-speed design. This leads to a compact e-motor in order to limit the transmission elongation. An additional one-speed transmission is thus needed for the electric motor. It can be placed inside the electric motor, not hampering the compact design of the product. The hybrid transmission was tested in field tests by several customers.

This concept works well on a hybrid base but does not fulfill the expectations a plug-in hybrid has to deliver due to the limited power of the electric motor. Thus, ZF revised its concept in

order to meet the requirements of plug-in hybrids. Usually, a stronger electric motor adds up to more costs and longer payback time, but the aim was to compensate this effect by taking the electric motor off ZF's new Commercial Vehicle eDrive Platform. This platform is currently in the development phase and will provide a completely new generation of electric axle and electric central drives [2]. One of the two electric motors from ZF's Commercial Vehicle eDrive Platform is well suited for the use in TraXon Hybrid. The electric motor provides the latest technology including for example the PSM with hairpin windings. Therefore, this electric motor allows for another leap forward with regard to compactness and efficiency. In addition, considering the costs, it is a very competitive approach since the e-Mobility components profit from the extensive scale effects the ZF's Commercial Vehicle eDrive Platform offers. The electric motor is a high-speed design as well, running at an even higher speed. Consequently, an additional one-speed transmission is still needed to supplement the electric motor. The basic concept is the same as the one of TraXon Hybrid. The plug-in hybrid concept, such as the hybrid concept, builds on the conventional TraXon transmission in order to be able to benefit from its economies of scale.

Fig. 3: Dedicated hybrid transmission DHT

In addition to the modular approach based on TraXon, ZF pursued a DHT solution (dedicated hybrid transmission). In this case, there is no conventional base transmission and the DHT transmission is designed solely for the use in hybrid drivelines. This opens tup opportunities for further means of system optimization. ZF's solution, for instance, has no conventional clutch

and fewer gears while offering additional functionality, e.g. power-shifting. The design of the prototype transmission is displayed in figure 3. It is obvious that this product is more suited for higher sales volumes to justify the development efforts. This is not foreseen in the current market outlook; therefore for the time being, TraXon Hybrid is ZF's concept of choice for a high voltage hybrid.

For a 48V hybrid, ZF selected a P2.5 architecture. The concept decision was motivated due to the installation space aspects. A 48V e-motor is compact enough so that it can be fitted at the PTO without compromising the existing installation space of today's conventional driveline. Thus, a solution can be provided which is installation-compatible with the conventional TraXon transmission. Also in this case, a transmission between the electric motor and the driveline is reasonable in order to achieve the required compactness.

Fuel Efficiency

In early development phases, fuel consumption simulation plays an important role for deciding on the right concept and assessing the market potential. In this field, ZF has a long history when it comes to combustion engine drivelines and also for electric and hybrid electric drivelines since the beginning of the new millennium. The respective tools were developed inhouse. Models are calibrated with real world data and considerable trust in the results and know-how has been built over time. In case of the simulation of the products presented here, there was also an alignment with customer simulations.

Savings generated by hybrids are always route-dependent. The ACEA routes and weights, which are also used in VECTO, were applied here [3]. Other routes were simulated as well. It has to be noted that the ACEA routes are not quite hybrid-friendly and other routes may better reflect real world savings, but the ACEA routes were chosen for reasons of better comparison. TraXon Hybrid was simulated with the new electric motor from ZF's Commercial Vehicle eDrive Platform, while for 48V-hybrids a typical electric motor configuration with 25 kW peak was used.

The share of fuel saved by stop-start and electric sailing is much higher for the regional route than for the long-haul route. In addition to savings by hybrid functionality, a certain share coming from electrified auxiliaries was considered, too, since it constitutes a crucial aspect when discussing mild hybrids. Following a more simplified approach, this share is more or less the same for the considered routes and weights.

TraXon Hybrid achieves fuel savings of around 5% on the long-haul route, whereas the 48V-hybrid leads to savings of around 1%. When additionally considering the potential of electrified auxiliaries, this leads to ca. 6% vs. 2%. This means that the mild hybrid can reach one third of

the savings the full hybrid generates; this is quite some result in itself, taking into account the potential costs which might occur in a mild hybrid system. But it further exemplifies the reason why mild hybrids are often regarded only in connection with electrified auxiliaries, as the potential may be too low when considering the hybrid functionality alone.

Additionally, a route and weight mix was created as an application mix for long-haul and regional missions. This shall reflect that a vehicle on a long-haul mission does not drive all the time on a long-haul route; the same applies to a vehicle on a regional mission. For long-haul application, a mix of 80% long-haul route and 20% regional route was taken into consideration, for regional application a mix of 50:50. Furthermore, the weight mix was 70% heavier and 30% lighter weights in all cases. The mixes should be more representative for real world savings and, when creating them, customer insights were taken into account. This results in about 6% fuel savings for TraXon Hybrid for the long-haul application and about 2% for the mild hybrid. Including electrified auxiliaries, this leads to about 7.5% fuel efficiency for TraXon Hybrid and about 2.5% for the mild hybrid. Consequently, the ratio equals again to 1:3 of the TraXon Hybrid and the mild hybrid.

The figures for TraXon Hybrid were more than confirmed by field test results. In general, the field test results are somewhat better than the simulation results which may be caused by the fact that not all details of a route are reflected in the simulation route and that the effects of the interaction with other vehicles is not considered as well.

Legislation

In the following chapter, we investigate the impact of the legal topics VECTO, Eurovignette and Euro VII on the hybridization of heavy duty trucks. These legal aspects were selected as they have a strong impact on the future market penetration of hybrid trucks. However, it must be acknowledged that further legal aspects exist that are not analyzed below.

For determining the CO_2 emissions of heavy duty vehicles in connection with the EU regulation, the simulation tool VECTO (Vehicle Energy Consumption Calculation Tool) was created [4]. Since 2019, its use has been mandatory for certain vehicle classes and others will follow soon. Initially, VECTO did not take hybrid drivelines into consideration, but this is currently being worked upon; a test version already exists. ZF participates in the testing and the objective is for the tool to reflect real world savings. One important issue is the implemented control strategy since this strategy determines whether the full potential of the hybrid system could be exploited or not.

Furthermore, the European Union is planning to introduce a CO_2-based toll system called "Eurovignette". The target is to give an incentive to haulers to use trucks with lower CO_2

emissions. The legislation process is handled by the so-called Triloque consisting of the European Parliament, the European Commission, and the European Council. By the end of 2020, the European Council has reached an agreement on the conditions of the new toll system. In a last step, the European Parliament will probably decide upon this proposal over the course of 2021. Germany will be among the first countries to implement the legislation with a planned enaction in 2022. By 2023, all member states of the European Union shall implement the legislation into national law. Basically, the target is to implement the Eurovignette in all member states by 2028. However, this legislation is not binding for the member states since there are several reasons for exceptions.

If a member state implements the new toll system, table 1 reveals which toll charges are valid for which vehicle class among heavy duty trucks according to the proposal of the European Council of 2020. Vehicles that do not provide any CO_2 reductions are allocated to class 1. This class makes up the baseline. In the future, toll fees for these vehicle categories might be up to 50% higher than today. For hybrid trucks standalone without additional means of CO_2 reduction, the following framework is intended: Mild hybrids standalone most likely do not profit from the CO_2-based toll system since they can reach a carbon reduction by less than 5%. Hybrids standalone profit from 5-15% reduced toll charges. Plug-in hybrids standalone probably will benefit from 15%-30% reduced toll charges. In addition to that, low emission vehicles (LEV) might profit from 30%-50% toll fee reductions and zero emission vehicles (ZEV) from 50%-75%. LEV is defined is a heavy-duty vehicle with CO_2 emissions lower than 50% of the reference CO_2 emissions of its vehicle group, other than a ZEV.

Table 1:   Eurovignette toll fee reductions by vehicle class (status 12/2020) [5], [6]

Vehicle Class	CO_2 Reduction	Toll Fee Reduction
1	0% - 5%	0%
2	5% - 8%	5% - 15%
3	8% - 50%	15% - 30%
4	> 50% (LEV)	30% - 50%
5	100% (ZEV)	50% - 75%

Besides CO_2 limits and CO_2-based toll fees, the upcoming Euro VII-norm will also affect the penetration rate of hybrids in Europe. The Triloque of the European Union is responsible for

the definition of Euro VII. Euro VII tackles many different types of pollutant emissions. So far, the limit values have not yet been defined. However, it is very likely that, on the one hand, the limit values of Euro VII, e.g. for NOx and Solid Particle Number, will be much lower than the ones of Euro VI which is currently in place and, on the other hand, that new testing procedures will be installed [7], [8]. In order to meet the new limits, the combustion engines including the aftertreatment systems will probably have to be updated.

Based on the new testing procedures of the Euro VII-norm, which are in discussion right now, the emissions during cold-start phases might be of relevance. Plug-in hybrids can help to overcome this obstacle, since they can drive electrically until the exhaust gas aftertreatment is heated up. As a consequence, plug-in hybrids eventually need less technical updates than conventional trucks to become ready for Euro VII. This would be a cost advantage for plug-in hybrid compared to conventional trucks, making them more attractive in the future.

Euro VII also provides an additional benefit for the penetration rate of mild hybrids. The emissions during cold-start phases might make pre-heating devices necessary to shorten the cold-start phase. If these pre-heaters are driven electrically, mild hybrid technology might be the promising option to pursue. Mild hybrids can recharge the batteries while driving by recuperation. This energy is available during cold-start phases. As the Euro VII-norm has to be fulfilled not on a fleet average basis but by every single truck, Euro VII has the potential to be a real booster for mild hybridization penetration rates.

However, the following must be clearly stated: First, the mentioned effects regarding plug-in hybrids and mild hybrids must be studied in much more detail and second, the Euro VII limits need to be defined before any final conclusions are possible.

Market Potential

After having investigated the topics technology, fuel efficiency and legislation, it is necessary to derive a conclusion regarding the future market potential of hybrids in Europe. This, however, is a quite challenging endeavor at the current point of time since several legal aspects are not set yet. For example, the implementation of hybrids in VECTO, the Eurovignette and the Euro VII-norm have not been finalized so far. Thus, it is possible to give only a very vague outlook, and this forecast might change significantly, if one factor changes.

Starting from a technological point of view, the complexity of the system increases from mild hybrids to hybrids to plug-in hybrids. Increasing system complexity leads to increasing costs. Therefore, mild hybrids are the cheapest solution. However, mild hybrids also provide the smallest fuel efficiency potential, followed then by hybrids and plug-in hybrids. The fuel efficiency potential of plug-in hybrids strongly depends on the size of the installed battery

capacity. A bigger battery capacity leads to a longer electric driving distance and, consequently, to less fuel consumption. Furthermore, it is of high relevance for vehicle manufacturers on how fuel efficiency is considered in the VECTO tool in respect to CO_2 reductions, since the manufacturers need to meet CO_2 targets for their fleets in 2025 and 2030. If the VECTO tool implements the CO_2 reductions congruent to the fuel efficiency potentials, mild hybrids will contribute less than hybrids and hybrids less than plug-in hybrids to fulfilling the vehicle manufacturer's CO_2 fleet targets. In case this assumption turns out to be true, it is most likely also going to apply to the Eurovignette. Thus, haulers would benefit more from toll fee reductions by using plug-in hybrids in comparison to using hybrids or mild hybrids. Moreover, Euro VII might make plug-in hybrids more attractive regarding costs compared to conventional trucks. This is due to their ability to drive electrically which may lead to lower costs on updating the aftertreatment system. Additionally, mild hybrids could become necessary to provide the electric energy that is needed to heat-up the aftertreatment system to achieve the Euro VII emission targets.

These reflections lead to the conclusion that mild hybrids might have the biggest market potential among hybrids in the future. They even have the possibility to become a new standard for heavy duty trucks by being part of the technical solution to fulfill the Euro VII norm which is of relevance for every single truck. Plug-in hybrids could become an application for haulers who, on the one hand, need the full flexibility of driving electrically in zero emission zones and, on the other hand, having the range of the combustion engine available on the highway. This, however, will probably rather remain a niche application due to the high costs of having two complete drivetrain technologies as well as a big battery capacity onboard. The penetration rate of plug-in hybrids might increase if they achieve a significant cost advantage over conventional trucks with respect to Euro VII updates. The market potential for hybrids is likely to be rather marginal since their overall benefit is not sufficient for neither haulers nor vehicle manufacturers. Dedicated hybrid solutions only pay off at high volumes. As these volumes are rather unlikely to materialize, dedicated hybrids will most probably not have large market penetration rates in Europe.

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Lightweight Construction and Cost Reduction

a lean, agile MSCDPS® product development process

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Abstract

In the commercial vehicle sector, lightweight construction is one of the key technologies for reducing the CO_2 footprint. Lightweight construction is combined with high-strength or special materials with low density and high strength or else anisotropic properties. These materials have their price, both in terms of purchasing costs and due to the limited application possibilities.

The lecture shows how, with the holistic MSCDPS® product development process, cost-efficient lightweight construction can be achieved through the use of cost-effective base materials. By avoiding waste and using large-scale production processes, manufacturing costs are reduced. The use of global location advantages is promoted by the agile and lean MSCDPS® development landscape.

Case studies are the use of NETSHAPE production processes in the development and the disruptive replacement of existing production technology with more cost-effective materials such as hot-rolled strip and fiberglass composite materials as well as processes such as forming techniques, 3D cutting and laser hybrid welding techniques.

As case studies, the weight reduction of the unsprung mass and cost savings through the development of a torsion beam axle and a brake caliper made of hot wide strip with forming techniques for pneumatic disc brakes are carried out for heavy commercial vehicles.

Introduction - Why product development process?

The analysis of permanently successful and market-leading companies, such as TOYOTA see literature | 4,7 |, is exemplary for the automotive industry, shows the importance of general procedures and lived mechanisms for innovation and generic growth. TOYOTA is constantly optimizing its process culture. TOYOTA's product development process extends from the initial product idea to the time the product leaves the market.

Why MSCDPS®?

One objection to the introduction of TOYOTA methods in medium-sized companies is the seemingly high organizational and personnel effort, which seems only to be appropriate in large projects for which employees can be completely released. MSCDPS® stands for Medium Sized Company Development and Production System with the claim to combine the successful TOYOTA approach with the advantages of smaller, agile organizations. The so-called 4Ps are found at the heart of the method: the first P stands for Philosophy, a set of values and a pronounced vision on which all further action rests. The second P stands for Process, which describes a documented approach and is continuously developed based on the results of previous approaches. The third P stands for people and partners who help to identify and eliminate the blind spot of the organization and with whose commitment and special knowledge innovation becomes reality.
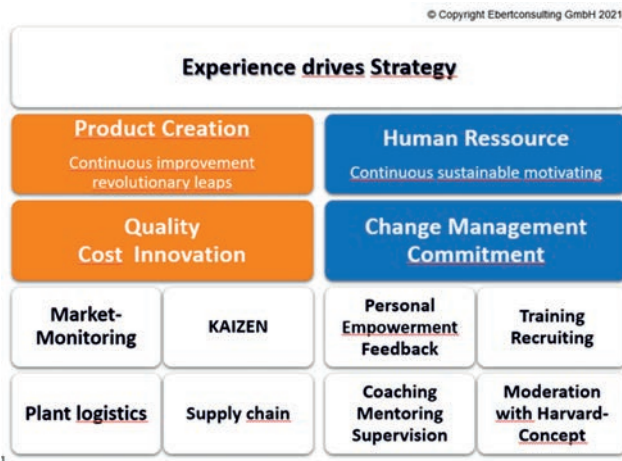
Fig. 1: The two pillars of the MSCDPS® method: social and technical competence

Here Ebertconsulting GmbH helps with a network of excellent highly experienced partners, who bring in different know how from different industries. Partners are also suppliers, who we often got to know and appreciate through their working. The fourth P is problem solving, the way tasks are identified, specified and systematically solved. We also rely on a social science approach such as methods like coaching and mentoring to empower and encourage employees to bring ideas into the discussion early and sustainably, and to simply stick with it.

Philosophy

Development in commercial vehicles generally follows the goals of reducing costs and increasing customer benefits. These goals can only be achieved by closely networking development, production and supply chain management, the product development process. The process is based on a simple production philosophy. Figure 2 shows the principles of the MSCDPS® production philosophy.
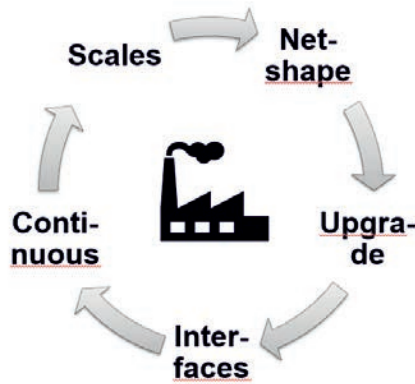
Fig. 2: The MSCDPS® production philosophy

Scales at component level are the prerequisite for significant savings: they create advantages in procurement and in the use of effective production processes. If standardization is at the beginning of the development process, see literature | 5 |, it requires only a certain steadfastness to see it through.

Lean production means avoiding unnecessary processes. The net shaped design means that a finished part is created from one production step without post-processing, for example laser cutting with weld seam preparation and welding in one process. We go one step further with the MSCDPS® philosophy: production steps must offer an improvement of the material properties: **touch and upgrade.** Only processes are used that ensure that with each process step an improvement of the product properties takes place at the same time.
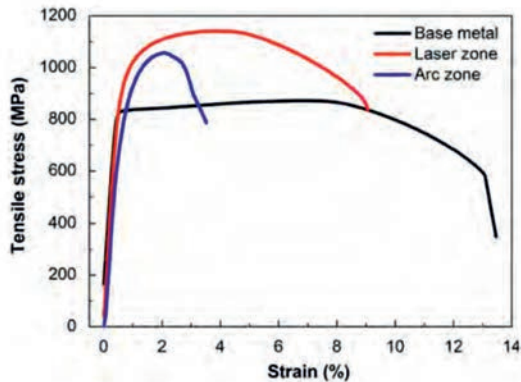
Fig. 3:   MSCDPS® production philosophy: no touch w/o upgrade low-temperature tensile
          strength of a laser-hybrid weld made of, see literature | 2 |

The properties of the laser-hybrid joint after welding are significantly better than those of the
base material (see Figure 3). Professor Yanbin Chen (see literature | 1 |) Harbin University of
Technology states an improvement of the fatigue strength by at least a factor of 2 using laser
hybrid welding processes. The procedure effects the formation of a pronounced fine grain
structure in the weld seam and heat-affected zone.

The sustainability of the processes is also an essential part of the philosophy. The careful use
of natural resources and energy is necessary to meet future demands for CO_2-neutral produc-
tion. The strict environmental requirements for air pollution control in China already require a
rethinking against air polluting processes in order to be able to ensure delivery reliability all
year round.
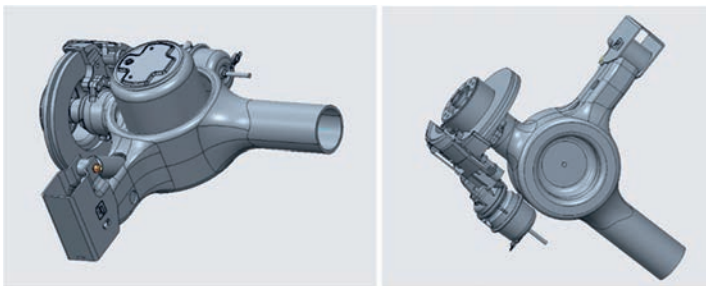
Fig. 4:   Integration of the air spring bell - left picture of air suspension in plan view, right
          picture view from below with integrated design of the floor as air spring pisto

Very impressive savings can be achieved through the management of interfaces or function integration, especially by the elimination of interfaces. The product characteristics are improved by the elimination of interfaces. Exemplary Fig. 4 shows the integration of an air spring piston. The piston is a separate component mounted on the axle by cold joining techniques, on which the rubber of the air spring bellows rolls. By integrating the air spring piston into the lower shell, the parts cost, the assembly process and the costs for external purchasing are eliminated.
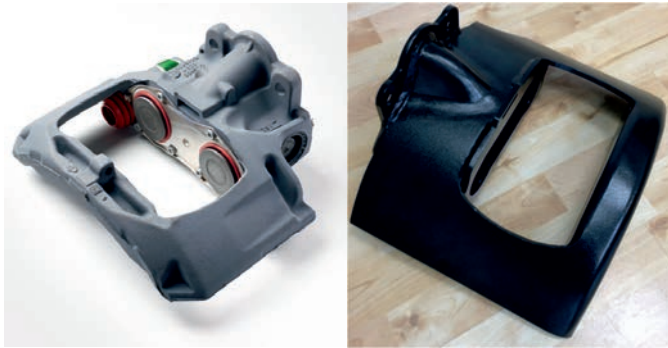
Fig. 5:   Brake caliper of a pneumatic disc brake - left figure KNORR-BREMSE caliper housing made of spheroidal graphite cast iron - right figure Ebertconsulting caliper housing made of hot-rolled wide strip

Commercial vehicle

Continuous processes enable the favorable unit costs of the passenger car industry for sheet metal and formed parts. Medium volumes, like typical for comercial vehicle industry, require automatic, flexible processes with limited investment. Standardization at component level makes forming technology economical. Figure 6, shows the forming of the top shell of a brake housing from hot-rolled strip.
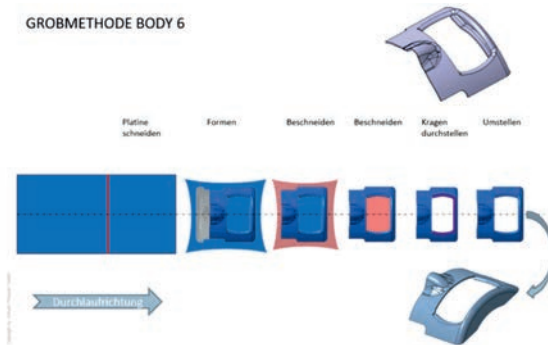
Fig. 6:   Upper shell of a brake caliper produced in a continuous process on a progressive
            press. Unpublished image, Schuler Presses, 2014.

Product development process

The increasing challenges facing companies require an organization that continuously adapts
and independently optimizes, see literature | 5 |. At the same time, the demand is to anticipate
innovation. For the product development process a holistic view of all processes from the idea
of a product to its exit from production and use is required. Organization learns from mistakes,
a positive culture of mistakes is a prerequisite for sustainable innovation.

The identification and fulfillment of customer benefit are the drivers of the product development
process. The claim is, to fascinate the customer with the product performance.

The process requires stakeholders and advocates and high attention from management.
Standards ensure continuous adaptation and improvement.

Logistics or supply chain organization are key competencies for globally positioned procure-
ment and distribution markets, offering optimization potential. Quality is a prerequisite. It re-
quires documented processes. Automation creates reproducibility and independence from hu-
man inadequacies.

Partner Qualification and Development

The development of the twist beam axle and the brake caliper, see Figure 5 showing existing
casted caliper and innovative prefabricated caliper, requires high investments for prototypes
or the availability of production facilities, welding equipment and large presses. Forming tools
are a particular cost driver. The complex production of the tools makes the development in-
flexible, as changes are avoided due to the high time and cost involved. Thanks to cooperating

with two development partners from China, the tools and first prototypes were produced within three months and tool changes were uncomplicated and carried out in a short time. The welding process was developed at a technologically world-leading institute of Harbin technical university.

The selection of supplier requires great care. In an MSCDPS® approach, it is carried out by means of standardized audits of potential supplier partners. In addition to high technological competence and well-established development resources, supplier partners must also have personnel fit with the company's own development organization.

The main suppliers were already audited before Corona. However, supplier partner development could not be continued to the required extent due to the pandemic situation. The development partner for the laser-hybrid welding has been a Chinese university.

Problem solving

Series development was carried out according to SCRUM principles, see literature | 8 |, with a small team in Germany and China. Due to the distributed development locations, daily SCRUMS were only conducted when necessary and replaced by weekly video conferences.

The focus was on weight and cost optimization, so any kind of overengineering had to be avoided. The design, material and semi-finished product selection follows the expected stresses. Usually these are taken from past tests and continuously supplemented by new special or abuse events. This leads to constantly tightening test conditions and ultimately to oversizing.

For cost-optimal development, this oversizing must be eliminated. The test collectives are determined from load collectives, see literature | 3 |, for representative driving situations recorded with prototypes, see Figure 7. This approach is in line with TOYOTA's Genchi Genbutsu approach - a manager can only get a real, unfiltered impression at GEMBA, the place where the action takes place. With the recorded stresses, a comparison was made with the stresses caused by the applied forces of a servo-hydraulic vehicle test bench until a sufficient correlation is given.

Other cost drivers include materials, interfaces, trade levels, energy use and the choice of production location. In the end, there is one trading level, OE and producer of the component.

Fig. 7:   left: Recording of load spectra for demanding operating conditions, right: Vehicle test
           bench operated with measured road load spectra.

Development example brake housing

The systematic identification of worthwhile components is at the beginning of an MSCDPS®
development loop. A Pareto analysis regarding cost distribution, (see Table 1: Cost shares of
a disc brake caliper of a pneumatic disc brake) identifies cost drivers. The housing is the cost
driver. The adjuster, which is continuously optimized with high engineering efforts, can only
make small contributions to cost savings. The housing has been and is of course examined
for weight savings using numerical methods. However, nodular cast iron generally only permits
minimum wall thicknesses in the range of t = 10 mm, so that the weight-saving effects were
limited.

Table 1:   PARETO Analysis cost distribution of disc brake caliper
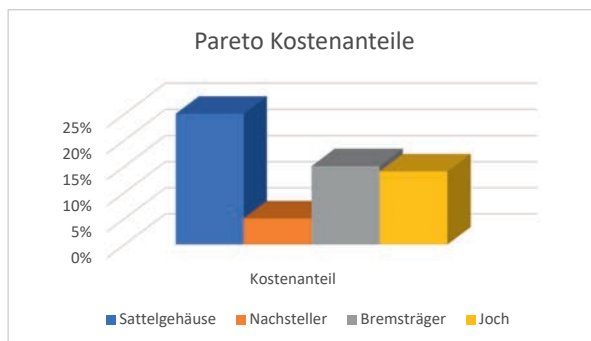
The way out of the lightweight design- and cost impasse can only be the use of completely new processes and materials. Hot-rolled wide strip in globally available dimensions of low strength S315 or Q350 - thickness t = 7 mm was selected as the material for the brake caliper. The great advantage of shaping from sheet metal semi-finished products is the scalability of the wall thicknesses according to the stresses. The design from deep-drawn parts reduces the interfaces.

There are reservations regarding the general suitability of this material for the brake caliper housing application due to its unfamiliarity. Table 2 shows that the mechanical and thermal properties of steel forming materials are significantly better or at least at the same level as nodular cast iron material, with significantly lower procurement costs.

Table 2: Comparison design properties spheroidal iron and hot-strip S315
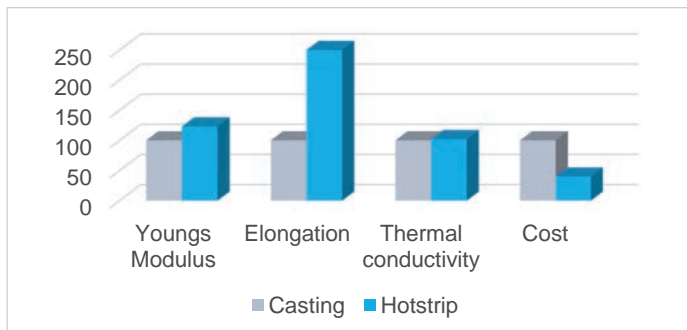
Future viability and robustness against adjustments to the boundary conditions of the selected processes pose a challenge. Here, too, the hot-rolled wide strip material and the forming and welding process offer major advantages. Table 3 shows the net forming work for forming two brake caliper housings. The CO_2 impact for the production of the brake caliper housing is many times lower for the formed caliper than for the cast one.

Table 3:   Comparison energy content for shaping for spheroidal iron – left grey - and Hotstrip
           S315 – right blue
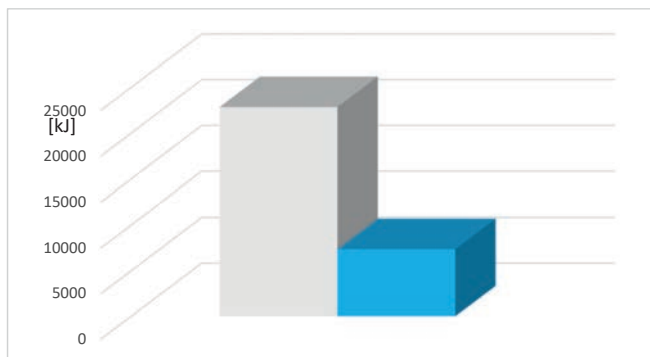
The use of forming techniques must overcome the hurdle of high tooling costs. By cooperating
with a Chinese manufacturer who has the necessary forming and joining equipment and ac-
cess to the local tooling industry, it was possible to solve this problem and also the disad-
vantage of the long procurement times for prototypes. The first prototypes were available after
only 3 months.

Result

Due to the pandemic that occurred in the meantime, the development process was not perfect,
aggravation of communication led to errors and delays. The establishment of competence cen-
ters at our foreign partners, working strictly according to MSCDPS® principles, has enabled
independent work with high creativity. As a result, the development goal was clearly achieved.
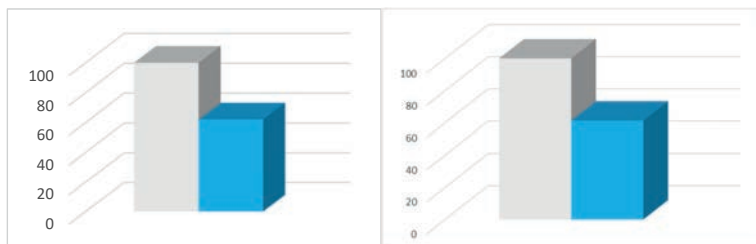
Fig. 4: Left: Cost savings, right: Weight reduction of unsprung masses.

Figure 4 shows the reduction in manufacturing costs and unsprung masses compared with the existing solution. The costs were reduced by 38% and the unsprung masses by 39%.

Preview

Manufacturing and joining technology are also experiencing rapid progress through the use of Industry 4.0. This leads to a reduction in the critical output for the use of the technology. For example, 3D laser cutters, see Figure 7, can be competitive with conventional trimming on a press for medium quantities. The integration of the trimming and joining process offers further potential.
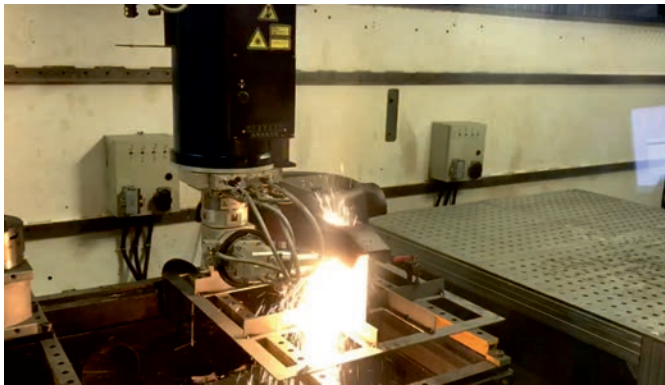
Fig. 7:   3D Lassercutter from TRUMPF in their Taicang Laboratory for prototype production cuts t = 8 mm hot wide strip

The use of artificial intelligence (see literature | 8 |) will revolutionize the forming process, since with precise knowledge of local material properties, springback behavior, for example, will be better controlled, i.e. trimming will be avoided. Manufacturing depth in companies will become affordable and in turn help the product creation process to find optimization potential.

| 1 | Jiecai Feng, Liqun Li, Yanbin Chen, Yingzhong Tian, Yongle Sun, Xuanjun Zhang, Jie Zhang
        Inhomogeneous microstructure and fatigue crack propagation of thick-section high strength steel welded joint using double-sided hybrid fiber laser-arc welding
        Optics & Laser Technology 134 (2021) 106668, journal homepage: www.elsevier.com/locate/optlastec

| 2 | Yanbin Chen, Jiecai Feng, Liqun Li, Shuai Chang, Guolong Ma
        Microstructure and mechanical properties of a thick-section high strength steel welded joint by novel double-sided hybrid fiber laser-arc welding
        Materials Science & Engineering A 582 (2013) 284-293, journal homepage: www.elsevier.com/locate/msea

| 3 | Arkadiusz Czarnuch, Marek Stembalski, Tomasz Szydlowski, Damian Batory, Jörg Ebert
        Mapping of the passing through obstacle a three-axle trailer with a tractor on the road simulator
        Technical University Wroczlaw, unpublished, Wroczlaw, 2021.

| 4 | James M. Morgan, Jeffrey K. Liker
        The TOYOTA Product Development System – Integrating People, Process and Technology
        Productivity Press, New York, 2006.

| 5 | Shunji Yagyu
        Das synchrone Managementsystem
        mi-Fachverlag, Redline GmbH, Landsberg am Lech, 2007.

| 6 | Hitoshi Takeda
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| 7 | Mike Rother
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        TOYOTAs Erfolgsmethoden
        Campus Verlag, 2. erw. Auflage, Frankfurt, New York, 2013.

| 8 | Joachim Pfeffer
        Produktentwicklung Lean & Agile
        Carl Hanser Verlag München, 2020.
        www.hanser-fachbuch.de
        downloaded from www.hanser-elibrary.com by FOM Essen on April 29, 2020.

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        Vortrag Digital in NRW, Kompetenz für den Mittelstand
        IHK zu Köln, 12. November 2019.

eDrive & Fuel Cell Powertrain Systems Engineering for Commercial Vehicles

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IAV GmbH, Gifhorn

Abstract

The automotive world is changing in tremendous pace. Future commercial vehicle designs will be characterized by systems integrated in base vehicle topologies and interconnected by software. In this context, business models for OEMs, engineering consultants and suppliers are changing: the role "system integrator" will gain importance. High levels of interconnection and the integration of various supplier systems result in the need for tailored Systems Engineering methods, knowledge of the supplier landscape for off-the-shelf components, in-depth understanding of electrified and hydrogen based propulsion systems, an ISO26262 compliant soft- and hardware architecture, integration management, as well as efficient verification & validation processes. This involves not only a change in technology, but also a change in development culture. "Function orientated development", "agile vs. classical collaboration models" and "seamless engineering" are just some of the main keywords. In order to cope with these challenges, IAV introduced and evaluated a holistic, Systems Engineering based development process for commercial vehicle applications.

1. Introduction & Motivation

The technology change in commercial vehicles is accelerating in a tremendous pace. While over decades, vehicles – independent of application – were predominantly mechanical engineering products, run with fossil fuels, vehicles of the future will be continuously developing to digitalized and electrified products. In awareness of climate change, global efforts are being made to achieve a clear reduction in greenhouse gas emissions. As a result, CO_2 regulations or Zero Emission Vehicles (ZEV) target Fig.s are either introduced or under development in several markets [1, 2]. In the European Union (EU) legal requirements are stipulating a progressive decrease in CO_2 emissions and thus in fuel consumption for the transport sector by 2030 [3]. Consequently, all on-road commercial vehicles manufacturers are facing OEM specific challenges for introducing corresponding vehicles to their fleets [4]. Fig. 1 gives an exemplary overview on possible technology paths.
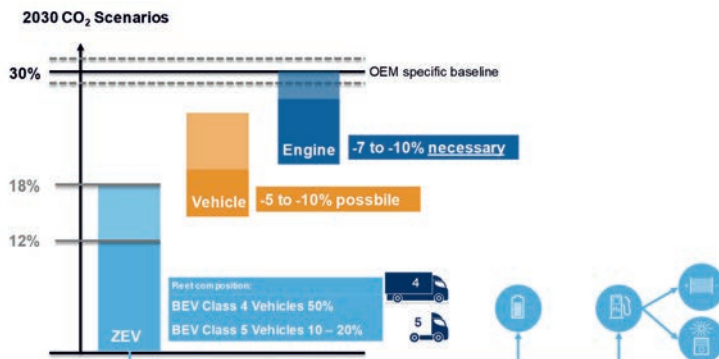
Fig. 1: CO_2 reduction potential on basis of synthetic fleet calculations [4]

Potential CO_2 reduction measures are ranging from efficiency enhancements on conventional powertrain systems, overall vehicle optimizations (predominantly aerodynamic measures) and ZEVs. Apparently, a substantial amount of ZEVs in the fleet is essential for achieving the 2030 limits, nominal Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEVs) and hydrogen internal combustion engines (H2-ICEs).

Further main drivers of future commercial vehicle designs are customer specific use cases as well as Total Cost of Ownership (TCO). In this regard, BEV systems will become more prevalent for heavy-duty regional delivery tasks, while FCEVs can be see for long-haul applications as the preferred hydrogen technology in the long-term [5].

Based on comprehensive experience in customer series projects and in-house development projects on electrified commercial vehicles, the IAV Future Truck concept was introduced. The concept unifies efficiency measures ranging from advanced aerodynamics design, to high-efficient diesel engines up to electrified powertrain systems as BEV or FCEV. Fig. 2 shows the FCEV vehicle variant in a 4x2 EU version. The design consist of a modular Fuel Cell (FC) system, one electrified axle with wheel hub motors, battery pack, a 700bar hydrogen storage system (liquefied hydrogen tanks optional), a single control unit connecting all sub-systems and a FC appropriated thermal management.

Fig. 2: IAV Future Truck FCEV concept

Using the IAV Future Truck concept, the following paragraphs gives insight to technical challenges in FC system integration and demonstrates a tailored development process for overall vehicle projects applying Systems Engineering methods.

2. Challenges in commercial vehicle FCEV development projects

2.1 Functional and physical system architecture

When talking about eMobilty in general, Systems Engineering and specially adopted CV development processes, one of the primary questions is about divergences between

conventional and eMobility development projects. Fig. 3 demonstrates this from on a functional point of view.
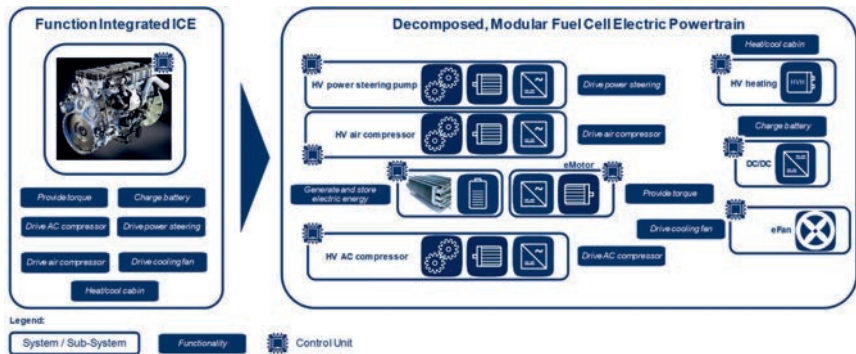
Fig. 3:   Functionalities conventional Vs. FCEV powertrain

Starting on the left hand side of Fig. 3, a conventional ICE is shown as a system with corresponding functions such as "provide torque", "charge battery" or "drive AC compressor" and one single ECU (Engine Control Unit). All of these functionalities are integrated in one assembly group, or system with one interconnection link. Having a look on a decomposed, modular FCEV powertrain architecture, on the right hand side of Fig. 3, it becomes obvious that the number of functionalities is almost constant, compared to a function integrated ICE. However, these individual functionalities are no longer integrated in one system, but allocated in various sub-systems. Furthermore, all of these sub-systems are using single interfaces and carry own control units with corresponding proprietary software functions and varying maturity levels.
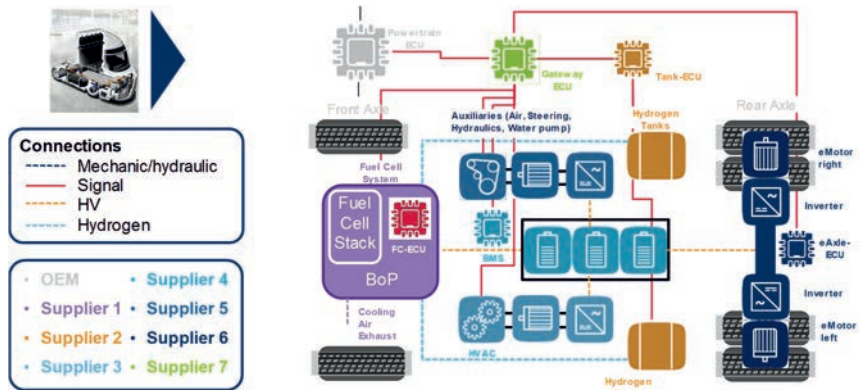
Fig. 4:   IAV Future Truck FCEV physical system architecture

A second possible approach demonstrating the differences is using a physical system architecture. Fig. 4 illustrates all physical components necessary for a complete FCEV using the IAV Future Truck platform. As indicated by the colours, the components ranging from e-axles, hydrogen storage system, fuel cell system, batteries to auxiliaries come from different sources. The connection between them is software, either using multiple or a single control unit (here shown as gateway ECU) that carries all software functionalities including an interface to the OEM base vehicle.

However, all of these individual components have to work together as a system. In addition, a safe and stable vehicle operation has to be ensured under all circumstances. In this context, safety relevant aspects ranging from High-Voltage (HV) safety, to emergency shut-offs of the hydrogen storage system to Functional Safety (FuSa) and cyber security play key role with in the product life cycle. In particular, FuSa, involving both software and qualified hardware development as well as comprehensive verification & validation measures up to corresponding documentation are pivotal areas in the development of electrified vehicles.

2.3 Technical Development
A systematic and consistent requirement management is essential for an efficient development process. The identification of technological challenges (Fig. 5) for FC system integration in an early project stage is one of the main goals. Parameters, such as range per day, durability,

possible payload, thermal management and system efficiency are specific for each application and have to be considered in the system definition and architecture phase. Additionally, TCO parameter studies have to be carried out for a holistic system design.
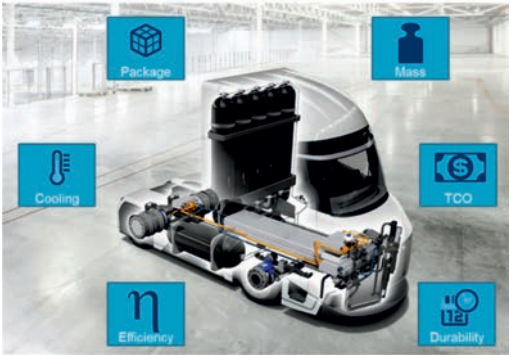
Fig. 5: Technological challenges for PEM FC systems for CV application

Fig. 6 shows common requirements and customer use-cases for different CV applications. The IAV Future Truck FCEV concept corresponds a HD long-haul application.

Application	LD	MD / HD	Citybus	Non road mobile machinery
Use Case	Urban	Long-Haul	Urban	Extreme
Range [km/day]	300	1600	300	<100
Total Operating hours [h]	8.000	25.000	15.000	10.000
Operation Conditions	Hub to hub	Constant highway speed	Dynamic	Dust, vibration
Fuel Cell Power [kW]	50	< 300	50	=<100

Fig. 6: Common CV use-cases and requirements

After defining use-cases and initial requirements, a model-based development approach supports the powertrain dimensioning and is essential for a detailed requirement specification on system and component level as well as a business-case and TCO definition.
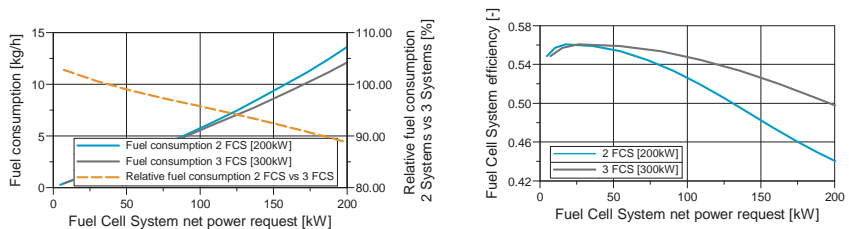
Fig. 7: Comparison of FC system efficiency and resulting hydrogen consumption for modular FC powertrain

FC system efficiency in comparison for a modular approach is shown in Fig. 7. Due to a typically high efficiency of FC systems at low load points, the overall system efficiency can be enhanced by increasing the installed fuel cell power. For instance, a powertrain consisting of three fuel cell systems, rated at a net power of 300 kW, achieves an efficiency of 50% at a constant load point, compared to 44% system efficiency of a powertrain with two fuel cell systems and a combined net power of 200 kW. At the same time, the waste heat of the FC systems decreases significantly. Based on the efficiency increase of a modular three FC system design, fuel savings can be obtained especially at high power requests. At a rated FC system net power request of 200 kW, hydrogen savings of more than 10% can be achieved.

Consequently, the operational costs of a 300kW FC powertrain are lower, compared to a 200 kW design. In contrast, the overall powertrain costs are higher for the 300 kW FC powertrain. Fig. 8 shows needed operating hours to achieve a cost parity between the 200 kW and the 300 kW FC powertrain due to hydrogen savings. The study assumes FC system costs of 100 €/kW. It can be obtained that the 300 kW fuel cell powertrain has to operate longer at lower hydrogen costs of 5 €/kg, which is an optimistic hydrogen price estimation. At higher hydrogen costs of 9,50 €/kg (a current market scenario), the cost parity can be achieved with correspondingly less operating hours. At an average power of 70 kW at low hydrogen costs of 5 €/kg, the 300 kW fuel cell powertrain has to operate around 15500 h until cost parity can be reached, compared to only 8000 h at a fixed hydrogen price of 9,50 €/kg.
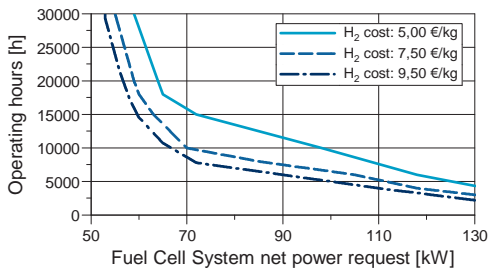
Fig. 8: Cost sensititvity analysis for modular FC powertrain

One of the key issues is the design of a feasible thermal management system. PEM fuel cell systems operate on a temperature level below the typical coolant temperature of an ICE which results in a lower temperature gradient between cooling system and ambient for heat dissipation. Besides more heat is transferred directly to the coolant due to less enthalpy inside the cathode exhaust compared to the exhaust gas of an ICE. As a result the required radiator space differs significantly from conventional driven powertrains.

The lifetime of a FC propulsion system mainly depends on the stack design as well as the operation parameters. Furthermore, hybrid strategies defining the power split between the FC system and the high voltage battery has to be optimized taking FC degradation into account. Basically, PEM FCs are subject to aging mechanisms during operation, which leads to a continuous cell voltage loss and consequently to a loss of performance. This loss of performance can be mainly attributed to a reduction in the Electrochemically Active Surface Area (ECSA) of the cathode catalyst. For an ECSA determination, a dynamic physicochemical model of platinum degradation within PEM FCs is used [7]. With the described modeling approach, lifetime predictions as well as a suitable operation strategy can be developed in an early project stage. Additionally, a model integration into the FC Control Unit in order to implement an online remaining lifetime prognosis (State-of-Health Monitoring) becomes possible.

For the transportation industry, TCO, operation range and a favorable vehicle load capacity are essential parameters. Fig. 9 shows a weight and cost estimation for different powertrain systems, including tank using a model-based simulation model.
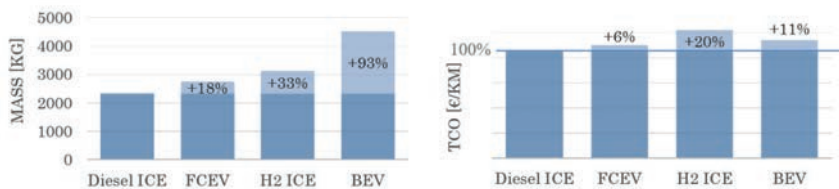
Fig. 9: Weigth and TCO comparison for conventional and electrified CV powertrains [5]

All powertrains are scaled to the same range level. Due to the high power density in liquefied hydrocarbons, the conventional Diesel powertrain reaches a low weight level. In contrast, pure BEVs are often less feasible for heavy-duty applications due to the comparable low power density of the batteries. In between the two boundary values, hydrogen based powertrain train systems show a good compromise in weight. The lower total mass of FCEVs compared to H_2-ICEs is related to a higher system efficiency of FCs and a respectively smaller hydrogen storage system. Under a TCO perspective, conventional Diesel powertrains, as well established and commercialized products, remain the most promising option. BEV variants show higher TCO values, mainly driven by costs of the battery system and decreased load capacity compared to other powertrain concepts. For hydrogen-based systems, FCEVs show potentially lower TCO values in relation to hydrogen ICEs due to higher system efficiencies.

Coming from a technical point of view, the next paragraph shall give insights about how the Systems Engineering development process allows to deal with these challenges.

3. Systems Engineering

Systems Engineering can be described as a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect. [8]

First introduced as a term in 1940ies by the Bell Laboratories in the US, Systems Engineering was gradually introduced especially in the military and aerospace industry [8]. One of the major factors was an increasing complexity of the products itself as well as an ascending interconnection of different company branches and facilities within projects. Besides the aspects looking at a problem in its entirety complexity and interdisciplinary, frontloading and

requirements traceability are key points within Systems Engineering. Fig. 10 shows the correlation between committed costs, time and costs related to extract defects. It can be obtained, that in a very early stage of the product life cycle, most of the costs are predetermined. However, the costs for correcting defects and design errors are increasing strongly disproportionate over time. Consequently, a high focus on the beginning of projects in the concept phase leads to potentially lower overall costs and to efficient project execution.
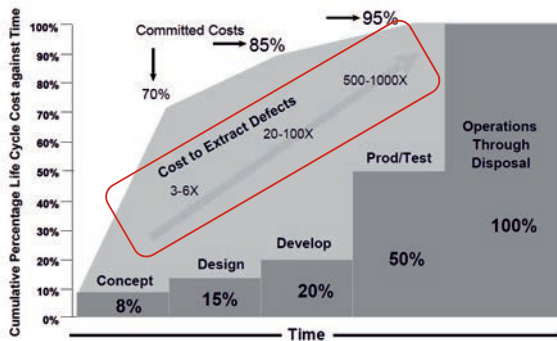
Fig. 10: Committed life cycle cost against time [8]

Today, Systems Engineering can be especially found in software projects and continuously more and more also in the automotive industry. Systems Engineering methods and process framework are defined in the ISO/IEC/IEEE 15288 standard [8]. Especially for electrification and system integration projects – such as the here presented IAV Future Truck concept – with a high degree of interconnection and complexity, Systems Engineering methods can be essential for a successful project execution. Therefore, Systems Engineering methodologies were chosen for the design of the CV Development Process. The result is a comprehensive process and tool landscape for commercial vehicle development topics from scratch to ready-to-use vehicles, which shall be presented in detail in the next paragraph.

4. Commercial Vehicle Development Process

Combining experience in customer series projects with in-house development projects on electrified vehicles resulted in IAVs Commercial Vehicles Development Process. Fig. 11 gives a generic view on the v-process, system, sub-systems and element levels.
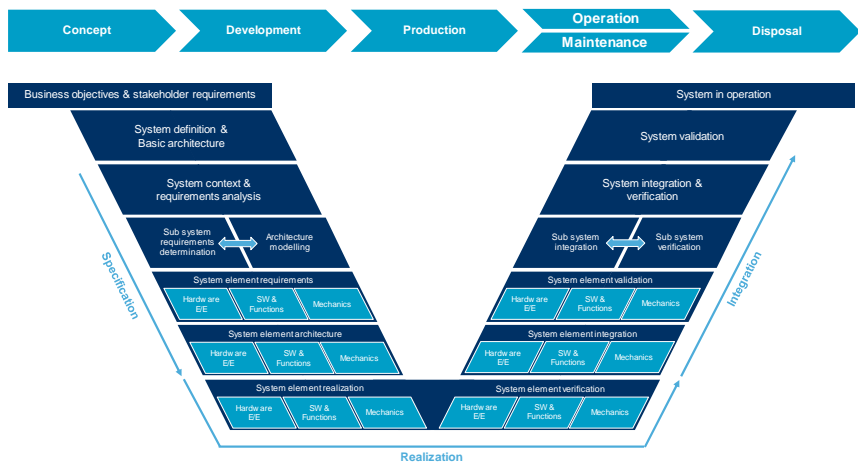
Fig. 11: Generic Commercial Vehicles V-Process

The process has a focus throughout the product life cycle ranging from scratch concept & business case development up to ready-to-use systems in operation, maintenance solutions and finally, the disposal. Starting with business objective analyses, business case development and first stakeholder requirements, initial concepts drafts can be established. "Frontloading" is a key point within the process, resulting in a strong focus on requirements and system architecture. All work results, or artefacts, documents and roles are defined using IAVs in-house process landscape P4E (Processes 4 Engineering) in order to ensure a constant quality level. The system element levels are formed by hardware E/E, software and function and mechanical development. Efficient and forward-looking integration strategies, in combination with verification & validation measures ensure a target-oriented completion of the system.

The role "Systems Engineer" play an important role within the Commercial Vehicles Development Process. Together with the project manager, Systems Engineers are responsible for wide scope of technical, management and supporting processes as shown in Fig. 12. Systems Engineers are acting in a technical and processual way on system and partly sub-system level, setting the framework for projects, introducing and monitoring of tasks together with the project management, as well as supporting and coordinating the domaine experts.
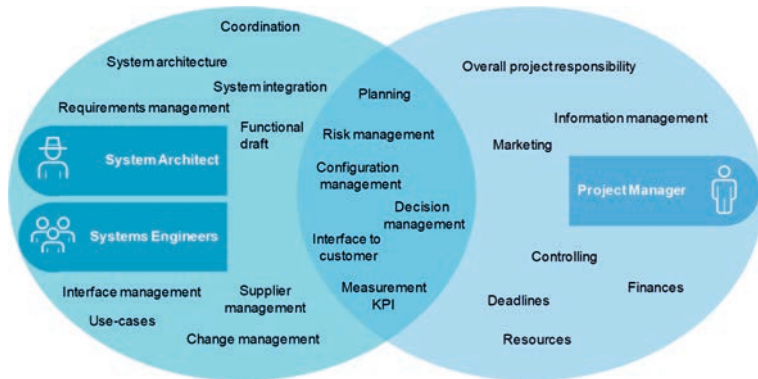
Fig. 11: Role Systems Engineer, System Architect and Projet Manager

Complementary, the role "Systems Architect" acts as a primary responsible Systems Engineer throughout the project. Metaphorically, the Systems Architect can be compared to an architect in the construction industry. Architects are designing and drafting, taking care about the function as a unit, while the deeper technical detailing is part of construction engineers. The project manager bears the overall responsibility for the project including controlling, (human) resources and the master schedule.

Coming back to the IAV Future Truck FCEV concept, the generic v-process can be tailored to meet the boundary conditions of FC system and e-drives integration projects. Besides the different stages, Fig. 12 gives a detailed breakdown of all necessary activities.

For interdisciplinary projects with multiple tasks and team members from different departments, a set-up by functions has shown to be beneficial for a successful project completion. The function "drive" for instance, contains every single work piece that is necessary to provide a desired movement of the vehicle including e-axle integration, recuperation, operation strategies, etc. Also the FC system integration is located in this work package. The main advantage of function-orientated development is, that no single parts or activities (e.g. software or hardware) with natural boundaries and interfaces are dominating the development, but the correct operation of the whole function becomes the achievable target. Additionally, all function teams can be interdisciplinary composed with engineers with diverse technical backgrounds.
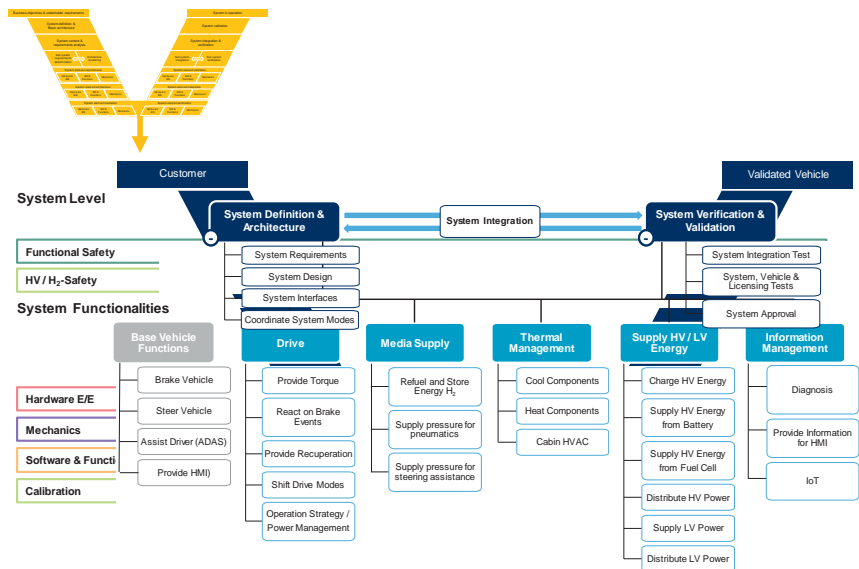
Fig. 12: Specific Commercial Vehicles V-Process

A further important feature of the process is the implementation of cross-functions that are needed for almost every sub-function. These cross-functions (FuSa, Hardware E/E, Mechanics, Software and Calibration) are indicated in Fig. 12 by colored, horizontal rows. Each of them represents a specified team that contributes to the successful completion of the corresponding functions. Within the project, the FuSa, HV and H$_2$ safety cross-functions play a dominant role for safety compliance and are therefore acting on system level, providing support for all sub-functions.

The Systems Definition & Architecture phase is the both the starting point for all following tasks and the parenthesis for the complete project. Within this phase, all requirements are defined by System Engineers and experts from the domain levels. In parallel, the system architecture including all interfaces and system modes is drafted and determined. A model-based system development environment (GT-Suite and MATLAB models), as well as vehicle driving cycles and TCO calculations are used for supporting and detailing the system architecture draft. All of the technical challenges (refer to "2.3 Technical Development") can already be evaluated in this early project stage using model-based approaches and expert knowledge. Software tools assist the modeling process. One the one hand, different tools for requirements engineering,

simulation and system architecture design can be used. On the other hand, Model-Based Systems Engineering (MBSE) are beneficial for an effective system design, combining all disciplines in one tool. The output of the Systems Definition & Architecture phase can literally be described as a "blue print" of the vehicle design including all information necessary for the development and realization in the sub-sequent domain work packages.

Additional project relevant tasks, roles and process initializations are carried out within the Systems Definition & Architecture phase. An early introduction of a system integration management as well as initial verification & validation measures are essential for a successful and on-time project completion. As Fig. 11 shows, system integration and verification are mutually depended tasks. The system integration team develops schedule charts for each system element and determines appropriate integration strategies. On this basis and using an initial Requirements Verification Traceability Matrix (RVTM), suitable verification measures can be determined and timed. "Hybrid integration strategies", combining model-based development approaches for simulating the continuously integrated system, with sub-system and component verifications are preferentially applied. The cross-function "software & function development" uses x-in-the-loop from virtual SW tests up to testing of complete control units on HiLs (Hardware-in-the-Loop). The target is to verify as much as software functions and modules as possible before integrating modules and control units into the vehicle topology. A build-up of the complete powertrain on HV test rigs can be beneficial for an early starting trouble shooting. However, for commercial vehicle applications with smaller volumes, verification costs can be substantially lower by integrating the system elements instantly to the base vehicle. Especially in this context, an efficient integration and verification strategy is vital. Eventually, the validation of the vehicle, or in other words the proof that all stakeholder and business requirements are met and the vehicle design performs as expected, is usually carried out on test tracks.

Requirements and system architecture are essential parts within the development process. How do these aspects fit together and why is this strong focus essential in particular for comprehensive e-mobility projects?

An exemplary path is shown in Fig. 13. Starting on the upper left hand side of the v-process, the aim is to establish every information needed for a description of the target system and to provide this information to all subsequent tasks. Together with requirements, the final system architecture is basis for all further development activities. In most cases, a physical architecture shows the actual components of the target system including all interconnections and sub-systems.
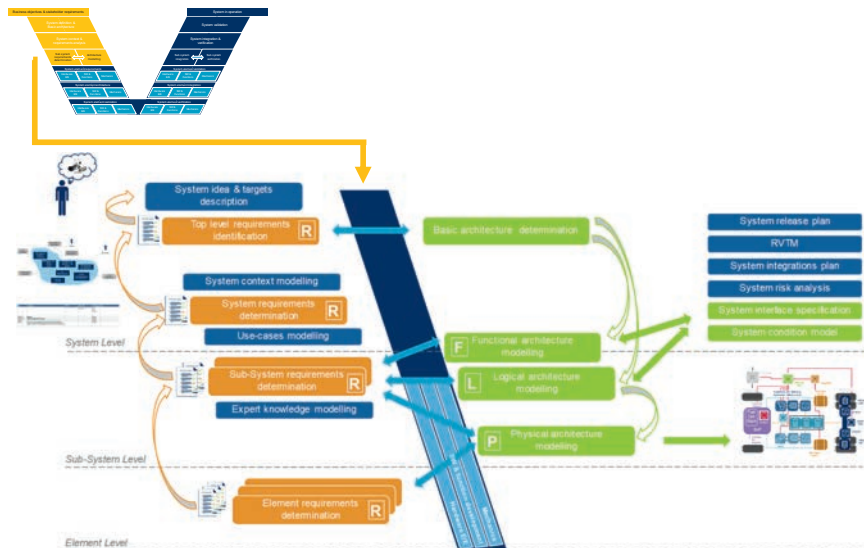
Fig. 13: From Requirements to Functional, Locical and Physical system architecture

The working method interactive and recursive. From first stakeholder and customer demands, top-level requirements are derived and a first basic architecture is designed. On this basis, the functional architecture development leads to system & sub-system functions from which logical, and physical architecture definition becomes possible. The result is a specified and coordinated system architecture: system functions as well as system requirements and draft validation & verification measures. This set of information is the basis for the further technical development on system functionality level.

Systems Engineering implies "thinking in requirements and architectures", not "thinking in hardware". Consequently, the solution is continuously developed from **R** to **F**, to **L** and **P**. Initial ideas are formed to **R**equirements, these are transferred to **F**unctional, **L**ogical and **P**hysical architectures. The physical architecture corresponds mostly to actual components (hardware), the functional architecture is often used as an instant input for SW and functions development. Mechanical engineering projects are often based on "thinking in hardware". Capabilities and performance parameters are usually related to external/geometrical features. However, in e-mobility projects, like the here shown IAV Future Truck concept, these parameters are

integrated in individual components and can usually not be evaluated instantly. Each of them has different proprietary software, with varying maturity levels and interfaces. The evaluation of these components in correspondence with the required project safety levels and their behavior in the overall systems is an essential step. "Thinking in hardware" in an early project stage usually narrows the solution space dramatically, risking incompatibilities and potential failures of the complete system. For this reason, using Systems Engineering methodologies in combination with a strong focus on the system and "frontloading" potentially lowers projects risks as well as costs and eventually ensures a successful project completion.

Conclusion

The automotive world is changing. While over decades, commercial vehicles were predominantly mechanical engineering products, powered with fossil fuel, vehicles of the future will be continuously developing to digitalized and electrified products. Future commercial vehicle designs will be characterized by systems, integrated in base vehicle topologies and interconnected by software. In this context, business models for OEMs, engineering consultants and suppliers are changing: the role "system integrator" will gain importance.

Consequently, IAV introduced a Systems Engineering based development process, tailored for commercial vehicle applications:

- **A holistic v-process**: covering the product life cycle from scratch to validated vehicles
- **Collating all disciplines in one framework:** hardware, E/E, SW & functions development, mechanics
- **Functions orientated work packages:** for expanding the development focus
- Introduction of the supervisory and coordinative acting roles **Systems Engineer** and **System Architect**
- Using classical and **agile collaboration models** where applicable
- Focusing on **substantial frontloading** at project start:
  - System requirements and architecture development for minimizing project risks,
  - Defined documents and interface handshakes between the disciplines for a seamless engineering and
  - An early set-up of an integration management in connection with verification and validation measures.

Using this Systems Engineering inspired, and in in-house and customer projects approved methodology – tailored for the individual project –, the complexity of electrified vehicle

developments gets manageable, leading to an efficient system integration as well as to a safe and compliant operation of future commercial vehicle designs.

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Fatigue development of a 10x10 commercial vehicle frame using dynamic and/or strength simulation, virtual iteration and component testing together with measurement data acquisition

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Introduction

Due to ever shorter development times which entail the elimination of entire prototype phases, it has become necessary to develop a suitable basis for component design in the form of load data for use already in very early phases of development. In order to be able to react efficiently to technical problems, it is important to apply a validation approach in the development process that combines the competencies of a strength or dynamic simulation with those of a strength test including the acquisition of measurement data. Using the example of the development of a commercial vehicle frame, it is shown at which points which subprocesses are used and how the individual disciplines interact in order to finally deliver a sufficiently validated system for the off-tool pre-series with only one prototype phase.

Scope of Development

The scope of the project was the redevelopment of the rear frame segment of a 10x10 commercial vehicle frame, taking into account two different body variants with various wheelbases for each body. It was possible to adopt the front frame segment and the cab from an 8x8 base vehicle. In addition to the design of the frame, the scope of the project also included the integration and adaptation of the axles, including the integration of a rear-axle steering system, and various electrical and hydraulic add-on parts. A strength verification for the frame was required as a safeguard measure. **Cover picture** shows a later prototype of the development vehicle.

Validation process

The process began with coordination efforts between the customer and all interdisciplinary teams to adequately define the requirements. The vehicle's use profile and the test focus were defined here.

From that point on, the experts from the test and simulation teams worked in parallel. On the test side, a test concept was developed designed to transfer the required loads into and out of

the system and to block corresponding degrees of freedom. This was followed by the design work, the procurement of the adaptations, and the construction of the test bench.

On the simulation side, the question of the load data was a key issue. In this respect, load data were determined using a reference vehicle in cooperation with the metrology department. The maneuvers to be performed were specified by the customer. This data then formed the basis for the MBS model to be able to make the derivation for the development vehicle. The result data of the MBS simulation are internal forces, which served as input variables for the following step, the FEM analysis. Together with the fatigue life analysis, the maturity of the product was confirmed. The basis for this was the given target spectrum. This allowed further steps in the development process, such as strength tests, to be carried out in a meaningful way. Together with the generated or measured loads, the test specification signals and the test program were created. Here, based on the damage to the signals, multipliers were determined in order to achieve in total the target damage specified by the customer.

After finalization of the test program, the fatigue test was started. During the test, all channels were monitored for their maximum values, but also for their damage. Regular inspections were carried out with regard to any damage that occurred. After the running time, all findings and results were summarized in a final documentation and submitted to the customer for further approval. **Figure 1** shows the process diagram.

Load data determination

Upon commencement of the load data determination, the question of the parameters to be recorded must be answered first. In the development of a commercial vehicle frame, the first question addresses the possible loads. In this case, these are quasi-static loads, such as torsion about the longitudinal axis of the vehicle and bending about the transverse or vertical axis of the vehicle. Furthermore, operation in light offroad terrain was specified. Then, the measuring points had to be defined for the components located directly in these load paths. For torsion, these are primarily the wheel paths or dedicated torsion measuring points. For vertical bending, the wheel paths are also decisive. To record the vertical load, pressure transducers were installed in the Heplex cylinders, and strain gauges on the cylinder and shock absorber brackets. To record the load transmitted to the frame via the axles, all control arms were fitted with strain gauges and calibrated for force. A total of almost 80 measuring points were applied. These included over 40 individual strains on the frame and frame brackets. After the application of all measuring points, which are summarized in a measuring point list, a plausibility check of the measuring points was carried out after some quasi-static

measurements on a torsion test bench. Here, the display and/or the signs were checked for correctness before the actual measurements were started.

After the testing and plausibility checks of all measuring points, the final ballasting of the vehicle was carried out. Afterwards, the previously defined maneuvers were performed on the test track. After completion of the measurement campaign, the data was prepared for the next process. Filtering, channel sorting or blending was performed to evaluate the damage over the complete life cycle. In this process, the customer specified the composition of all maneuvers and the total damage calculated from this served as the basis for subsequent processes from this point forward.

CAE process – Dynamic simulation

State-of-the-art MBS models of the vehicle and the test bench were developed. In the ADAMS/Car software used here, the individual subsystems were assembled to form an overall vehicle model. **Figure 2,** shows the overall MBS vehicle model.

The spring and shock absorber characteristics were stored as nonlinear curves. The flexible vehicle frame was implemented as a modally reduced FE model. A complex 3D tire model was not required for this application; it was possible to use a surrogate model of the tire with linear stiffness to represent the vertical support of the model. The longitudinal and lateral forces were neglected because they represent a subordinate stress for the main frame. The excitations were applied via vertical posts providing displacement at the wheel contact points, which has the additional advantage of providing a stable simulation boundary condition.

Virtual iteration for load generation

The task of VI is to iteratively generate external excitations from common measured variables on the vehicle (accelerations, relative spring deflections, shock absorber force...), such that they can be considered invariant and best satisfy the measured target variables (e.g. in terms of damage). To accomplish this, a matrix of transfer functions must be created based on noise excitations in the excitation channels and the simulated system responses. When measured system responses (desired) are specified, inverse transfer functions can be used to determine excitations (drives) for the simulation. In the case of a linear system behavior, the problem would be clearly solved after the first step, since excitations could be generated which would provide simulation results in the target variables identical to those of the measurement. However, since this is a non-linear problem, the task cannot be solved directly, but instead, the best possible solution must be determined iteratively. All of these steps are performed

automatically in the software. Ultimately, the result must still be evaluated by the user in the time domain, frequency domain and in terms of relative signal damage.

The external excitations obtained in this way were then applied to the model of the development vehicle, and it was possible to pass structural loads in the form of load-time series at the interface points, or in modal form, for use in subsequent strength studies.

CAE Process – Strength analysis

The strength assessment is performed in two sequential analysis steps. First, finite element analysis is used to determine the stress distributions on the meshed structure. To accomplish this, a unit load case is defined for each degree of freedom at each interface point considered. A separate stress distribution is determined for each load case. The inertia relief method, in which the external load is compensated by inertial reaction, is often used for this purpose. It is essential that all masses considered in the FE model be distributed correctly. Masses not included in the FE model must be considered in the MBS model and their effect on the frame structure is taken into account by means of sectional loads.

In the final step, the operational strength analysis with FEMFAT, the stresses of the unit load cases are combined with the associated load time series to form what are known as load channels. The total load is obtained as the superposition of the load channels at each time point at each node of the assessment area. FEMFAT Weld allows welds to be evaluated in addition to the base material using the same analysis. Shell models are typically used for this purpose. Notch factors from the associated weld database are used to determine the local stress at the weld notch. This concept offers the possibility to repeat the analysis for newly defined welds very quickly.

For the fatigue strength range, the damage is determined as a measure of the fatigue life consumed. This allows statements to be made about the expected resistance of the loaded components with respect to the analyzed loads or maneuvers, taking into account the selected survival probability.

Test bench concept

The typical loads and the dominant load directions must be known when development of the concept is begun. The test bench concept does not need to cover all degrees of freedom as this would not allow a cost-effective physical design or test operation. In addition to the incoming load transfers, the corresponding outgoing load transfers and/or component support points must also be defined. The structure is thought through in light of the load flow of each maneuver. The test bench must be able to reproduce these situations, in a technically correct,

albeit simplified, form. The inertia forces applied by the structural setup are also transmitted via cylinders that act on the structural brackets and flatbed bearings. At the same time, these cylinders are also used to transfer force outward, or for vertical support, so that the specimen is not lifted upwards. Thus, there is a closed load flow from the foundation back into the foundation. To represent the rigidity of the structural setup, steel brackets are connected in a simplified form to the structural bearings and flatbed bearings in order to support the frame. An exact replication of the stiffnesses can be dispensed with in this context, since the majority of the movements are absorbed in the bearings anyway. This approach makes it possible to run through all loads and maneuvers and compare them with the test bench concept. The final test bench setup has 15 hydraulic cylinders of 200-400kN nominal force installed with corresponding force and displacement sensors. An addition, four load cells are installed in the supports for lateral force as well as in the flatbed and cab joints. A total of 16 strain gauges were applied to the bearing brackets and frame brackets, and six force-calibrated strain gauges were applied to the A-arms. In addition, the spring deflections of all ten wheel positions are monitored with wire displacement sensors. The overall structural setup is 11 m long and at some points requires almost the entire 4 m width of the 500t foundation on which the structural setup is fixed. **Figure 3** shows the final CAD model of the testrig.

Definition of the test program

A target spectrum must be established as the basis for each test program. This is specified directly by the customer in most cases. Pseudo-damage is calculated based on a standard S/N curve with k=5, σ_D=1000, n_E 10,000,000, according to Miner elementary. This evaluation was then used as the basis for specifying the target spectrum. Since it was not possible to trace all of the real-time data with the simplified test concept, some tracks were only traced approximately or signals were created synthetically. In total, seven test signals or maneuvers were iterated:

- Parallel obstacles, based on a real-time signal which was traced approximately.
- Torsion 1, synthetically generated signal with maximum values from the measurement. A diagonal torsion of the two front axles relative to the three rear axles was traced.
- Torsion 2, like torsion 1 except at 10% greater cylinder paths and without the two front axles.
- Off-road, synthetically generated signal. Due to its stochastic characteristic similar to that of an off-road track, "pink noise" was generated. This was applied to the vertical cylinder as a displacement signal.

- Horizontal bending, synthetically generated signal. The load is introduced via the front lateral force cylinder onto both front axles and transferred out through the A-arms and the rear axles into the supports.
- Vertical bending, washboard, synthetically generated signal. A sinusoidal load is applied to the rear axles at 6 Hz and with a phase shift of 45° between the axles. As this takes place, the front axles remain rigid.
- Off-road with vertical bending superimposed, synthetically generated signal similar to "pink noise" except introduced predominantly via the flatbed bearings or, in the later course, via the rear axles as well.

The final signals were then blended to form the target spectrum. The result of this is the number of repetitions for each individual track. **Figure 4** shows the damage comparison of the test program to the target spectrum. Those components that were tested by this program were also sufficiently validated in downstream component tests.

Endurance testing

After the test program has been blended, only the number of repetitions per track is available. These must still be converted into a test program sequence – the actual endurance test program. To do so, a search is made step by step for the largest common divisors of the repetition numbers and they are classified into corresponding groups (loops). The final test program was blended to approximately 220 hours and is composed as shown in **Table 1**.

Repetitions	Tracks	Repetitions Loop 1	Repetitions Loop 2
1550	Tree trunk		1
4650	Torsion 1		3
1550	Torsion 2		1
7750	Off-road	1550	5
1550	Hor. bending		1
6200	Washboard		4
12400	Off-road/bending		8

The endurance test was monitored continuously in terms of maximum values, but also in terms of cumulative damage per channel. The results of the test run were various loose screw connections, which, after the intermediate inspections, were retightened according to the

torque specifications, indications of cracks on some brackets, and some broken screw connections. A cross member crack was detected which was indicated both on the reference vehicle and in the FEM simulation. **Figures 5 and 6** show the crack on the real part as well as the FEM plot showing the safety factor.

Summary

Simulation of the loads made it possible to create a basis for the component design already at an early stage. The method of virtual iteration allows the creation of very realistic load spectra with a minimum of input data. Depending on the arrival of the first prototypes and in order to be able to run in real measurement data, it is also possible to fall back on purely simulated data for the test. Or, as in the example provided, to use a combination of the two. The test results coincided with the simulation results and so the failures were expected. Components that were not sufficiently loaded due to the test concept were subsequently validated via component tests. It is clear that the close interaction between simulation and testing, guided by a well-interconnected process, undoubtedly brings an absolute added value to the process of vehicle development.

Cover picture: Prototype development truck

Fig 1: Validation process

Fig 2: MBS Modell
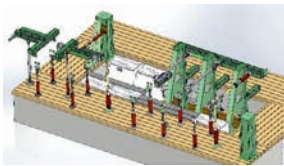
Fig 3: CAD model testrig

Fig 4: Damage comparison

Fig 5: Crack crossmember
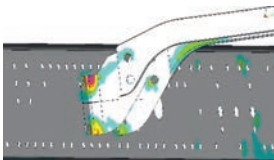
Fig 6: Crossmember safety factor plot FEA

Data-driven selection of vehicle variants for the E/E integration test

Increasing variants and complex technology versus test coverage

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Disclaimer: The results, opinions and conclusions expressed in this publication are not necessarily those of Volkswagen Aktiengesellschaft.

Abstract

As a result of innovation, the scope and complexity of electrical and electronic systems in the automotive industry are increasing, leading to a highly interconnected control unit network. The need to customize vehicles, particularly for commercial vehicle customers, also results in a very large number of variants. This complexity creates challenges for vehicle manufacturers when it comes to the integration into the overall vehicle network, as a large number of vehicle variants must be tested and validated.

The test strategy for integration and testing is usually function-oriented and based on a risk analysis. This paper describes how this procedure can be supported, among other things, by the continuous use of data from the development process. A methodology is presented which, based on a modeling of the variant diversity with feature models, enables an automated selection of vehicle variants for testing.

The first step of the methodology includes the modeling and linking of vehicle configurations, components and functions variability. In addition, non-functional information from development artifacts such as sales forecasts, risk assessments, and metrics from the testing process are integrated into this model.

Based on this overall model, the next step is the selection and prioritization of vehicle variants for the construction of test benches and test vehicles. The linked database serves on the one hand to reduce complexity and on the other hand as a selection criterion within the framework of optimized variant selection.

For the first time, this methodology considers the combined variability of equipment features, components and functions and thus enables the holistic coverage of vehicle variants. In addition, the linking with further information from the development process allows a systematic selection of optimal variants for the overall E/E integration test.

1. Introduction

Current megatrends such as digitalization and autonomous driving are having a major impact on the development of electrical/electronic (E/E) systems. Vehicle functions are constantly increasing in scope and complexity, resulting in highly interconnected ECU networks. This trend poses a great challenge especially for the integration of all the E/E hardware and software systems into the complete end-to-end system.

In the case of light commercial vehicles, this situation is aggravated by the fact that the customers have the option to highly customize their vehicles. In addition to the usual equipment variants for passenger cars, customers can choose between different wheelbases, heights, cabin variants and individual body and conversion solutions. Even more variants arise when taking into account the over-the-air software updates. Because continuous testing of all these variants is impossible, an efficient strategy for the selection of vehicle variants for the E/E integration test is essential.

This paper addresses this problem and presents a solution approach for an optimal selection of variants for the overall E/E integration test. The methodical procedure for this consists of two sub-processes. Firstly, the variability of vehicle configurations, ECU networks and functions are modeled and linked. Based on this, secondly, an efficient selection and prioritization of variants can be performed. For demonstration purposes, examples from the Volkswagen AG are used throughout the paper.

To provide an understanding of the problem statement, this paper starts with an introduction to the E/E integration test and to the different types of variants. This is followed by an overview of the state of the art field of feature modeling and selection of variants. Section four presents the methodology and implementation for the selection of vehicle variants, including the modelling as well as the selection and prioritization of variants. The final section concludes this contribution and provides an outlook to the future work.

2. Problem statement

A vehicle project provides up to one thousand configuration options (features), leading to an extremely high number of possible vehicle configurations. Due to this combinatorial explosion, testing all these configurations product-by-product is unfeasible in practice. Thus, it is necessary to find a representative subset of configurations for the test.

To capture this problem in more detail, this chapter provides an introduction to the E/E integration test and the different types of variants which must be considered in this context.

2.1 E/E integration test

Vehicle development is usually based on a function-oriented approach, due to the increasing complexity. In contrast to the isolated development of individual components, this development approach focuses on the implementation of functions (also called systems).

The development process of functions is usually based on the Automotive SPICE standard which is shown in Figure 1 [2]. The first two steps in this process are the requirements analysis and the architectural design on system level. On this basis, the development of the required system components can then take place. This includes the following steps: requirements analysis, architectural design and software detailed design and unit construction. Once the components are developed, they are integrated step-by-step up to the fully integrated system. To achieve this, at each integration step tests are carried out.
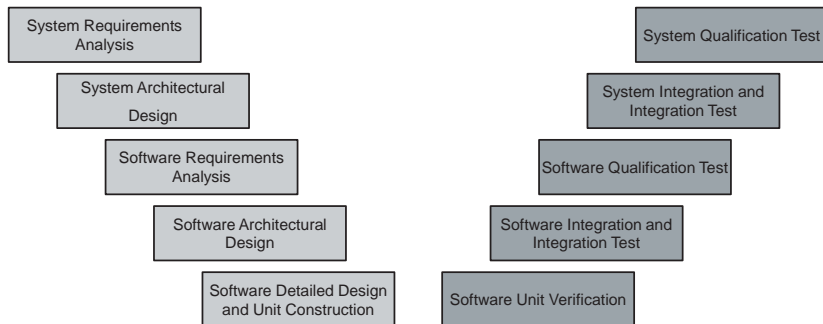
Fig. 1:   System development according to the Automotive SPICE process reference model [2]

This contribution focuses on the E/E integration test, where all E/E functions and components are integrated into the overall vehicle network. The objective here is to confirm the customer suitability of the overall vehicle network from the point of view of E/E integration. Therefore the activities of the integration test address the system integration and integration test level and the system qualification test level of each E/E function.

Instead of integrating all functions in one big step, functions are integrated at multiple defined milestones along the product development process. These milestones are called integration steps at Volkswagen. At each integration step a defined set of functions is integrated into the overall vehicle. The available functional scope is then intensively tested at each integration step. This results in tests accompanying the vehicle development from the early prototype phase to the start of production.

The E/E integration tests are primarily executed on Hardware-in-the-Loop (HiL) test benches. These test benches include as many real control units (ECUs), sensors and actuators as possible. A real-time simulator enables a similar way of testing like in a driving vehicle. In addition development mules and prototype vehicles are used temporarily to carry out tests.

At the beginning of a vehicle project, a test concept for the E/E integration test is developed. This concept includes a detailed planning of the test scope and resources and is continuously updated and further developed. A risk-based test strategy forms the basis of this concept. For both functions and ECUs a detailed risk analysis is carried out, where several risk categories are rated in terms of probability of occurrence and impact. The results serve as the main input for the planning of the test scope (e.g. test depth for specific functions). Another input for this is the functional ramp-up defined by the integration steps.

When planning the test resources, an efficient selection of vehicle configurations for the test resources is crucial. Due to the significant costs for the buildup of test resources, they are available only in small numbers. In order to cover all functions, it is necessary to take the possible vehicle configurations into account. In addition, specific configurations can be prioritized by sales forecasts provided by the sales department. This information is usually directly linked to vehicle features.

Continuous changes in the vehicle development process also makes it necessary to update the planned configurations of test benches and test vehicles regularly. Therefore this complex task is getting even more difficult.

2.2 Three views on variability

In the context of E/E integration, there are three views on the variances to be considered. The first view considers the configuration options describing the possible vehicle configurations. Depending on these configurations, different variants of ECU networks can be produced. Both types of variants lead to variations in the functional scope.

Features of vehicle configurations range from body types (e.g. double cabin pickup truck), over different drive concepts to functional features such as advanced driver-assistance systems. Many of these features can be individually selected by the customer, resulting in an immensely high number of possible vehicle configurations. The Audi A3, for example, came in 2014 with up to 10^{38} possible configurations [1].

In order to manage this complexity, it is necessary to have an unambiguous description of the features and the dependencies between them. For example, this can be done using a specific notation to describe product features, which apply to all the vehicle models of a brand. In addition, features that are mutually exclusive are grouped into families, where one feature per

family must be selected (see Fig. 2). To give an example: One possible family could describe the configuration of the tailgate, which can either be a lid or hinged doors. By selecting one feature per family, an explicit configuration for a vehicle is created. Doing this, different dependencies between the features must be taken into account. Dependencies can result from technical, logistical, legal or sales requirements. These dependencies can be managed in form of constraints, which can either be obligations or prohibitions. They form the basis for the vehicle configurator.

The second view, involves the variance of ECU network and can be derived from the configuration space of the vehicle configuration described in the first view. An ECU network can consist of around 100 control units and its composition depends on the vehicle configuration. This dependency is usually mapped within a parts list that specifies which parts are to be installed in which configuration. Therefore, each ECU version gets an individual part number. Different types of ECUs can be distinguished by their diagnostic address ID, which is also used for on-board diagnostics (OBD) purposes. There can be more than 10 ECU versions for a diagnostic address ID in one vehicle project. As with the vehicle configurations, this also provides a very large configuration space.

Since it's the core mission of E/E integration to test every ECU version, the variety of ECU networks has to be considered in the strategy to select vehicle configurations.

The third view is the variability of the functional scope, which is also important to consider due to the function-oriented development and test strategy. The functional scope depends on the vehicle configuration, but must be considered separately and in more detail. Vehicle functions can have a different scope and specification, depending on the vehicle configuration. Country-specific requirements can, for example, result in different function specifications and thus function variants. In addition, function variants can be divided into sub-functions. The presence of a function variant or sub-function may depend on different combinations of features. Furthermore, function variants with an installation rate of 100% cannot be described with features of the vehicle configuration. This is why all function variants and sub-functions, including their dependencies to the vehicle configurations, could be summarized in an additional catalogue.

On top of that, dependencies between functions and the ECU-network must be documented in a similar manner. Many functions are highly interconnected, as they are using software components on multiple different ECUs, whereby the type and scope of the involved ECUs can differ between sub-functions. As a result, the testing of one single function variant can require multiple vehicle configurations, which has to be considered when planning the test resources for the E/E integration test.

3. State of the art

Software product line (SPL) engineering is the standard approach for the development of highly configurable systems. When modelling and analyzing the variability of SPL it's common to use feature modelling techniques. This section introduces feature models (FM) and describes how they can be used in the automotive domain. In addition, an overview of existing methods for the selection of representative configurations for the test is provided.

3.1 Feature modelling

Feature models represent all features of a product line and the dependencies between them. Thus, a feature model specifies the space of possible configurations. They are often visualized as tree-like structures, which are called feature diagrams.

Figure 2 shows the feature diagram for a small feature model example from the automotive industry [14]. The diagrams in this work are created with the FeatureIDE tool, which provides various functions that support users in working with SPLs such as a visual feature model editor [15]. Features in these diagrams are arranged hierarchically below a root node. Graphically it is described whether the presence of a feature is mandatory or optional, whereby the selection of a feature requires the selection of its parent feature. Multiple features can also be grouped together into or-groups and alternative-groups. The described feature families (see section 2.2), for example, can be represented by a mandatory alternative-group. In addition, a distinction between abstract and concrete features is made. Abstract features are only used to structure the SPL and are not part of the final configuration of a product. Since feature families merely serve to give a structure, they can be implemented as abstract features. Dependencies that go beyond the hierarchical structure of the feature diagram can be defined by using propositional logic. With these so-called cross-tree constraints dependencies between arbitrary features can be described.

Following the example of the cross-tree constraints, the entire feature model can also be described in form of propositional logic. Therefore each feature is represented by a Boolean variable and their dependencies are expressed by logical operators. Many algorithms for analyzing feature models can be reduced to problems in Boolean algebra. This provides a great advantage, as it allows an automated analysis of feature models with off-the-shelf solvers [16]. The number of valid configurations, for example, can be calculated using #SAT solvers [17]. Further possible operations are the identification of dead features, core features and redundant constraints.

Another advantage of the representation in form of a propositional formula is the possibility of feature model slicing. Feature model slicing allows the removal of features from the feature

model while maintaining all dependencies between the remaining features. This can be helpful during feature model evolution and for various feature model analysis techniques [18].

Furthermore there are several approaches to extend feature models. A common approach is the possibility to define additional attributes on features. Extended feature models in FeatureIDE, for example, provide four different types of feature attributes: String, Boolean, Long, Double. These attributes can be used both in analyzing the feature model and the selection of configurations.
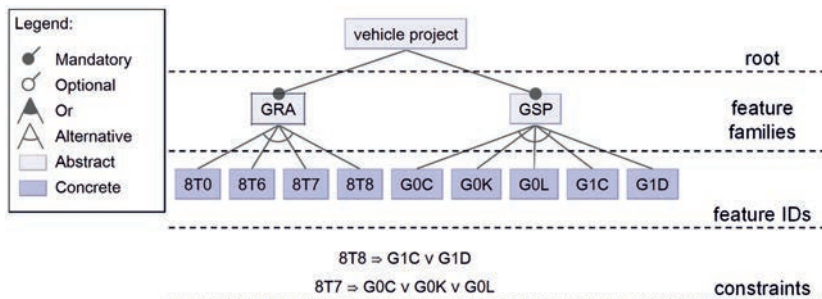
Fig. 2:   Feature diagram for an example feature model with two feature families [14]

3.2 Selection of representative configurations for the test

Testing every possible configuration of a large SPL individually is infeasible, due to the exponentially growing configuration space. Thus, various approaches have been proposed to generate a subset of configurations that is representative for the behavior of the whole product line. A summary of these, also called product sampling, techniques has been published by Varshosaz et al. [3]. They classified the algorithms based on the input data, the selection technique and the type of coverage. Figure 3 shows this classification, complemented by an additional sub-category for the distinction of different criteria for a prioritization. Feature models are used as input by almost every technique and are used to generate valid configurations. Some approaches allow to incorporate additional expert knowledge in the form of manually pre-selected configurations. Only a few approaches also use implementation and test artifacts as input. In addition, the approaches differ in terms of their objectives. A widely used coverage-based approach is combinatorial interaction testing (CIT). Here, the goal for the sampling is to provide coverage for all possible interactions of features in the SPL. Therefore, different degrees of coverage can be considered. The most common are 1-wise, pair-wise and t-wise. Where 1-wise (t=1) is the lowest degree and aims to cover every feature at least once in each possible form (selected and not selected). Other approaches consider the coverage of

requirements or software code. Beyond the coverage strategy, some approaches also offer the possibility to prioritize the generated configurations, based on one or more criteria like risk, costs or sales figures. With regards to the fundamental technique for the selection, a distinction can be made between manual selection, semi-automatic, and automatic selection. The techniques for the automated selection can be further divided into greedy and meta-heuristics approaches. Both greedy and meta-heuristic algorithms attempt to approximate the global optimal solution by performing multiple small steps in which a locally optimal choice is made. Whereas the choices in greedy algorithms are permanent, they can be revised in meta-heuristics. Depending on whether meta-heuristic algorithms are operating on a single candidate solution or are operating on multiple candidate solutions, they are referred to as local search or population-based search techniques. If a sampling algorithm provides the possibility to define user-specific requirements, this is referred to as semi-automatic selection. A possible requirement could be, for example, to start the sampling with a predefined selection of configurations. Finally, manual selection describes the completely manual selection of configurations e.g. by domain experts.
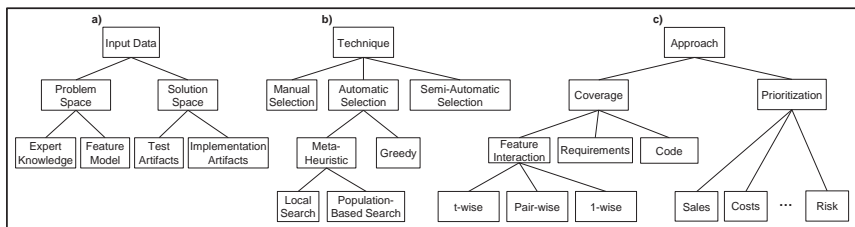
Fig. 3:   Classification of approaches for the selection of configurations [3]

Using a range of different approaches as examples, the following describes why existing approaches do not scale for very large feature models. An example of a state-of-the-art greedy algorithm is YASA [7]. YASA tries to address the scalability problem of large size SPLs and guarantees t-wise coverage for feature models. However, the author himself admits that long sampling times currently still prevent a practical use for very large models [8]. The main problem here is the high number of features and feature interactions, which lead to expensive queries for the SAT-solver, checking the validity of configurations. For this reason, most meta-heuristic approaches try to avoid these checks and instead work on a set of in advance generated configurations. Hierons et al. proposed an algorithm based on evolutionary strategy (ES) which uses configurations with full pair-wise coverage as input [4]. A similar approach is used by Ferreira et al. for many-objective evolutionary algorithms (MOEA) by reducing the

number of possible configurations to a predefined number [5]. In this way, the algorithm cannot guarantee coverage of feature interactions. The same applies to the local-search technique uniform random sampling (URS). With the goal to compute t-wise samples for feature models, Oh et al. use URS to generate uniformly distributed samples [6]. However, they conclude that URS alone is not enough to achieve 100% 1-wise and pair-wise coverage.

In order to improve the scalability of sampling algorithms, several approaches were developed. They can be divided into two categories. The first idea is to reduce the size of the feature model so that sampling only needs to be performed on a smaller partial model. This can be done by using the feature model as the only source of information. One way to do so is to remove mandatory features from the feature model using atomic sets [11]. With the help of expert knowledge, the number of relevant features can be further reduced. For this Kowal uses feature model attributes that contain information regarding shared resources and communication to identify a reduced model [9]. The second idea is based on reducing the amount of feature interactions which has to be considered for the coverage criterion. This can also be done using atomic sets, because they provide information about features that can never appear in a product separately [10, 19]. Johansen et al. proposed an approach to integrate additional expert knowledge [13]. They add weight to feature-pairs in order to focus on the relevant feature interactions. For this they consider the given market situation. Some other approaches use test and implementation artifacts. Kim et al., for example, apply static program analysis to detect features that can influence the test results [12].

We can conclude that scalability with respect to large feature models still poses a problem and that automated selection of configurations remains a challenge.

4. Methodology and implementation

In this section, the methodical procedure for an optimal selection of variants for the overall E/E integration test is presented. This optimal selection of variants consists of two sub-processes shown in Figure 4. The first part covers the necessary modelling and mapping (see Fig. 4a) whereas the second part consists of the variant selection. A detailed description of the individual steps is provided in the following.
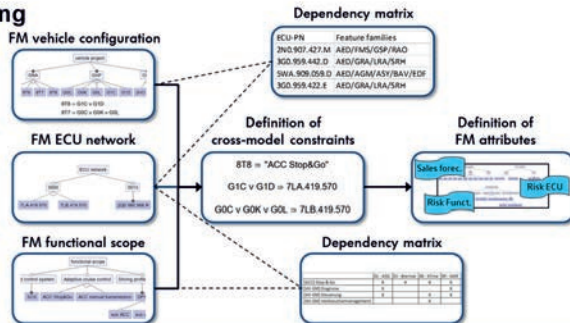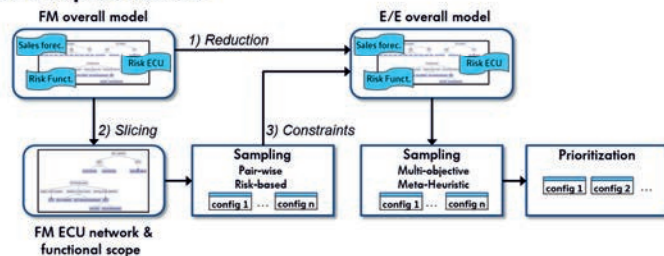
Fig. 4:   Process for modelling and searching for solutions

4.1 Modelling

The optimal selection of variants process starts with the creation of models for the three types of variances (vehicle configurations, ECU networks and functions). This is done using feature models created with the FeatureIDE tool and results in three individual feature models, one for each of them:

Firstly, the model of possible vehicle configurations consists of feature families and feature IDs (see section 2.2 for more details). The feature families are arranged below the root and serve as alternative groups for the different product features. Dependencies between the features are formulated in propositional logic. With the help of these cross-tree constraints, all possible combinations of feature IDs and thus all valid vehicle configurations can be described. Secondly, the feature model for the ECU network consists of diagnostic address IDs and ECU versions in form of their individual part number. Similar to the feature families, the diagnostic addresses serve as an alternative group. Although some of the diagnostic addresses and thus also ECUs are only optional. Thirdly, modelling the variability of the functional scope, follows

the structure of the catalogue described in section 2.2. Each function can be implemented in form of different function variants which can be optionally further divided into sub-functions.

In the next step, these three individual models have to be linked. Therefore, dependencies between the features of the different models are formulated in propositional logic similar to the cross-tree constraints. These so-called cross-model constraints generate an overall model as shown in Figure 5.

For the efficient selection and prioritization of variants, the overall feature model is extended by feature attributes. The first attribute which can be linked with the vehicle configurations are sales forecasts. With a number between 0 and 1, they describe how often a product feature will occur in a vehicle configuration. They thus refer directly to specific feature IDs. Further attributes can be taken from the E/E integration test process. The risk analyses carried out in this context result in risk values for both functions and ECUs and can be assigned to the corresponding features.

In addition to this overall feature model, there are two more aspects that can be used in the context of selection and prioritization. The first are architecture-related dependencies between functions and ECU versions, which are special cases that cannot be completely represented by cross-model constraints. For example, the presence of a trailer hitch affects the functionality of the ultrasonic-based parking assist system when reversing. Since, a trailer hitch is not necessarily required to enable the parking aid function, these dependencies are described in form of a dependency matrix. The second aspect relates to the relevance of product features for the coding of the ECUs and is also described with a dependency matrix. For each ECU version, the set of product features that are used in the coding process is known. This information can be used to consider which feature families are relevant for the E/E integration test.

The resulting overall model enables automated analysis of the variability and searching for optimal variants based on sales forecasts, component risk and functional risk analyses.

Feature models

Cross-model constraints

$$8T8 \Rightarrow "ACC\ Stop\&Go"$$

$$G1C \lor G1D \Rightarrow 7LA.419.570$$

$$G0C \lor G0K \lor G0L \Rightarrow 7LB.419.570$$

Fig. 5:   Overall feature model example

4.2 Selection and prioritization of variants

The methodology shown in Figure 4b includes different algorithms for the selection of feature model variants as well as different approaches to reduce the complexity. A divide-and-conquer approach (step 2 and 3 in Fig. 4b) together with the identification of nonrelevant features (step 1 in Fig. 4b) allows the search for optimal variants based on several selection criteria. The selection criteria consist of fixed requirements regarding the coverage of feature interactions as well as a number of other criteria that need to be optimized. A fixed requirement is, for example, that pair-wise coverage is achieved for the feature models of the functional scope and the ECU network. In addition, the configurations must be optimized with regard to the feature model attributes (sales forecasts and risk) whereby the number of configurations should be kept as low as possible.

The basic idea of the divide-and-conquer approach is to focus on the functions and ECUs as they are fundamental to the E/E overall integration test. In the first step, the overall feature model is reduced to a model that only includes the functional scope and the ECU network. This is done using feature model slicing, so that all dependencies from the overall model are retained (see section 3.1). A sampling algorithm is then applied to this model to obtain configurations that provide the required pair-wise coverage. Suitable for this purpose are lightweight greedy approaches such as YASA [7] or IncLing [20]. In our case, we have adapted the IncLing algorithm so that it also takes into account the risk values represented by the feature model attributes. When choosing between two features with the same rank, the new algorithm selects the one with the higher risk value. The resulting configurations consisting of functions and ECUs are then incorporated into the overall model. This is realized by additional

features and constraints in the feature model. Each configuration is represented by an additional feature, whereby these features are structured as an alternative group so that they are mutually exclusive. In addition, the risk values for each configuration are summed up and included as feature model attributes in the model. Finally, for each feature from the configurations a constraint is created. Each of these constraints builds an implication between the feature representing the configuration and the feature representing the respective function or ECU.

The resulting model is then reduced again by feature model slicing. In the first step, feature families whose feature IDs are not relevant for the coding of ECUs are determined and are not included in any cross-model constraint. These feature families and feature IDs are sliced out of the overall model. Since the configuration options for the functions and ECUs are already defined by the first round of sampling, these part-models can also be sliced out.

This results in a reduced feature model for the E/E relevant feature families, which is restricted by the definition of fixed configurations for the functional scope and ECU network. On this basis, a second round of sampling is carried out. For this, a meta-heuristic approach like GrES by Hierons [4] can be used. The input required for this are configurations with full pair-wise coverage and can be generated with greedy algorithms like YASA or IncLing. GrES is a selection and prioritization algorithm which considers many objective functions, but the pair-wise coverage is seen as the most important. In addition to pair-wise coverage, in our case the number of configurations should be minimized and sales forecasts maximized.

In the final step, the resulting configurations can be arranged based on the risk value assigned to the functional scope and ECU network.

5. Conclusion and outlook

Due to the increasing variants and complexity of electrical and electronic systems, the selection of vehicle variants for the automotive E/E integration test remains a major challenge. This work provides a holistic modelling approach for E/E variability and a framework which can be used for an efficient selection and prioritization of vehicle variants.

The modelling of the variability covers vehicle configurations, ECU networks and functional scope. In addition, information from development artefacts such as sales forecasts and risk assessments are directly linked to the model. This is realized in form of feature models, extended by cross-model constraints and feature attributes. For the implementation the tool FeatureIDE was used. Furthermore, it was described how, based on this overall model, the selection and prioritization of vehicle variants for the construction of test benches and test vehicles can be realized. In order to reduce the complexity, a divide-and-conquer approach

using feature model slicing was proposed. This allows the use of state of the art algorithms for searching optimal variants. The selection criteria used here, are full pair-wise coverage for ECUs and functions combined with the optimization of feature model attributes (sales forecasts and risk).

The approach is applicable along the entire development process, as the modelling can be continuously updated directly with information from the development artefacts. In that way a systematic selection can constantly be achieved, leading to an increased test coverage in the E/E integration test. Moreover, throughout the automated analysis of the variability, inconsistencies in the development process can be identified at an early stage.

Regarding future work, the framework must be validated with regard to runtime behaviour and result quality. For this purpose, tests have to be carried out with sample data from different vehicle projects. Furthermore, it would be possible to extend the framework to enable an automated test planning. This could be done by extending the modelling to include information regarding test cases for the different functions.

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High Performance and Efficiency Hydrogen Engine Using Westport Fuel Systems' Commercially Available HPDI Fuel System

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Abstract

There is a growing interest in hydrogen as a transportation fuel. The transportation sector is currently undergoing rapid transformation driven by a need for finding suitable low or zero carbon energy solutions and to further mitigate regulated ambient air pollutants. This rapid transformation has been partly enabled by technological breakthroughs in battery and hybrid electric vehicles and hydrogen fuel cells. Fuel-cell vehicles are seen as a key technology driver for hydrogen powered mobility solutions. Lately there has also been some interest in considering hydrogen fuel cells for heavy duty applications. These recent trends raise an obvious question regarding what role ICEs are to play in the coming decades. Internal combustion engines (ICEs) power almost all vehicles globally and have attained a high degree of maturity over the last 100+ years through sustained technological and manufacturing improvements and breakthroughs. The medium and heavy-duty sectors have been typically dominated by the diesel engine due to its superior attributes in terms of power output, efficiency, reliability, and total cost of ownership. A highly integrated and optimized development, manufacturing and supply chain ecosystem currently exists for internal combustion engines. ICEs have been adapted to utilize gaseous fuels (e.g. natural gas) both for premixed or partly premixed fuel-air engines (using low pressure port fuel injection with spark ignition) and for non-premixed engines (using low pressure dual fuel combustion or high pressure direct injection with pilot ignition). Hence it is imperative to understand whether hydrogen as a fuel can be adapted to take advantage of these developments in ICE technology and which combustion technology would be the most suited to fully leverage the properties of hydrogen as a fuel. A combustion study (modelling and engine testing) was carried out to evaluate the impact of hydrogen on a heavy duty engine performance, efficiency and emissions. The results of the study indicate that high pressure direct injection of hydrogen with pilot ignition is the most promising method and has the potential to deliver the highest engine performance (torque/power) and efficiency. The engine testing also revealed that H2 HPDI engine can achieve very high power density and efficiency (~30 bar BMEP with 46% brake thermal efficiency) without exceeding engine mechanical limits.

1. Background

The transportation sector is currently undergoing rapid transformation driven by a need for finding suitable low or zero carbon energy solutions and to further mitigate regulated ambient air pollutants. This rapid transformation has been partly enabled by technological break-throughs in battery and hybrid electric vehicles and hydrogen fuel cells. Recently there has been a resurgence of global interest in hydrogen as a zero-carbon fuel for powering PEM (proton exchange membrane) fuel-cell based mobility solutions initially aimed at light and me-dium duty vehicles. Lately there has also been some interest in applying PEM fuel cells in heavy duty applications. These recent trends raise an obvious question regarding what role ICEs are to play in the coming decades. Internal combustion engines (ICEs) power almost all vehicles globally and have attained a high degree of maturity over the last 100+ years through sustained technological and manufacturing improvements and breakthroughs. The medium and heavy-duty sectors have been typically dominated by the diesel engine due to its superior attributes in terms of power output, efficiency, reliability, and total cost of ownership. Great progress has also been made in drastically reducing regulated exhaust emissions from gaso-line and diesel engines. In addition to gasoline and diesel, natural gas (including gaseous fuel from renewable sources, i.e. biomethane) is also considered a promising transportation fuel due to its reduced carbon intensity. ICEs have been adapted to utilize natural gas, both for premixed or partly premixed fuel-air engines (using low pressure port fuel injection with spark ignition) and for non-premixed engines (using low pressure dual fuel combustion or high pres-sure direct injection with pilot ignition). A highly integrated and optimized development, manu-facturing and supply chain ecosystem currently exists for internal combustion engines. Hence it is imperative to understand whether hydrogen can be used to take advantage of these de-velopments in ICE technology and which combustion technology would be the most suited to fully leverage the properties of hydrogen. Being a company focused around gaseous fueled engine technology, Westport Fuel Systems (WFS) has always recognized the long-term po-tential of hydrogen to transform the transportation sector, with multiple OEM projects and re-search into novel hydrogen fueling approaches. Between 2004-10 work was carried out to adapt lean burn PFI SI engines to operate on a mixture of hydrogen and natural gas under two separate projects targeted at medium duty transit buses [1, 2]. In parallel, WFS also developed fuel injectors for high pressure direct injection of hydrogen in multiple light duty OEM engine programs [3]. Over the last several years WFS subsidiary GFI Control Systems (https://wfsinc.com/brands) has also developed fuel system components (e.g. tank valves, fuel delivery modules, pressure regulators, etc.) for hydrogen fuel supply systems.

2. Hydrogen and Engine Technologies

Table 1 summarizes the physical and chemical properties of hydrogen, methane and gasoline that are relevant to engine applications.

Table 1:   Physical and chemical properties of hydrogen, methane and gasoline [4,5].

Property	Hydrogen	Methane	Gasoline
Minimum ignition energy (mJ)	0.02	0.28	0.28
Flammability limits in air (vol%)	4–75	5–15	1.1–6
Lower heating value (MJ/kg)	120	50	44.3
Air Specific Heating Value (MJ/kg air)	3.5	2.9	2.7*
Stoichiometric air-to-fuel ratio (kg/kg)	34.2	17.1	15
Stoichiometric air-to-fuel ratio (kmol/kmol)	2.39	9.55	59.67
Auto ignition temperature (°C)	572	540	440
Maximum flame velocity in air (m/s)	2.9	0.45	0.58*

*For iso-octane.

It can be seen from Table 1 that hydrogen has the highest volume fraction for a stoichiometric mixture with air, which leads to a low volume specific heating value. On the other hand, the air specific heating value of hydrogen (3.5 MJ per kilogram of air) is significantly higher than for methane (2.9 MJ/kg) or gasoline (2.8 MJ/kg). To assess the combustion related properties for hydrogen, a detailed hydrogen reaction mechanism published by Lawrence Livermore National Laboratory (LLNL) [6] was utilized to compute the adiabatic flame temperature, the laminar flame speed, and the autoignition conditions for hydrogen under engine-relevant conditions. As expected, the laminar flame speed for hydrogen is substantially higher than that for natural gas over a wide range of equivalence ratios. The adiabatic flame temperature for hydrogen is also substantially higher than that of natural gas at a given equivalence ratio. More interestingly, the difference between the two fuels increases as the equivalence ratio moves towards the rich side. The above two characteristics for hydrogen combustion are advantageous for diffusion combustion as a significant fraction of the fuel starts combustion on the fuel-rich side.

Medium and Heavy-duty vehicles have typically relied on diesel engine combustion technology. Potential use of hydrogen in such an engine platform could potentially rely on several combustion approaches, namely:

1. H2-PFI SI (H2 **P**ort **F**uel **I**njection with **S**park **I**gnition) - PFI SI has been commonly used for gasoline powered engines and can be adapted to burn hydrogen. The fuel is injected into the intake port at low pressure with ignition provided by a spark plug to initiate combustion of a fully premixed charge of H2 and air.

2. H2-ECDI SI (H2 **E**arly **C**ycle **D**irect **I**njection with **S**park **I**gnition) - In the case of ECDI, the hydrogen injection takes place after intake valve closure at the start of the compression stroke, and the ignition is provided by a spark plug to initiate combustion of a mostly pre-mixed charge of H2 and air.

3. H2-HPDI (H2 **H**igh **P**ressure **D**irect **I**njection with pilot diesel ignition) - HPDI technology is a commercial technology originally developed for heavy duty natural gas engines. The fuel injection relies on late cycle direct injection of hydrogen at high pressure (~300 bar). A small quantity of pilot fuel injection at a similar pressure precedes the injection of hydrogen and acts as an ignition source.

3. HPDI Engine Technology

WFS's HPDI technology uses late cycle, direct injection, compression ignition combustion with the vast majority of the energy derived from the combustion of a gaseous fuel. Combustion is initiated via late cycle direct injection of a small quantity of pilot fuel, with injection of both fuels via WFS's proprietary dual concentric needle HPDI injector design. By utilizing Diesel Cycle thermodynamics, the HPDI fuel system retains the thermal efficiency, power, torque and engine braking of the base diesel engine.

Early-generation HPDI product (HPDI 1.0) was commercially available in North America and Australia on a 15L HD truck engine platform (MY 2001 through 2013). HPDI 2.0 (see Figure 1) is currently commercially available in HD trucks in Europe on a 13L platform, and will launch soon in China on a 12L platform. HPDI 2.0 uses natural gas as the primary fuel, with LNG as the onboard fuel storage medium. High pressure natural gas is supplied to the engine via WFS's proprietary onboard, in-tank LNG pump.

WFS has extensive product development and product industrialization experience with a range of gaseous fuels (CNG, LNG, LPG, H2), including a dedicated H2 fuel supply and fuel pressure management components business, under the GFI brand. WFS recognized an opportunity to adapt the HPDI technology for operation with H2, whereby H2 HPDI would fully leverage the existing NG HPDI fuel system architecture and component designs, albeit requiring H2-specific upgrades including material selection, certain validation activities, and H2-specific component certifications. The unique aspect of an H2 HPDI product will be the off-engine fuel storage and supply system, to provide a continuous supply of high pressure H2 to the engine throughout the fuel depletion cycle. WFS's current R&D work is focused on developing an onboard high pressure gaseous fuel compressor, integrated with 700 bar compressed H2 fuel storage tanks using GFI-branded fuel pressure management components. WFS has previous experience with design of onboard high pressure gaseous fuel compressors for prior applications of HPDI; this will form the starting point for the compressor development. This next phase of work is in anticipation of 700 bar H2 becoming the predominant fuel supply and storage medium for H2 on-road vehicles. If the H2 fuel supply infrastructure develops in favour of liquefied H2, then WFS is very well equipped to leverage its extensive cryogenic fuels expertise and quickly adapt the current LNG tank and pump architecture for liquefied H2 fuel storage and supply.

Fig. 1:   HPDI 2.0 fully integrated system for heavy duty applications.

4. Combustion Modelling

Two-zone Combustion Model for Premixed Combustion

The two-zone combustion model is a control volumed based analytical engine model developed based on the work of Catania et al [7]. The model was extended by adding predictive functions for flame propagation in premixed engines. The model divides the combustion chamber into two domains for burned and unburned gas mixtures and solves the differential equations for energy and mass conservation to obtain cylinder pressure and temperature in both domains at each computational timestep. Knock prediction is achieved by analyzing the probability and intensity of autoignition in the end gas (the unburned mixture domain). The thermodynamic properties of the burned and unburned gas are obtained from the NASA thermodynamic database [8] using Chemkin III. The heat exchange between the gas mixture and the combustion chamber walls was captured using the Woschni model [9]. The two-zone combustion model was calibrated and used in the development work for several medium-to-light-duty, premixed natural gas engines at WFS.

CFD Model for HPDI Combustion Simulation

The details for the combustion CFD model used in the current study have been provided in our previous publication [6, 10]. A brief description of the model follows. The engine combustion solver was built on the platform of OpenFOAM [11] (version 2.3.1), We implemented a modified Conditional Moment Closure (CMC) method to model the interaction between the combustion chemistry and the turbulence in the flow field. Detailed chemical kinetic mechanisms were used to compute the conditional reaction rates for the pilot fuel and the gaseous fuels. For pilot combustion, a reduced n-heptane mechanism (159 species, 770 reactions) [12] from LLNL was used; and for natural gas combustion, a modified GRI mechanism developed in our previous work (55 species, 278 reaction) [13, 14] was used. For hydrogen, the LLNL mechanism [6] (10 species, 40 reactions) discussed earlier was used. The reaction progress variables and detailed reaction rates were pre-computed and tabulated using a trajectory-generated low-dimensional manifold method (TGLDM) [15] which allows quick retrieval and computation of the chemical source term for the specie mass conservation equations. To further reduce the computational time, advantage provided by the axisymmetric nature of the combustion chamber geometry and the flow field was utilized by using a sectional domain defined as a one-n^{th} sector of the combustion chamber, were n is the number of gas spray holes. The combustion model described above has been validated over various HPDI engine platforms in the past.

5. Results and Discussion

The modelling work covered three different combustion systems: PFI SI, ECDI SI, and HPDI with Pilot ignition. Simulations were carried out for two gaseous fuels - natural gas (NG) and pure hydrogen (H2). The simulations were focused on a heavy-duty engine application, typically used for long-haul trucks. The rated power for the base engine is around 330kW, with the peak torque at around 2400 N.m and 1200 rpm.

Premixed Combustion Engines

The PFI and ECDI combustion systems were modelled using the two-zone combustion model described above. The simulations were conducted in a full factorial parameter space covering fuelling, ignition timing, and compression ratio at various air/fuel equivalence ratios (0.6-1.0) and two different intake temperature levels (320 & 355K). For PFI SI, a homogeneous mixture of gaseous fuel and air were introduced at the intake port when the intake valve opens. For ECDI SI, the fuel injection occurs near the bottom dead centre (BDC). Figure 2 shows an example of indicated thermal efficiency (ITE), knock index and peak cylinder pressure (PCP) for a PFI engine with various ignition timing and compression ratios at the rated power point. The highest thermal efficiency at a given fuelling level can be selected from these curves for each combustion system configuration subject to the constraints of knock and peak cylinder pressure limits. The optimal timing for the midpoint of heat release is affected by various factors including the flame speed, the burn duration, and the rate of wall heat transfer, but typically appears between 5 and 10 degrees ATDC.

As described in section 2, hydrogen has a higher tendency for knocking than natural gas. From Figure 2 we can see that at a given compression ratio and intake temperature, hydrogen premixed combustion shows a significantly higher knock index than its natural gas counterpart. To reduce the knock index, either the start of combustion timing must be retarded, or the compression ratio has to be reduced in order to lower the end-gas temperature. Both measures have a negative impact on the engine efficiency.
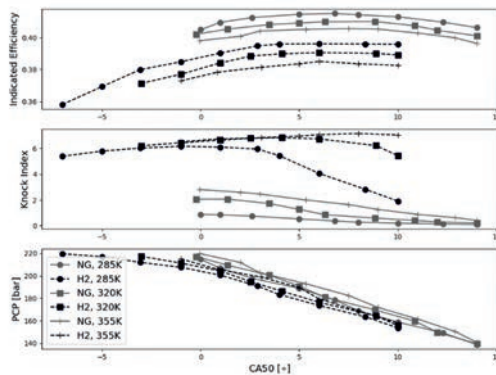
Fig. 2:   Indicated thermal efficiency, knock index and peak cylinder pressure as a function of
          50% cumulative heat release timing for natural gas and hydrogen at different intake
          temperatures at 14:1 compression ratio for a premixed combustion.

It can be seen that in general, the hydrogen engines with premixed combustion systems show
lower thermal efficiency than the natural gas engines of the same type. This is mainly due to
the combined effect of lower (knock limited) compression ratio and higher wall heat loss. Note
that the current model does not capture fugitive emissions caused by crossflow due to valve
overlap and the charge blowby. If these factors were considered, the net efficiency of the hy-
drogen premixed engines would be further reduced due to the higher molecular diffusivity of
hydrogen compared to that of natural gas. Figure 3-a also shows that the lean burn engines
produce higher thermal efficiency than the stoichiometric engines with the same combustion
system. The benefit of lean burn engines comes from the reduced exhaust energy and wall
heat loss, which is partially offset by the lower flame speed.

The simulation results from modelling indicate (Figure 3-b) that HPDI offers the highest engine
efficiency among the combustion systems investigated for hydrogen powered IC engines. The

thermal efficiency of hydrogen HPDI engines can be 14-20% higher than the best premixed hydrogen engine configurations.
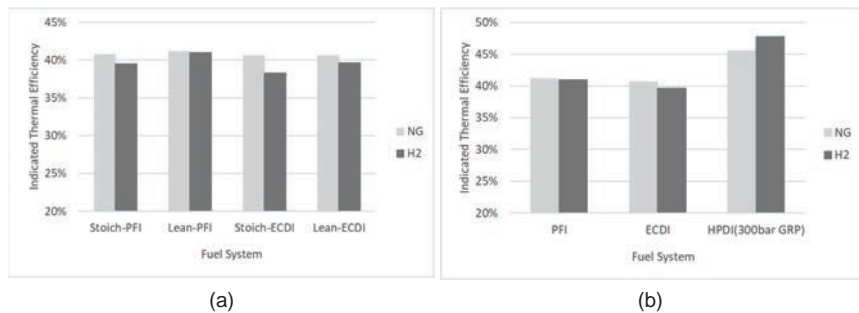

(a)   (b)

Fig. 3:   Comparison of optimal indicated thermal efficiency as predicted by modelling, a) pre-
mixed hydrogen engines - stoichiometric and lean combustion, b) lean premixed (PFI
and ECDI) vs non-premixed (HPDI) combustion.

HPDI Combustion

As explained earlier in section 3, in HPDI the gaseous fuel is injected late in the cycle directly into the combustion chamber at high pressure (~300 bar). A small quantity of pilot fuel injection at similarly high pressures precedes the injection of hydrogen and acts as a source of ignition. The hydrogen HPDI combustion was simulated using the combustion CFD model introduced above. A total of four operating conditions were selected, which represent typical peak power (C100 - 1600 RPM/100% load), peak torque (A100 - 1200RPM/100% load), cruise (A50 - 1200 RPM/ 50% load), and light load (A25 - 1200 RPM/25% load) operating conditions for a typical heavy-duty truck application. The maximum fuel injection pressure is 290 bar for gas and 300 bar for pilot. The fuel rail pressure is reduced when operating at medium-to-low load conditions. For each operating point, simulations were conducted for natural gas with pilot ignition and then repeated for hydrogen with pilot adjusting the gaseous fuelling quantity (hydrogen) to produce equivalent torque as natural gas. The quantity of pilot fuel varies typically from 2% to 8% of the total energy input depending on engine load, with the high load points having the higher substitution rate (low pilot quantity). The injector hole numbers, size and nozzle config-urations used were identical between natural gas and hydrogen cases.

In addition to H2 HPDI combustion CFD modelling it was deemed necessary to get experi-mental confirmation of modelling results to validate the conclusions offered by the modelling

study. Engine testing of a multi-cylinder heavy duty engine was targeted for the first quarter of CY2021. WFS's engine testing facility was upgraded to allow for high pressure (300 bar) direct injection of hydrogen in a multi-cylinder heavy duty engine for H2 HPDI testing. As part of the safety review, preliminary assessment of compatibility of engine components coming into contact with hydrogen was also carried out. Preliminary assessment confirmed that the engine is capable of running on hydrogen with existing HPDI fuel system hardware for short test durations.

A heavy duty engine used for testing is an unmodified version same as that was used in the past for NG HPDI development. The engine was successfully fired on pure hydrogen operating on HPDI combustion. The engine operated over a wide range of the engine map from idle to full load and in between load conditions at various engine speeds. The engine operation was found to be quite smooth and repeatable. Analysis of engine test data confirmed the modelling predictions, i.e. HPDI engine efficiency is significantly higher for H2 as compared to NG.

Figure 4-a shows the comparison of brake thermal efficiency between hydrogen and natural gas HPDI combustion at the four operating points listed above. Results are shown for both CFD modelling predictions and engine test results. As seen from the results the simulation and engine test results match quite well. For the same operating point, hydrogen HPDI shows higher efficiency than natural gas HPDI. At full load the H2 HPDI engine achieved about 46-47% brake thermal efficiency as compared to about 41-43% for NG HPDI. It should be kept in mind that the NG HPDI efficiency typically very closely matched to the base diesel engine efficiency. The relative gain is bigger for the high load points than those for the lower load points. For instance, the relative efficiency gain for hydrogen HPDI (as compared to NG HPDI) at the full load (A100 & C100) points is around 6-10% and is 2-3% at the 25 to 50% load points. This is because mixing quality and efficiency in diffusion combustion play more important roles at higher engine loads than at lower loads.
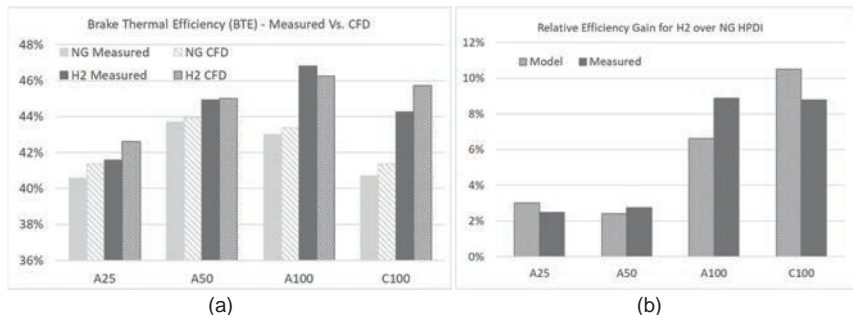
(a)   (b)

Fig. 4:   Brake thermal efficiency (BTE) at various engine operating conditions for NG and H2
           HPDI, a) Measured vs Predicted %BTE , b) Relative BTE gain for H2 over NG HPDI.

There are a few reasons that contribute to the higher thermal efficiency for hydrogen HPDI combustion. First, at a given air mass and fuelling quantity, the global equivalence ratio for hydrogen HPDI is lower than that for natural gas (recall that hydrogen has a higher air specific heating value than any other fuels). The leaner condition leads to higher combustion efficiency, reduced exhaust energy and reduced wall heat loss. Secondly, at a given fuel injection pressure-to-cylinder pressure ratio, hydrogen jets contain higher kinetic energy due to the high flow velocity, which increases the mixing rate and benefits the combustion efficiency. Finally, the mechanical work done by the expansion of the compressed hydrogen is substantially higher than that of natural gas due to its low density.

Figure 5-a shows the reduction in tailpipe CO2 emissions as compared to the diesel engine. NG HPDI typically provides about 18-20% reduction in CO2. Switching to H2 HPDI, the CO2 reductions are increased to 88-97% (the residual CO2 comes from the small quantity of pilot fuel used for the ignition process). These results were obtained where the pilot fuelling quantity was unchanged between NG and H2 HPDI. With no hardware changes or changes to pilot quantity, H2 HPDI offers significant CO2 reductions.

Pilot Quantity Reduction for Hydrogen HPDI
The CO2 emissions for hydrogen HPDI combustion mainly comes from using diesel as the pilot fuel. As shown in Figure 5-a typically switching over to H2 HPDI results in tailpipe CO2 emissions reduction of 88-97% (compared to diesel). To explore the potential for further reduction of pilot fuel, a series of CFD simulations were conduct with reduced pilot quantity to

examine its effect on gas jet ignition at rated power. Table 2 summarizes the pilot quantities and observed results from the simulation study specifically for the peak power condition (C100). Below this level, an increase in ignition delay time and a spike in the rate of heat release due to a larger fraction of premixed charge at the time of ignition was observed. The minimum level of pilot at rated power corresponds to around 1.5g of CO_2 emission per kilowatt-hour of energy generated.

Table 2 CFD Model Results with Pilot Quantity Sweep at C100 point.

Pilot Qty mg/Str	Pilot Energy%	Main Fuel	Brake Specific CO2 g/kW.h	CO2 %Reduction	Ignition Stability
	NA	Diesel	597	0.0%	Baseline Diesel
5.34	2.09%	NG	482	19.3%	Baseline NG HPDI
5.34	2.09%	H2	13.2	97.8%	Baseline H2 HPDI
2.67	1.04%	H2	6.6	98.9%	Little Impact
1.34	0.52%	H2	3.3	99.4%	Little Impact
0.67	0.26%	H2	1.7	99.7%	Longer Delay, HRR Spike
0.33	0.13%	H2	0.8	99.9%	Longer Delay, HRR Spike

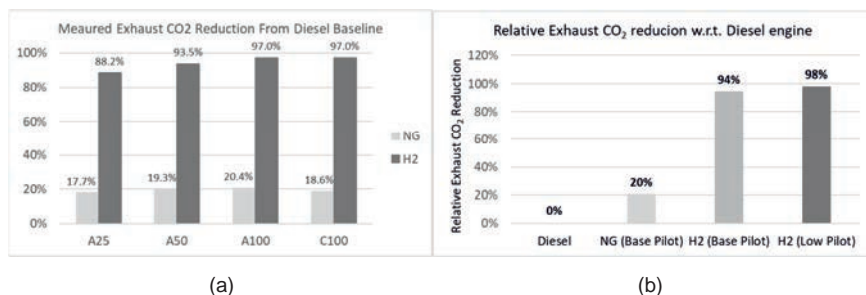(a)   (b)

Fig. 5:   CO2 emissions at various engine operating conditions, a) Measured reduction in CO2 for NG and H2 HPDI relative to diesel combustion, b) Impact of pilot quantity on reduction in CO2 for H2 HPDI.

Engine tests were carried out at the mid load condion (A50 point) to study the effect of reduction in pilot quantity. During the engine test pilot quantity was gradually reduced from the baseline value for H2 HPDI. About 2/3rds reduction in pilot quantity could be achieved without any

signficant impact on the engine combustion. As shown in Figure 5-b the CO_2 emissions were further reduced from 94% to 98% due to reduction in pilot quantity.

Based on the initial success and then subsequent operating experience running the H2 HPDI engine it was decided to further explore the capability of the combustion system. From earlier modelling and analytical estimates it was anticipated that combustion with H2 could further improve the power density of the engine by as much as 15-20%. Engine testing was carried out at the A-speed starting with A100 point (2400 Nm brake torque). The brake torque was gradually increased while ensuring the critical parameters (e.g. maximum cylinder pressure, exhaust temperature etc) are maintained within the safe mechanical limit for a real world engine. As shown in Figure 6-a the torque was increased from 2400 Nm to about 3000 Nm (25% higher, 30 bar BMEP). Similary the engine power (at C-speed) was increased from a baseline value of about 460 BHP to 600 BHP (~ 30% higher, Figure 6-b). It should be noted that the comparison is made here with NG HPDI base calibration. The baseline values should not be interpreted as an upper limit for NG HPDI as there is also some room (not as much as H2 HPDI) to further improve its maximum torque and power output (this has been confirmed through engine testing in a separate program). For guidance, the actual improvement in maximum achieveable H2 HPDI torque and power as compared to maximum achievable NG HPDI torque and power (i.e. not baseline NG HPDI values) is approximately around ~15-20%.
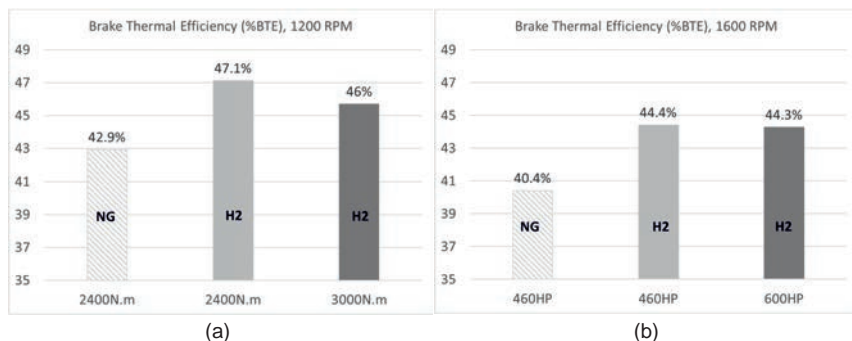

Fig. 6:   Improvement in H2 HPDI torque, power and efficiency, a) H2 HPDI - measured maximum torque, b) H2 HPDI - measured maximum power.

In summary, the current 13L NG HPDI engine has a Peak Torque of about 2400 Nm (24 bar BMEP @ 43% BTE) and rated power of 460 HP @ BTE of 40%. In comparison, H2 HPDI 13L

performance demonstrated a Peak Torque of 3000 Nm (30 bar BMEP @ 46% BTE), and a Max Power of 600 BHP @ BTE of 44.3%. These improvements were achieved while keeping the operation of the H2 HPDI engine within the mechanical limits of the base engine (e.g. a turbine Inlet Temperature ≤ 680C and the maximum cylinder pressure ≤ 220 bar). As far as we know there is no other H2 engine combustion method that can currently achieve this performance, and certainly not at these efficiency levels while staying within the mechanical limits of the base engine. The key significance of these results is that a smaller H2 HPDI engine (for example a 10 or 11L engine) could provide the same power & torque as a 13L diesel or NG HPDI engine.

As expected, the higher flame temperature and more abundant excess air for hydrogen HPDI combustion does increase the rate of NOx formation. Figure 7 shows that the indicated specific NOx emissions for hydrogen HPDI as predicted by the CFD model are noticeably higher than that for natural gas HPDI. There are several levers available to reduce NOx, such as, fuel injection pressure and timing, exhaust gas recirculation (EGR) and optimization of the Urea-SCR exhaust aftertreatment system. Impact of 20% EGR at C100 point on hydrogen HPDI combustion was also assessed using the model. It was found that NOx can be reduced to a level below that of the baseline natural gas HPDI combustion with a 3% impact on the thermal efficiency. Subsequently, engine tests confirmed the benefits of EGR in reducing NOx to lower levels. Adjusting the fuel injection pressure and timing were also found to be very beneficial in bringing NOx to baseline diesel levels.
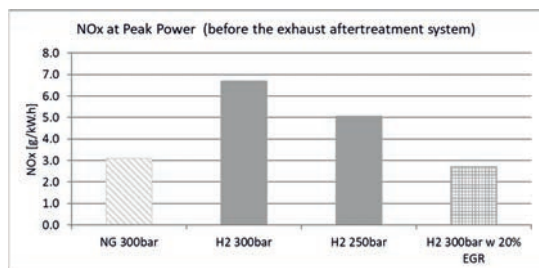

Fig. 7:   Engine out NOx (before the exhaust aftertreatment system) as predicted from CFD model for NG and H2 HPDI and impact of EGR in reducing NOx.

6. TCO and CO2 Reduction Potential

WFS collaborated with AVL to calculate the Total Cost of Operation (TCO) for heavy duty commercial trucks with the following powertrains: (1) Conventional diesel powertrain with 12-

speed automated manual transmissions and EURO VI compliant exhaust aftertreatment system, (2) H_2 fuel cell (PEM) trucks with 700 bar H_2 storage and (3) H_2 HPDI trucks with same transmission and aftertreatment system as conventional diesel powertrain, 700 bar H_2 storage and a booster compressor. The major assumptions and boundary conditions for this TCO comparison are described in the literature [16, 17].

The various assumptions in view of initial truck prices and efficiencies can be used to reflect different (future) points in time. Figure 8 shows the results for the near-term view for the different powertrains, around year 2025. The lighter parts of the bars are representing the range in TCO from the range in assumptions stated in the literature.
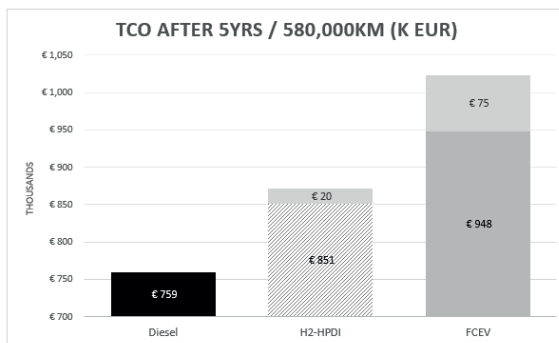

Fig. 8: Total Cost of Ownership After 5 Years of Operation.

Without considering road tolls, the diesel powertrain as reference is still the one with the lowest TCO, and the H2 HPDI powertrain has the potential for lower TCO than FCEVs. The main reason for the H2 HPDI advantage vs. FCEVs is that H2 HPDI provides a sound balance between acquisition costs and operating expenses. As noted in the assumptions in the literature, the acquisition cost for H2 HPDI-powered trucks will be much closer to the price of current diesel trucks, since H2 HPDI powertrains will leverage the existing, mature, and highly optimized supply chains for internal combustion engines, while also providing operating costs that are forecasted to be comparable to FCEVs in commercial vehicle applications, and possibly better than FCEVs in applications with high load-factors.

The CO_2 reduction potential, from a tank-to-wheel perspective relative to diesel-powered trucks, is 100% for fuel-cell trucks. For H2 HPDI solutions considering hydrocarbon pilot fuel consumption, lube oil and AdBlue, the CO_2 reduction potential is greater than 98%. For fleet operators with the objective to reduce transport-related CO_2 emissions, trucks with H2 HPDI powertrains would certainly be an attractive option in terms of their CO_2 reduction potential, offering substantially higher CO_2 reduction than other measures like hybridization of diesel powertrains.

Another measure of CO_2 reduction is the cost per ton of CO_2 avoided. The values in Figure 9 reflect the TCO for the different powertrains (reference year 2025) divided by the amount of CO_2 "avoided" (tank-to-wheel, relative to diesel-powered trucks) over a 5-year period. Due to the high absolute CO_2 reduction of H_2 HPDI and the moderate increase of TCO compared to diesel powertrains, H_2 HPDI trucks show the lowest costs per ton of CO_2 avoided.
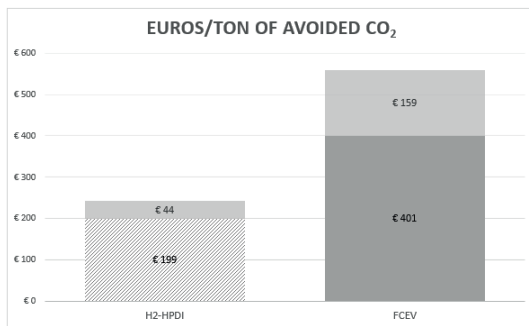

Fig. 9: Costs per Ton of CO2 Avoided (Reference: Conventional Diesel Truck).

In the near term, H2 ICE and especially H2 HPDI engines are a suitable solution for building up H2 fueling infrastructure. Going forward, the acquisition cost for fully industrialized fuel cell powertrains is expected to reduce. H2 HPDI solutions also show future potential to improve efficiency through further optimization of engine parameters (e.g. injection pressure, timing, equivalence ratio etc.) as well as integration with a hybrid powertrain. WFS intends to continue H2 HPDI development to further reduce or eliminate the residual CO2. With these measures, H2 HPDI is expected to offer attractive TCO and significant, highly cost-effective CO2 reduction long term, with lower product development risk.

7. Summary and Path Forward

This paper examined the combustion properties of hydrogen as an alternative, zero-carbon fuel for internal combustion engines and which combustion technology would be the most suited to fully leverage the properties of hydrogen as a fuel for heavy duty applications.

A modified, detailed chemical kinetic mechanism was used to assess the combustion related properties for hydrogen under engine-relevant conditions. Compared to conventional fossil fuels, hydrogen has the lowest volume-specific heat value but the highest air-specific heat value, which makes it more suitable for direct injection applications in terms of maximizing the energy density for the engine. The high flame temperature in the high fuel-air equivalence ratio region also favours higher combustion efficiency in diffusion flames when compared to natural gas diffusion combustion. The autoignition temperature for hydrogen is lower than that of natural gas in an engine-relevant environment. This increases the tendency of hydrogen to knock in high-compression-ratio, premixed engines, which limits their potential to achieve high thermal efficiency.

A two-zone combustion model was used to evaluate the efficiency of hydrogen engines with two different premixed combustion systems – PFI with spark ignition, and early-cycle DI with spark ignition. The simulation results show that for a hydrogen-fuelled engine with a premixed combustion system, lean-burn configuration with compression ratio between 13 and 14 offers optimal thermal efficiency while keeping the engine under the knock limit. The efficiency for hydrogen premixed engines is in general lower than their natural gas counterparts. This was attributed to the lower maximum compression ratio limit and higher wall heat loss for the hydrogen engines.

A 3D combustion CFD model with detailed chemical kinetic mechanisms was used to simulate both natural gas and hydrogen HPDI combustion at various engine load and speed points. The simulation results show that, while natural gas HPDI was able to achieve significantly higher thermal efficiency than the premixed gas engines, hydrogen HPDI outperforms natural gas HPDI significantly in efficiency under identical operating conditions and combustion system configurations. A few factors contributed to the high efficiency of hydrogen HPDI combustion. First, at given air mass and energy-equivalent fuelling quantity, the global equivalence ratio for hydrogen HPDI is lower than that for natural gas. This leads to higher combustion efficiency, reduced exhaust energy and reduced wall heat loss. Secondly, at a given rail-to-cylinder

pressure ratio, hydrogen jets contain higher kinetic energy due to the high flow velocity, which increases the mixing rate and benefits the combustion efficiency. Finally, the mechanical work done by the expansion of the compressed hydrogen is substantially higher than that of natural gas due to the low density of hydrogen.

An unmodified NG HPDI HD engine was set up and tested with H2 fuel. Substantial improvement in engine performance efficiency was observed confirming the CFD predictions. A good match between model-predicted and measured efficiency was observed. Engine testing also demonstrated that with H2 HPDI the engine power density can be substantially raised (up to 30 bar BMEP) without exceeding engine mechanical hardware limits. Engine results also confirmed modelling predictions that the quantity of pilot fuel can be reduced by more than 50% to reduce tailpipe CO2 emissions without affecting engine combustion quality or sacrificing the performance or efficiency.

Based on the combined modelling and engine testing combustion study, overall, among the combustion systems investigated, HPDI combustion offers the highest power density, highest efficiency and is the most robust system for using hydrogen as a fuel in an internal combustion engine for heavy duty applications.

Input (e.g. brake thermal efficiency) from H2 HPDI CFD modelling was used for the AVL/WFS TCO study. The engine testing data for H2 HPDI has confirmed modelling predictions and has now validated the AVL/WFS TCO study. A more detailed analysis of TCO implications may be taken up in future as more information becomes available.

Having confirmed the compelling modelling results via engine testing on multiple engine platforms, WFS is now progressing to the next stage of H2 HPDI R&D, including full fuel system development and H2-specific component design iterations. As noted in this paper, the majority of the unique product development will focus on development, demonstration and sytem integration of the high pressure H2 fuel storage and fuel supply system. WFS's initial focus will be on 700 bar H2 storage and the associated development and integration of a high pressure onboard gaseous fuel compressor, with the future opportunity to also develop an LH2 H2 HPDI option by leveraging WFS's extensive cryogenic fuels expertise and existing LNG fuel tank and onboard integrated LNG architecture.

WFS is in active discussions with numerous OEM customers and industry stakeholders regarding H2 HPDI, including publicly announced H2 HPDI demonstration projects [18, 19]. By leveraging WFS's extensive gaseous fuel combustion expertise, product development experience, and existing best-in-class HPDI 2.0 fuel system, WFS will be well positioned to quickly execute H2 HPDI product development in response to market demand. In the meantime, and independent of the development pace of the hydrogen transportation economy, WFS will continue to offer HPDI natural gas products for use with rewewable fuels in blends up to and including 100%.

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E/E architecture and operating strategy for fuel-cell trucks

Challenges and solutions for energy- and cost-efficient operation

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Abstract

Manufacturers have to reduce CO_2 emissions from new trucks dramatically within the next decade, which require to consider emission-free/neutral vehicles in the fleet mix. Especially for the heavy-duty (HD) long haul truck applications fuel cell technology is seen as a key enabler to meet fleet targets for emissions and operation cost.

This requires the development of a holistic concept including an optimal energy management and an associated E/E architecture that enables and supports this.

This paper describes the development of an E/E architecture and deals with its challenges. Furthermore a final E/E architecture is explained based on the requirements applying a specific fuel cell system (FCS) and an integrated electric HD axle (e-axle) developed by AVL combined with off-the-shelf components. Last but not least an advanced predictive control system is described which ensures to reach the overall optimum considering different sub-system trade-off's.

Introduction

Climate change results in stricter future emissions legislations all over the world. According to passed CO2 legislation from the European Union, manufacturers have to reduce CO_2 emissions of newly registered commercial vehicles for the subgroups 1-5, 9-12 and 16 according the VECTO vehicle group classification, by 15 % until 2025 and 30 % until 2030 [1]. All these legislations are forcing the automotive industry to develop new clean propulsion technologies. This task is especially for heavy duty commercial vehicles like long-haul trucks quite challenging. Conventional powertrains are already highly developed and optimized in terms of fuel consumption and efficiency and therefore emission free/neutral vehicles in the fleet mix can support in achieving these strict targets.

One approach towards zero emission are battery electric commercial vehicles (BEV), which have been developed by the truck industry within the last years.

Specifically for light-duty (LD) and medium-duty (MD) applications BEV have proven to be appropriate in truck applications as well. Also for heavy-duty (HD) truck applications with medium range requirements OEMs are currently introducing BEV solutions.

However, for HD applications with long-haul range requirements the limited energy density as well as the high cost and weight of the necessary large batteries push the need for alternative powertrain solutions.

Fuel cell powertrains represent such a possible alternative for this application by using a fuel cell as the primary energy source to supply the electrical energy needed for driving the vehicle and supplying additional consumers. As a secondary energy source, a battery - much smaller than for BEV applications - is installed, to cover power peaks and to store energy during recuperation phases. This already indicates that the powertrain architecture and the associated E/E architecture of a fuel cell powered HD truck is more complex, requires many more components compared to a BEV and makes the design and integration of the drivetrain and its E/E architecture more challenging.

The possibility to utilize two different energy sources, fuel cell and HV battery, offers a higher flexibility to optimize the operation of the vehicle by an advanced energy management system. By considering the different characteristics of fuel cell and HV battery, e.g. efficiency characteristic or aging behavior, the power share between the different energy sources can be optimized to best fulfill the operation targets. Beside the development of the software functionalities, the design of the required E/E architecture enables and supports the implementation of such an operation and control concept and plays a decisive role in achieving the set emission targets and represents a challenge in the development of hybridized HD trucks.

Requirements and challenges for the development of an E/E architecture for a HD fuel cell trucks

The main system components of such a HD truck are fuel cell stack(s), hydrogen tank(s), a high voltage (HV) battery as secondary energy source and a low voltage (LV) battery, the electric drivetrain, DC/DC converters, power distribution units (PDU), the HV and LV cabling system, various auxiliaries and the necessary control units. All these electrical components together form the E/E architecture of the powertrain.

These electrical components together with the entire E/E architecture must primarily meet functional-, physical-, performance- and installation-space criteria. Therefore, the next step in the development, after the vehicle requirements have been defined, is to design an architectural E/E concept that fulfils functional requirements of the drivetrain system.
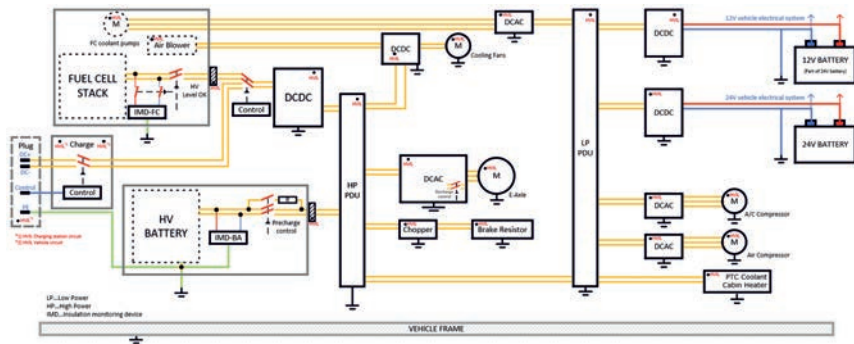
Fig. 1: Generic E/E Architecture for a Fuel Cell HD Vehicle

The concept shown in Fig. 1 reflects all major components together with its basic cabling. Based on the specification of the main components different voltage levels within the system are required and have to be defined accordingly. Generally, a high voltage level for the high-power consumers is aimed to reduce the resulting currents to keep the dimension of cabling small and reduce losses in the electric circuit. To find a feasible voltage level for the main components this approach has to be aligned with the specification of the components and has to fulfil functional safety aspects and legal regulations for the operation of electrical systems like the maximum voltage limit [4].

The current example utilizes four nominal voltage levels: the fuel cell HV level, the battery HV level and two LV levels. The battery HV level is connected via DC/DC converters with the fuel cell HV level and the LV level. The electric drivetrain and the HV auxiliaries are operating at the HV bus voltage level, which is defined by the HV battery.

During the development phase it has to be defined whether to use insulated or non-insulated FC DC/DC converters. Insulated converters insulate the input from the output by electrically and physically separating the circuit into two sections, preventing direct current flow between input and output. For safety reasons, the HV/LV connection is always done by means of insulated converters. Other advantages of insulated converters are breakage of earth loops and the possibility of voltage shifting. Disadvantages of insulated converters are higher costs and larger necessary installation space, compared to non-insulated DC/DC converters.

Most of auxiliaries are selected to operate at battery HV level so that the number of additional DC/DC converters for the LV circuit can be kept to a minimum.

For the LV circuit a voltage level of 24 V is standard in commercial vehicles, but the supply of various consumers require additionally a 12 V circuit in the system.

Beside that also the limited availability of electrical components for 24 V makes currently the use of 12 V components necessary. With the electrification of the entire powertrain also all required auxiliaries, e.g. brake air compressor, steering pump, have to be electrified and therefore electrical components have to be found.

The voltage level range of the fuel cell system is defined by its configuration, which allows different arrangements of cells in series within the stack. Developing the fuel cell system according to its final application enables to suit the voltage level to the final E/E architecture of the electrical drivetrain and therefore to find the best solution for the application. Additionally, the DC/DC converter which converts the power from the FCS to the HV bus has to fulfill the functional requirements to enable the transfer of electrical power to the HV bus circuit under all conditions. Depending on the voltage range of fuel cell system and HV battery the DC/DC must be able to boost the input voltage of the fuel cell to a higher output voltage of the HV battery, or to buck the voltage if the HV battery voltage is lower than the fuel cell system voltage.

To distribute the electric power of the HV circuit between the various consumers one or multiple power distribution units (PDU) are required. Splitting the different consumers to multiple PDUs based on the location of the components in the vehicle can enable a smarter packaging, which is one of the main challenges within the development of a fuel cell truck.

For the selection of auxiliary components different aspects have to be considered. Beside the availability of the components for certain voltage levels also the requirements for the operational safety of the vehicle have to be fulfilled. In case of any functional error in the HV circuit during the operation of the vehicle, which requires a shut-down of the HV system, the safety shall be still ensured. This requires that auxiliaries that are necessary to stop the vehicle under safe conditions (e.g. steering pump, control units,…) are located in the LV circuit.

To provide a certain continuous brake power of the vehicle, which hast to meet functional and legal requirements [5], different systems can be considered in a fuel cell truck. Beside the most reasonable way of using the electric motors for recuperation, also a conventional retarder or brake resistors can be used to convert excessive energy to waste heat. Both systems will utilize the vehicle thermal management system (VTMS) to dissipate the heat to the environment.

Once the E/E architecture concept has been defined, the components and the entire E/E architecture has to be packaged within the vehicle. This means, all subsystems and components, essential to operate the fuel cell HD tractor unit, need an appropriate space on

the vehicle frame. Fig. 2 shows a rough overview of how the necessary subsystems and components are distributed on the HD tractor unit.

Fig. 2: Rough E/E component packaging on a 4x2 tractor

Model based development approach to support E/E development

In order to be able to carry out a comprehensive analysis of the architecture in manageable time to optimize the sizing and development of the main components, like the fuel cell system or the HV battery, model-based development (MBD) approaches are the method of choice. For a proper selection and dimensioning of the components it is key to evaluate the energy flow in the system to identify the main consumers and therefore to identify the remaining optimization potentials to achieve a high overall system efficiency and meet the global operation targets. [6]

Furthermore, the MBD approach builds the basis for the development of the operating and control software for such a complex system, which is described in a following chapter.

Specific E/E architecture development challenges using off-the-shelf components

For the build-up of a fuel cell truck prototype vehicle one approach is to use mainly off-the-shelf components to reduce development time and keep costs on a lower level. The challenge for this approach is to find available components that best fit to the defined E/E architecture and fulfil the requirements, which might not always be possible and lead to adaptions in the final architecture.

To best fulfil the main vehicle requirements the focus was the development of an AVL fuel cell system, the development of an AVL HD integrated electrical axle (e-axle) on hardware side and the development of the vehicle control unit (VCU), e-axle control unit (EACU), fuel cell

control unit (FCCU) and the energy management system on the software system. To enable the full potential of the hybrid powertrain the control systems is extended by predictive control systems which optimize the operation of the system and therefore improve the target achievement of the vehicle under various conditions.

The selection of the other electrical components, such as HV battery (partly), IPSM motor controller, DC/DC converters, the PDU, diverse auxiliaries and other necessary control systems are selected out of off-the-shelf components.

Beside the vehicle auxiliaries, e.g. brake air compressor, electro-hydraulic steering pump, additional auxiliary components for the VTMS are required, which include e.g. electric fans and pumps for the different cooling circuits for the e-axle, fuel cell system and brake resistor.

In a first step the main components that define the HV level in the vehicle need to be selected, whereby the availability of those components is a limiting factor.

Based on the requirements of the e-axle a voltage range of 570 V to 800 V for the HV level is feasible. The maximum voltage was further limited by the available HV auxiliaries for the brake air compressor and the fuel cell cooling pump to a maximum of 750 V.

Next step was to find a DC/DC converter to convert the fuel cell voltage to the HV battery voltage, which defines the HV bus voltage. The chosen component is designed as boost converter, which defines that the converter is only capable of boosting the input voltage to a higher output voltage. The maximum output voltage is given by 780 V, but was further limited to a voltage level of 720 V to not exceed the voltage limits of the component under dynamic conditions.

The input voltage range of the DC/DC converter has to match with the operation voltage range of the fuel cell system, which is defined by the arrangement of cells in series within the stack, which also effects the efficiency characteristic of the fuel cell system.

Generally, the efficiency characteristic of a fuel cell system shows the highest values at low power levels and decreases with increasing fuel cell output power. By arranging more cells in series, the higher efficiency range can be shifted to higher power levels. This correlation can be used to shift high fuel cell efficiencies to the main operation range within the final application and therefore to increase the hydrogen efficiency of the vehicle.

Another aspect is that the cell voltage and therefore the fuel cell system voltage increases with decreasing power, which defines a limit for the minimum power level of the fuel cell system. If the fuel cell power goes below this minimum power level (defined as idle power) the cell voltage exceeds an upper limit, which leads to a higher degradation of the fuel cell. By increasing the number of cells in series this limit is also shifted to higher values, which limits the usable

operation range at lower power levels but increases also the maximum power of the fuel cell system.
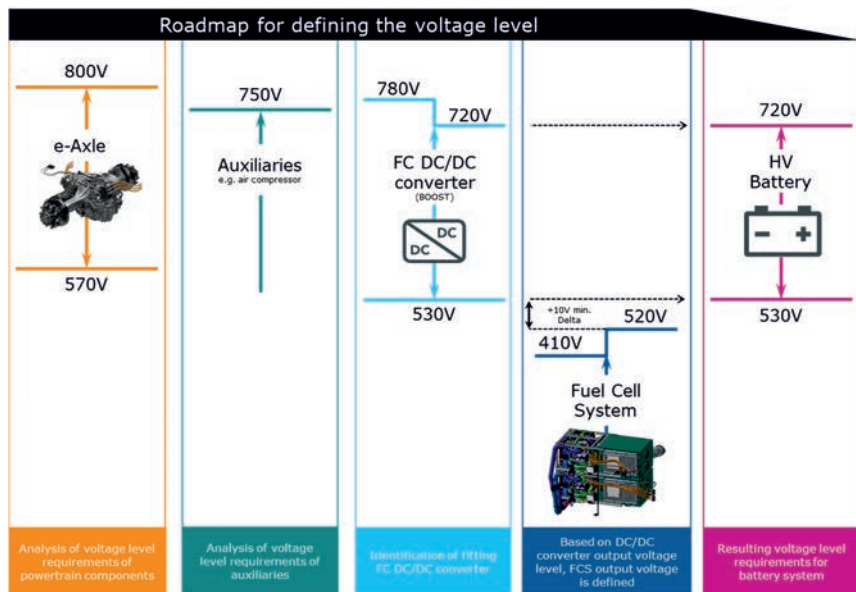

Fig. 3: Overview of the voltage levels in the E/E architecture

Beside these peculiarities of the fuel cell also the packaging in the vehicle limits the maximum number of cells, as this increases the overall component size.

Additionally, the availability of the balance-of-plant (BOP) components can limit the maximum size of one fuel cell system, because e.g. the required mass flows for hydrogen or oxygen cannot be supplied.

By considering these aspects the final arrangement was defined, which gives a voltage range of 410 V to 520 V for the fuel cell system. To boost the fuel cell voltage to a higher HV circuit voltage the DC/DC converter needs a certain difference between input and output voltage. In our case this was a delta of 10 V.

Summarizing this boundary conditions, the HV battery has to fulfil a voltage range of 530 V to a maximum of 720 V, to meet the requirements of the other HV components.

Beside the voltage range the main requirements for the selection of the HV battery are the useable capacity, the allowed power limits for charge and discharge power, packaging space and lifetime targets. To find a suitable battery different options can be followed. Using an off-

the-shelf component allows lower development costs and time but makes the challenge to find a solution that fits into the installation space and meet all requirements more difficult. Developing a battery pack for the specific application enables the highest flexibility to best fulfil the requirements, but with higher investment costs and development time. A promising solution is the use of off-the-shelf modules for the development of a battery pack which allows to find a suitable solution with a reduced development effort.

In the case available components do not fulfil the requirements, for instance the power capabilities are not sufficient, it might be possible to integrate two or more components to meet the required specification. Using multiple, but smaller components, e.g. for the PDUs, can enable additionally benefits for the packaging in the vehicle, but might have a negative impact on vehicle weight and complexity of the E/E architecture.

Energy management for fuel-cell powered heavy duty trucks

In parallel to the E/E architecture, the development of an energy management strategy supports to optimize the entire system capabilities and enables the best use of the system. The energy management strategy must be adaptable to the main customer requirements regarding usage of their commercial vehicle fleet, as:

- Efficiency: minimal mission energy consumption, resulting in minimal energy costs
- Durability: minimal mission component wear, resulting in minimal components costs
- Availability: optimal use of system components, resulting in best vehicle performance

These three targets are not exhausting but show some of the main objectives that have to be met by the control strategy. This means that there is no global optimum in general that satisfies all single targets best with one strategy, but the best balance between different mission targets must be found to match the needs of the customer.
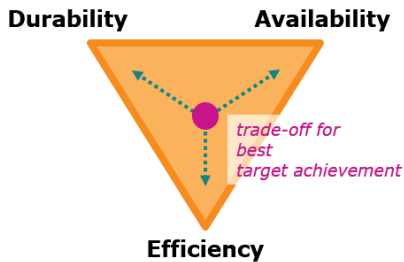
Fig. 4: Trade-off of operation targets

The development of an energy management control requires a comprehensive knowledge about the characteristics of the powertrain components and the energy flow within the system, considering the different power sources (fuel cell system and HV battery in this application) and all consumers.

Hybrid powertrains in general offer the possibility to utilize different power sources to meet the requested power demand. This can include the split between multiple e-machines to supply the requested wheel power demand or the split of electric power demand of the system between different power sources like fuel cell and HV. These possibilities to control the energy flow are degrees of freedom in the system which alows the energy management to set the power split based on the operation strategy to achieve different targets.

Looking at energy aspects of above given system, the fuel cell system is an energy source, which cannot store energy coming from the drivetrain. This is the reason why a HV battery, much smaller than in battery electric vehicles, needs to be installed, which is an energy source and energy storage as it can also store recuperation energy during braking manoeuvres.

To achieve the global mission targets an optimal power split between fuel cell and battery, which is the main control variable, needs to be found as it defines further the operation points of the components and therefore the system efficiency. A key factor to achieve a high system efficiency is to utilize most of recuperation potential and therefore it has to be ensured, that the HV battery is capable to store all available energy, which can be limited if the HV battery state of charge (SOC) reaches its maximum allowed SOC level.

Another target is to maximize the available system performance, which requires that the battery can supply energy under all conditions, which requires a sufficient HV battery SOC.

All these facts highlight the importance of an optimal control of the SOC of the HV battery as major task of the energy management. [2] Additionally to the targets of the fleet operator the demands of the driver still have to be fulfilled (power demand, system response time, noise-vibration-harshness (NVH), ..) which reduces possible degree of influence exerted by the energy management.

Model-based hybrid powertrain control software development

Looking at diverse vehicle requirements and operation targets the complexity of the operation strategy for a fuel cell truck application gets visible and shows the need for a flexible and comprehensive development approach. It can be seen that beside the proper definition and sizing of system components the operation strategy plays a major role to achieve global system targets. Using model-based development from an early stage on helps to find the most optimal system design and system control for different applications.
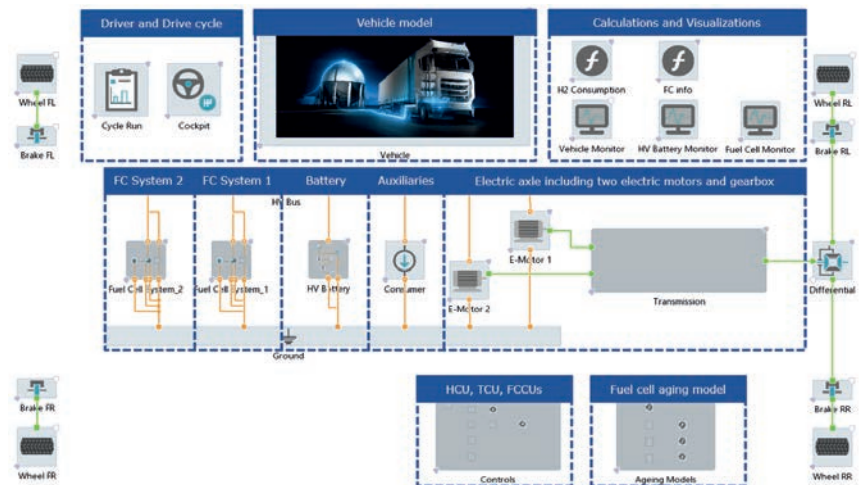
Fig. 5: Powertrain model within AVL Cruise M

For this project the powertrain was modelled in AVL Cruise M®, which offers the possibility to model the mechanical transmission including the e-axle, the electric circuit with fuel cell system and a HV battery model and the hybrid controls within a single environment.

The vehicle model considers longitudinal vehicle dynamics. The e-axle is modeled including the efficiency map and full load characteristic of e-motors and inverter efficiency. The fuel cell

system models are calculating the amount of consumed hydrogen considering the fuel cell efficiency. The electrical battery model is based on an equivalent circuit model including internal ohmic resistance characteristics, considering charging and discharging losses. To enable a logic for power derating from peak to continuous level of battery and e-motors, if upper temperature limits are reached, a thermal model of the VTMS is used. The calculated battery temperature is used as input to the electrical battery model, to include the temperature dependency of the internal resistance. Furthermore, the VTMS model calculates the auxiliary power demands for cooling fans and pumps in high detail. Additionally, vehicle auxiliaries are modelled separately (e.g. brake air compressor) or are integrated as component typical constant power values (e.g. steering pump).

The shown simulation environment allows to investigate the impact of different operation strategies of the energy management on hydrogen efficiency, system performance and component aging in short time and in high detail. To meet the lifetime targets of fuel cell and battery the operations strategy and especially the power split has a huge impact [3].

Using the environment with different use-case scenarios for this application, it is possible to derive optimal operation strategies for each mission target.

Development of non-predictive and predictive hybrid powertrain control software

Non-predictive controls define setpoints of a powertrain e.g. power split between energy sources based on the operation strategy using actual vehicle signals and the current output power demand. In contrast to that predictive controls are using information about the road ahead to calculate optimal operation setpoints for the powertrain components for the upcoming driving mission.

To achieve a high operation efficiency and to ensure a sufficient SOC of the HV battery under various conditions a non-predictive control needs to use certain modes, which allow the operation strategy to react if the SOC of the HV battery is reaching the limits. This means that the system is forced to deviate from an efficient operation mode to a charging or discharging mode, which shows that reaching a global optimum under all operation conditions is not possible.

Using predictive data about the route ahead enables to optimize the system operation in order to find the optimum for diverse driving missions and to avoid reaching the limits of the system. This data can be used to include a multi-objective optimization considering different mission targets into the operation strategy, which increases the flexibility for different operation requirements.
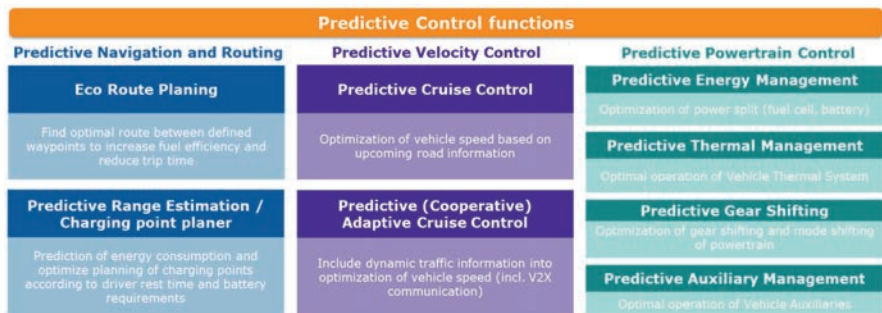
Fig. 6: Overview of predictive control functions for a fuel cell electric truck

This optimization is formulated using a cost function, which includes the objectives to be optimized in one context. By balancing of the different targets in the cost function, the optimal operation strategy over the driving mission ahead can be found. An exemplary formulation of a multi-objective cost function is given in Equation 1, which includes sub-costs to charge efficiencies deviating from the best point and a second exemplary term to add costs for additional objectives, e.g. the transience in the fuel cell power request. The weightings w_1 and w_2 in this formula represent the weightings to balance the different sub-costs to achieve a balance between different optimization targets.

Equation 1: Example of a multi-objective cost function

$$Costs = \int_{t_0}^{t_1} \left(w_1 \left(\eta(t) - \eta_{max} \right)^2 + w_2 D(t) + \dots \right) dt$$

Identifying which predictive functions, for example predictive energy management (PEM) or predictive battery thermal management (PBTM), are required or beneficial in a certain application, is one the first steps in the predictive control development. In a next step, the overall control architecture has to be developed and the interactions between the functions have to be defined, which is one of the main challenges. The predictive control architecture sets the interfaces between different predictive functions and shall be designed in a way that global system targets are achieved and real time capability and the implementation on the target hardware can be assured.

Generally predictive functions require a certain prediction horizon (distance or time basis) that is needed to realize a certain functionality. Depending on the predictive functionality and the related system properties a certain horizon length is required, to be able to predictively act or

pre-condition a system before a certain event occurs. On the example on the predictive energy management this can be a high-power demand due to an uphill section, which requires that the HV battery is loaded before this section is entered.

The overview of control levels in Fig. 7 shows that the optimization task can be split up to two different levels of long range and short range optimization. In general, the long-range optimization uses a longer horizon up to the entire route and is executed before the vehicle starts the driving mission. The results of the long-range are input to the short-range optimization, which is implemented in the vehicle software and finally optimizes the control variables that are handed over to the real time control.
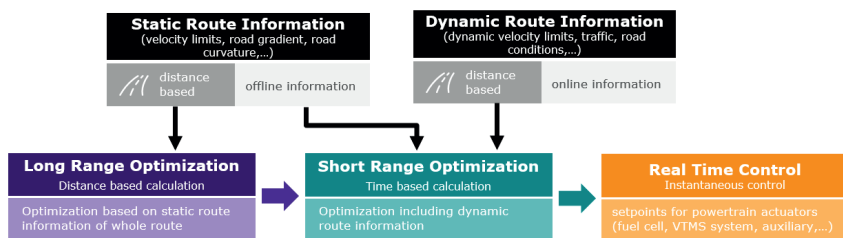
Fig. 7: Overview of control levels

The short-range horizon is limited to a few kilometers (e.g. 4 km), whereas longer horizon length up to knowledge of the entire route is defined as long-range. Within this project the focus was set to predictive energy management (PEM), predictive battery thermal management (PBTM) and predictive auxiliary management (PAM). For the fuel cell system, a predictive control of the cooling fan is considered to firstly address the instantaneous cooling demand based on the output power and secondly to optimize the NVH behavior. In contrast the battery has a higher thermal mass and allows to shift cooling operation on the time horizon, which allows also to pre-condition the battery before higher power demands.

The "Long-Range Optimization" can be executed online in the vehicle or offline in a cloud or locally within the fleet management system and uses static input data of the entire driving mission. This includes inclination and curvature profile, as well as static speed limits of the route. In a first step the velocity profile over the route has to be estimated to calculate the drive power demand of the vehicle.

The short-range optimization returns the calculated optimal power split for fuel-cell and HV battery, HV battery cooling power and control of the brake air compressor and hands over the information to the real time control, which finally defines the setpoints for the components.

The architecture described was implemented in Matlab® Simulink and integrated in the simulation model in AVL Cruise M®.

An exemplary simulation result on a typical Austrian highway route from Graz to Wiener Neustadt and back, is shown in Fig. 8, which compares the predictive controls approach to a non-predictive hybrid strategy. The simulation was done for a 42 to HD long haul truck.

The main differences between a non-predictive strategy and an advanced predictive energy management are highlighted in green and orange and are visible on the different trajectory of the HV battery SOC shown in the plot. Sections in green color show cases where the predictive controls act in advance to charge the battery to enable support by the battery for the upcoming uphill section, shown in orange. Based on the power prediction of the vehicle for the route ahead predictive controls is able to shift power demands over time to optimize the operation points of the fuel cell system, which leads to an optimized hydrogen efficiency. The plots in the lower area display the time shares over the entire power range of the fuel cell system, which show that the share at high to maximum fuel cell system power can be reduced significantly by a predictive energy management system. The increase of the mean efficiency of the fuel cell system over the entire cycle is given in the plot, which show an improvement from 49.35 % with the non-predictive control strategy to a higher mean efficiency of 51.49 % with a predictive management system. The potential that can be utilized is highly depending on the driving cycle and the characteristic of the system components. Generally a high benefit can be achieved if the driving mission allows to shift temporarily high electric power demands (e.g. during uphill driving) which would force the fuel cell system to operate at maximum power with poor efficiency to other time sections, which lead to a shift of the operation points closer to the high efficiency area at lower power levels. This effect can be also clearly seen in the exemplary simulation result when looking on the time share in the lower boxes.

Beside an increase of efficiency also a positive impact on the lifetime of the fuel cell can be achieved, which can be concluded based on the reduced time share of the fuel cell at zero power and idle power due to predictive control. Operating a fuel cell for longer timer at idle power can cause degradation, as well as shutting down the fuel cell. In Fig. 8 it can be seen that both the time share at zero power (shut-down) and idle power is reduced by predictive controls, which has in both cases a positive impact on the fuel cell degradation.
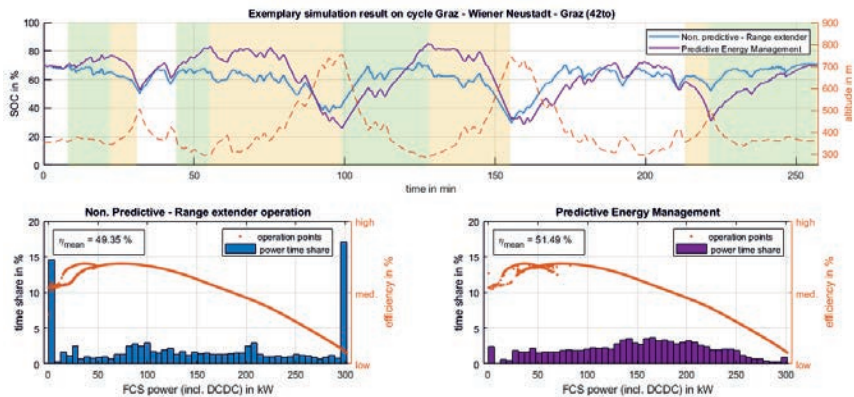
Fig. 8: Comparison of simple rule-based and predictive controls

Summary and outlook

Upcoming strict CO_2 emission legislation pushes the commercial vehicle industry to develop emission free/neutral trucks . One technological approach to reach future legislative goals are fuel-cell powered commercial vehicles. A fuel-cell powertrain for a HD truck provides not only the required electrical power but provides it also at very attractive system efficiencies. However due to the relative complex sub-system interactions the design and optimization of the E/E architecture as well as the powertrain controls are rather challenging.

Within this paper the main steps of the development of such an architecture were shown and the potential of an optimal operation of this system was described.

After conceptual design of the E/E architecture AVL developed a fuel cell powered commercial vehicle powertrain using an AVL fuel cell system and an AVL e-axle combined with off-the-shelf components.

Beside the development of the E/E architecture the optimal operation of this complex powertrain is required to meet the operation targets, which offer a great potential for advanced hybrid operation strategies, especially for predictive control systems. By the use of model-based development (MBD) the entire development process can be efficiently supported to find the optimal components and to develop and optimize control strategies to fulfill the overall mission targets:

- Optimized product cost
- Optimized operating cost
- Optimized operating strategy

Expecting further developments in the area of fuel cell BOP components - e.g. specific compressor and humidifier designs for high-power fuel cell systems - the overall fuel cell powertrain system performance will be further improved in future. Additionally, the availability of DC/DC converters for power levels up to 150 kW will improve, which will enable a higher flexibility in the design of the E/E architecture for HD truck applications.

For the battery the LFP (lithium iron phosphate) cell type is a promising option. It offers not only high power capabilities, to ensure the best use of the recuperation energy, but also enables sufficient lifetime to reach the durability requirements. Additionally, the quite safe cell chemistry supports the cell-to-pack design approach, which allows a compact packaging and reduces the disadvantage of the lower energy density of LFP cells.

In this project, AVL was able to show the close link between the definition of powertrain components and the powertrain control strategy. They jointly influence critical parameters like vehicle performance, vehicle packaging, energy efficiency, component lifetime and finally total cost of ownership.

First results already indicate, that predictive controls enable a broad further optimization potential to best fulfill diverse operation targets. With the developed models, predictive control algorithms and methods, AVL has established a toolchain which not only supports the development of fuel-cell powertrains for commercial vehicles, but all kinds of electrified powertrains. It enables AVL to support its customers comprehensively and efficient in the design and development of optimized powertrains for commercial vehicles.

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Tire contribution to truck sustainability – Roadmap to 2030

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Abstract

The truck tire rolling resistance is now facing to a new stake with the VECTO CO2 regulation and the targets given for 2025. Even if the tire is an interesting lever to help truck OEM to reach the target, the end user fleets are not kind of low rolling resistance tires and specify other tires when they buy new trucks.

When using tire technologies to enhance the tread wear and losses efficiency, the tire manufacturers are able to reconciliate the OEM and end user expectations.

By addressing both needs, the truck life cycle analysis is better leading to a global improvement of road freight environmental footprint.

Introduction

Climate change due to CO2 emissions is considered by far as the priority among all the sustainability criteria while air and water pollution come behind. Truck is the second CO2 emissions contributor after cars in the transport sector and use phase is by far the biggest part.

The European regulation 2019/1242 forces truck makers to decrease CO2 emissions by 15% in 2025 and 30% in 2030 through penalties that will raise to 6800 € per g/t.Km per truck sold above the threshold. Long Haul trucks (5-LH segment representing 68%

SHARE OF EU GREENHOUSE GAS EMISSIONS*, BY SECTOR

of CO2 emissions) sold in 2020 emits in average 56,5 g/t.Km CO2, then there is a need to decrease from 56,5 to 39g/t/Km CO2 by 2030 (Δ = 18 g/t.Km CO2 for that category).

What is the tire rolling resistance?

The rolling resistance of a tire is a drag force which is the consequence of energy losses in the tire. It is characterized by the rolling resistance coefficient (RRC), which stands for the rolling longitudinal resistive force due to the tire divided by the load carried by the tire. When the tire is rolling, it generates heat because it is made of rubber materials that are stressed and have viscoelastic

properties. This heating is the consequence of a loss of energy that creates the resistance force at the wheel center.

The dissipation of viscoelastic materials is highly dependent on many parameters: temperature, frequency, strain; so, it is not easy to model actual rolling resistance as it can vary a lot depending on usage conditions.
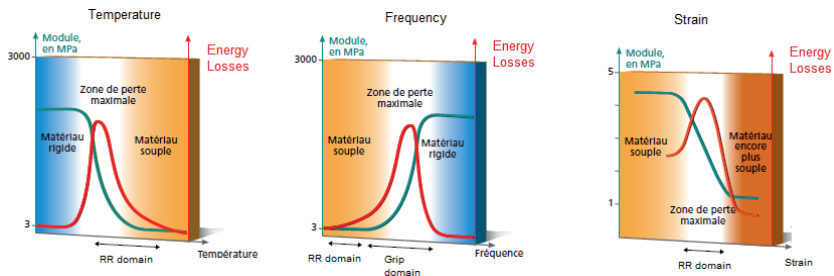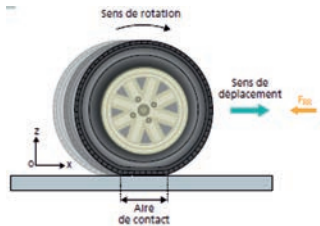
The rolling resistance is driven by several mechanisms, each one leading to specific design levers for RRC reduction. For truck tires, we can consider the 3 following mechanisms:

- Shear
- Compression
- Flexion

The strain rates plotted on the opposite figure explain why the tread compression and shear are identified as the main contributors to rolling resistance.
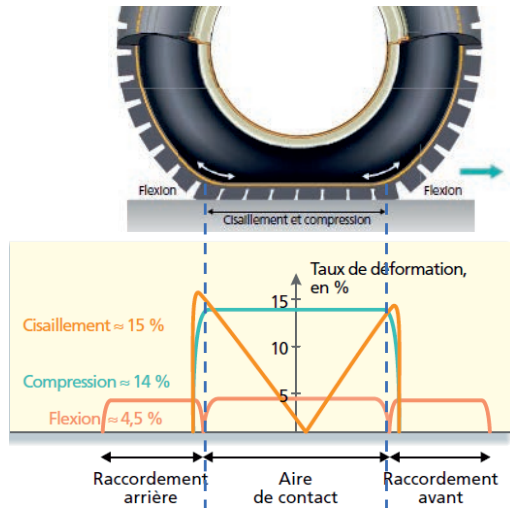
The result of a thermomechanical FEM calculation gives the energy dissipated per tire zone and confirms that the main contributor to the RRC is the tread; there is thus a big compromise to tune through the tread volume between RRC and tire mileage.
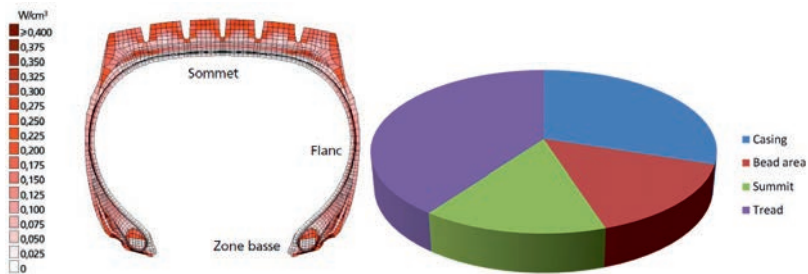
The RRC is a parameter that is measured on a test drum following a standard procedure and standard conditions (ISO28580), for a truck tire:

- Speed = 80kph
- Load = 85% of load index
- 3 hours warm up phase
- Ambient temperature = 25°C
- Pressure = nominal pressure as per tire markings
- Smooth steel drum as opposite
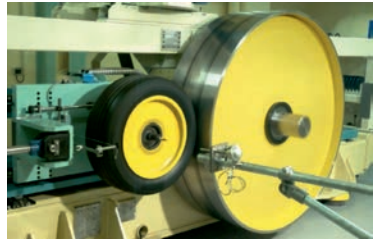
The RRC is then measured with a standard test in analytical laboratory conditions, but the reality is a bit different since:

- The actual load on the tire differs from the 85% of load index that is applied in the ISO test conditions.
- The pressure recommendations are sometimes different from the maximum pressure of the test to fit with the actual load and optimize the tire mileage with the most even wear.
- The speed of the test (80kph) is not far away from the trucks' average commercial speed in Europe (75kph).
- The actual average ambient temperature (15°C for Europe in average) is highly different from the test conditions (25°C) and it has a very significant impact on the RRC.
- The transient RRC before the tire reaches a stabilized thermal state must be considered as well.
- Real road roughness and flatness differ from the smooth steel drum.

If we consider realistic values for all the real-life trip parameters, we can, for example, expected from a European drive tire to have a real RRC value increased by 0.7kg/t from ISO value at 5kg/t at new stage. Considering this bias for all tire positions, it represents a fuel consumption increase by 5% or 1.5L/100km.
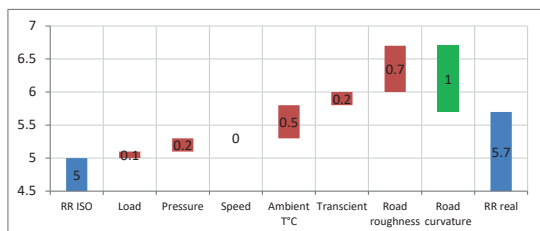
Furthermore, real life RRC is affected by tire wear. Since the tire wears itself, there are less losses in the tread, then a lower RRC. It is by far the most impacting parameter on real life RRC, since the tread represents 40% of RRC.

Truck tires RRC contribution to vehicle CO2 emissions reduction
The scheme to reduce the trucks CO2 emissions in Europe is based on Vecto. Some technologies are necessary to achieve the goal and the low rolling resistance tires has the advantage of a plug and play solution.

For a European truck combination tractor 4x2 and semitrailer in long haul usage at 40t GCW, the power required by the tire accounts for 30% to 45% of fuel consumption:
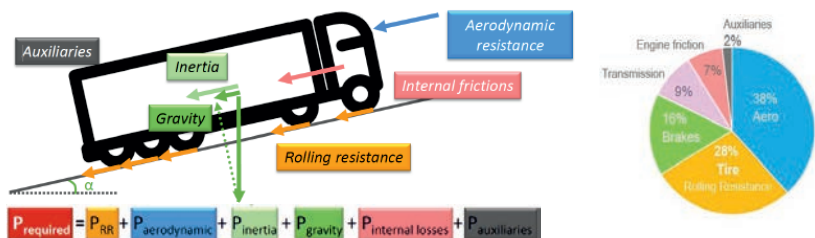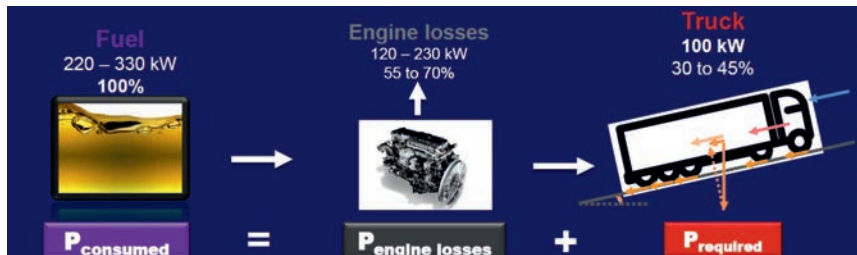
Michelin has defined a simple estimating equation to predict FC gain due to RR reduction:

$$\Delta FC = \alpha \times M \times \Delta RRC$$

ΔFC   Fuel consumption delta, in L/100 km

α   Coefficient, in L/100 km/kgm in range and [0.033-0.053] for heavy trucks

ΔRRC   Difference of rolling resistance (ISO 28580), in kg/t

M   Vehicle mass, in ton

The alpha coefficient is the sensibility of fuel consumption with reference to RRC and is defined by the following equation:

$$\alpha = \frac{g}{\eta_{trans.}\,\eta_{th.}\,PCI_f\,\rho_f} \cdot \frac{d_{mot}}{d} \cdot 100.$$

g   gravity acceleration [m/s²]

$\frac{d_{mot}}{d}$ ratio of total distance travelled under engine torque []

η_{trans} transmission efficiency []

η_{th} engine thermodynamic efficiency []

PCI_f fuel energy [kJ/kg]

ρ_f fuel density [kg/L]

This formula is very well aligned with the results given by Vecto and RRC sensibility analysis and finally leads to a fuel consumption reduction by 1.7L/100km (45gCO2/km) for a RRC reduction of 1kg/t on all tires of the convoy at 33t GCW (tractor and semi-trailer) , then nearly 1.5g/t.km.

**Low RR Tire can reduce HDV CO2 emissions by 3% out of 30% target for 2030**

In the past 10 years, premium Long-Haul tires Rolling Resistance has been improved by 20%.

Moving from 5,0 N/kN to 4,0 N/kN. According to Vecto simulation and the physics of longitudinal dynamics of a truck, when the tire rolling resistance is reduced by 1 N/kN, there is a gain of 1.5 g/t.km CO2 Truck in Vecto 5LH usage conditions.

Rolling Resistance / European Tire Lines

Most of the new trucks sold today are not equipped with the most energy efficient tires.
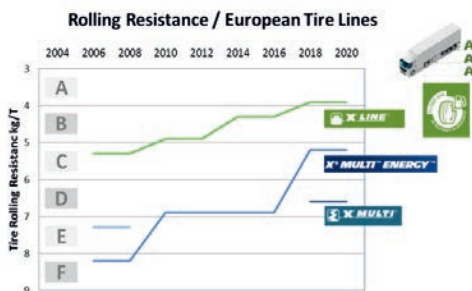
Below, is presented the statistic distribution of 5-LH RRC Vecto use in the 2019 monitoring Period to set up the Vecto baseline :
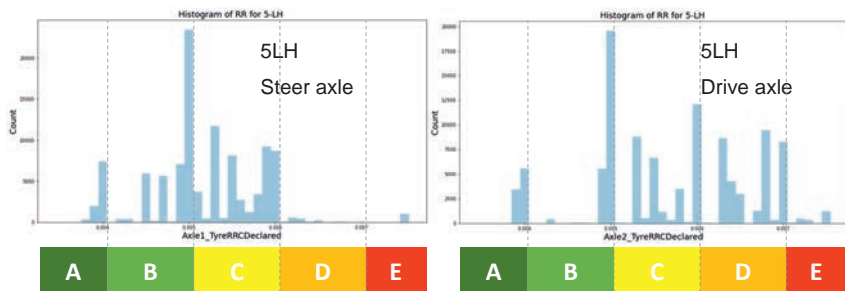

The proportion of low rolling resistance tires is still very low! But if those trucks were be equipped with the lowest Rolling Resistance tires already available, emissions would immediately drop by 1 g/t.km CO_2 out of the 18 g needed for 2030 (i.e -1.5 point out of the -30% requested by E.U).

New generation of low RR tires are under development by the different premium tire makers. It will help to drop by another 1g/t.Km CO_2 by 2030. Cumulating these 2 effects makes 3 points out of the -30% requested by E.U.

**Fleets prefer Conventional Tires rather than Low Rolling Resistance Tires**

Regional distribution usage is more severe than highway long haulage and requires tougher tire design and compound. Thanks to higher tread depth and tougher compound, regional distribution tires have higher mileage, better traction (uptime) and robustness.
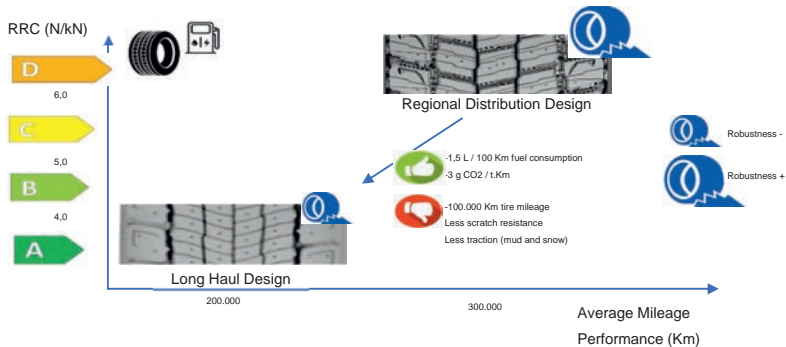
The fleet total Cost of Ownership (TCO) is mainly driven by fuel and tires purchasing account for a small part. Nevertheless, mileage is the easiest tire performance that can be assessed by end user because much easier to monitor.
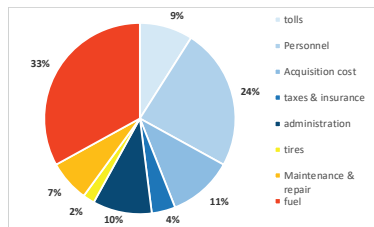
Indeed, fuel consumption improvements through RRC reduction are more difficult to quantify due to dispersion and trip dependency. Indeed, we have quantified the fuel consumption dispersion for a given control truck doing same trip, same hour, same payload. See opposite, the fuel consumption varies +/-2L/100km due to several parameters as weather, traffic conditions, driver behaviour etc, ...
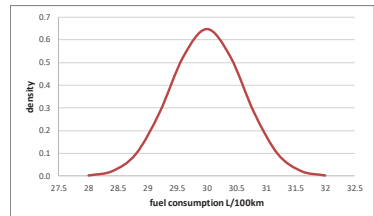
Then for most of the fleet owner, mileage is one key parameter to assess the value of a tire, and secondly the robustness in terms of endurance or traction to limit downtime. Therefore, most of the fleets prefer to order new trucks with long lasting tires rather than low rolling resistance tires.

We come to a paradigm where the truck manufacturers are requesting tire manufacturers to reduce de rolling resistance for CO_2 emissions reduction targets with a limited requirement on tire mileage, and in the same time the fleet operators, who are more able to measure tire mileage than tire RRC impact on fuel consumption, are expecting longer lifespan for tire and improved robustness.

Rolling resistance is evolving (nearly 30%) with the level of tire wear (e.g. 16mm tread depth new vs. 1,6 mm legal minimum). The more the tire is worn, the lower its rolling resistance. Unfortunately, on average, transport companies are dismounting their tires when they still have 4,8 mm tread depth whereas they could legally go to 1,6 mm. 20% of the usable part of the tire is thus not exploited. Worse still, that's when it is at its best energy efficiency level; doubling of negative effects from material waste and loss of energy efficiency. Following tire wear is indeed complex and expensive for fleets via manual inspection. They often prefer to change their tires too early rather than too late, to avoid safety risks and police fines. Time, money, and CO2 could be saved if end of life date for tires could be automatically predicted and communicated to fleets, allowing them to optimize and regroup tire changes with other maintenance operations.

Green tire without treadoff possible through technologies

When a manufacturer wants to improve rolling resistance, the challenge is to maintain the wear lifetime and the grip, which is possible only if innovative tire technologies are used in the design like tread material, tread geometry, casing architecture.

Due to the high contribution of tread in RRC and the big part of losses in that area due to tread compression, to achieve -1kg/t on a tire, without smart design, there will be an impact of:
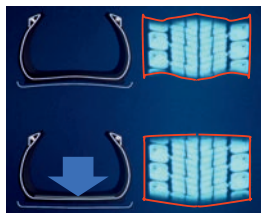
- -30% mileage
- -15% grip
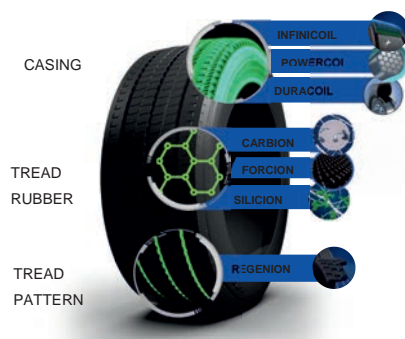
Thanks to following technologies, X Line Energy D2 offer the best mileage at same RRC (<4kg/t):

- Silicion: silica reinforcement of rubber instead of carbon blacks for improved RRC without wet grip trade-off. The losses are more balanced :
    - High losses at high frequencies for grip
    - Low losses at low frequencies for RRC
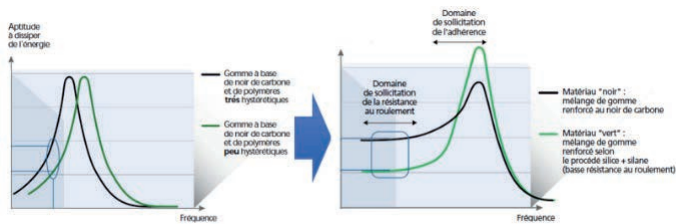
- Regenion: evolutive tread design with hidden channels to handle wet grip and RRC by a more compact tread design thanks to 3D metal printing molds. This technology allows to keep the same quantity of rubber to wear while reducing tread depth. In depth hidden grooves boost traction when the tire is worn.

- Infinicoil: a steel cord reinforcement of the summit plies to improve contact patch shape then mileage limiting RRC trade-off.

Here we present the results of tire mileage field in a fleet where several trucks are doing the same usage. 4 tire brands are compared on their 315/70R22.5 low RRC steer and drive tires. The 4 tire brands are regularly changed from one truck to the other to randomize the usage/driver effects:

Tire mileage test results. Steer and Drive Tractor Tires
Long Haul – A Fuel Label - 2019- 2021
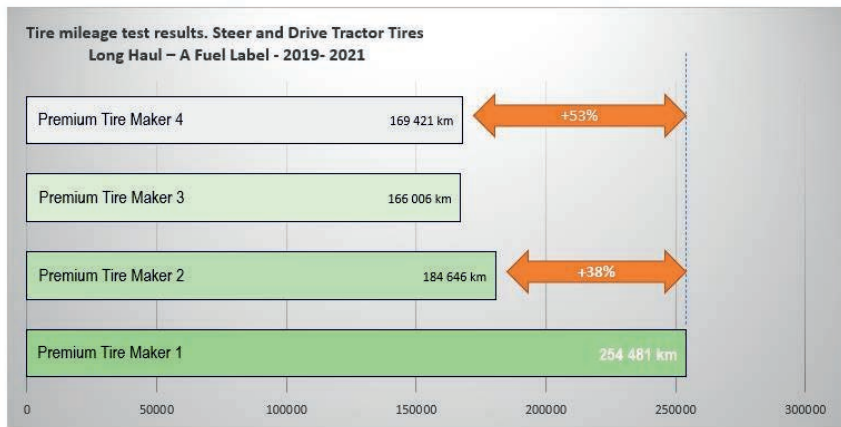
The most performing tire set achieved 38% more distance before wear removal than the second thanks to tires those technologies embedded.
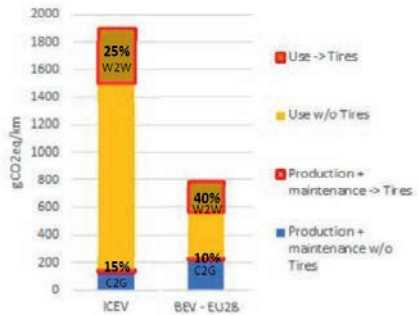
Life Cycle Analysis (LCA)

Truck Life Cycle Analysis shows that tires count for:

- 25% of the equivalent g CO2 / Km usage part (Well to Wheel)
- 15% of the production part (Cradle to Gate).

With electric truck powertrain, the part of tire will move to:

- 40% of the usage (Well to Wheel)
- 10% of the production (Cradle to Gate).

Then for the electric trucks going to be launched on the market in coming years, the tire weight in the LCA is increased what leads to new horizon of codesign between the truck and the tire.

In addition to the increasing share of bio-sourced, recyclable, recycled materials in tire composition, Digitalization will also play a role in the improvement of tire and truck sustainability.

Indeed, today, only 30% of European transport companies are retreading their used tires. Most tires are disposed of after 250.000 km, whereas their structural design (to resist 9 bars air pressure) allows their casing to run 1 million km.

However, the lack of automated traceability makes retreading operations complex.

Since 2019, 99% of the Original Equipment tires supplied by Michelin to European truck makers are equipped with RFID. The work done by the European Tire and Rim Technical Organization (ETRTO) to normalize RFID micro-chips in tires will allow tire makers to provide a better level of service to fleets with regards to tire management and sustainability.

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Consumption-optimized planning of transport missions using virtual drives

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Abstract

This contribution introduces work from the European LIFE project ECOTRAVID (project number LIFE18 CCM/FR/001095; homepage: www.ecotravid.eu). The project deals with the development of algorithms and the integration of a compute service for consumption-optimized route planning into the existing environment of a transport manager. It is based on the "Virtual Measurement Campaign" (VMC®) software developed at Fraunhofer ITWM and supposed to reduce the consumption of heavy goods vehicles and the associated CO_2 emissions. To achieve this, realistic vehicle models for trucks/trailers and the influence of the driver are taken into account. In addition, the algorithms use real world data, including the course of the road itself, but also influencing factors such as topography or traffic. The simulations enable detailed calculations of consumption and energy losses for specific transport missions, including the analysis of different types of losses (air, rolling and gradient resistance).

The service was integrated into the fleet management platform of the French project coordinator Collecte Localisation Satellites, which is a dynamic planning and decision aid tool for fleet management in road traffic and suggests the most cost-effective route and truck/trailer configuration for a specific transport mission. To demonstrate the efficiency of the innovative tool, a two-stage pilot test is carried out with 20 trucks and 20 trailers provided by the French project partner Groupe SAMAT SA under normal operating conditions and for various transport tasks.

1   Introduction

Road transport plays an important role in the discussion about reduction of GHG emissions since it is responsible for approximately 25% of the emissions and this contribution is even expected to grow. While much effort is put into the development of alternatives to a combustion engine, the latter will still be used for many years. Well known reasons are, for instance, the fact that alternative drivetrains are not yet in a state to fully replace conventional trucks and this applies also to railway or other types of transport.

The LIFE project ECOTRAVID aims at reducing the required energy for road transport by integrating realistic models for consumption prediction (virtual drives) into planning tools of logistics companies. The models and algorithms used within ECOTRAVID are based on the VMC® technology developed at Fraunhofer ITWM and some dedicated enhancements. The Software VMC® contains algorithms for estimating a vehicle's speed profile based on models for the driver, the vehicle, and the route (see [1]). In ECOTRAVID, this context is referred to as virtual drives. The kernel of this approach is the vehicle model for longitudinal dynamics. In addition, the driver's behavior is reflected as well as the properties of the route and traffic. The goal of the project is to adapt and enhance available algorithms to obtain a realistic consumption estimation on arbitrary routes including traffic effects.

Within the planning tools of a logistics company, routing algorithms are applied to find directions for the transport tasks. Standard routing algorithms usually suggest the trip with e.g. minimum distance or minimum travelling time. But also the altitude profile of a route has a large influence on the fuel consumption. Thus, a simplified consumption measure is introduced and combined with truck restrictions to parametrize a special energy-saving truck routing giving a further route alternative. Afterwards, the speed profile simulation including traffic information can estimate the consumption on all connecting routes and the most suited can be selected. In addition, different kinds of losses (air, rolling and slope resistance) can be identified, which may be used to assess for instance, how large the benefits of a potential reduction of the air resistance or the rolling resistance would be in a certain mission. All those features apply not only to conventional trucks, but may be applied beneficially to all kinds of road transport.

In principle, we could use the detailed simulation models within the optimization of the routing algorithm. However, this would slow down the routing drastically. Therefore, we combine the routing enhancements with the simulation capabilities in a two-step procedure:

1. The consumption oriented routing provides alternatives, which are supposed to save fuel by utilizing a simplified model.
2. We apply the more involved simulation models to the route alternatives in order to rank the alternatives with higher accuracy.

During the project, the virtual drives are integrated into an online monitoring and decision-support tool used by transport managers at logistics companies. The toolkit will support decision making to choose the cost-optimum route to take and the optimum truck/trailer configuration for a specific transport mission.

In order to calibrate the models and later validate the results, data from 20 trucks and 20 trailers operated by the project partner Groupe SAMAT SA under normal service conditions and for different transport missions is analyzed and evaluated.

This paper is organized as follows. We start with a brief introduction of the simulation capabilities and the features for modelling vehicle, driver and traffic effects in section 2. In section 3, we introduce our approach for the consumption-oriented enhancement of routing algorithms. Chapter 4 briefly describes the measurement campaign and some aspects of how to use the data for the calibration of the simulation models. In chapter 5, we briefly sketch the integration of the virtual drives into the planning tool as provided by CLS. Finally, section 6 summarizes the (intermediate) results so far and gives an outlook to further steps.

2   Basics of the speed profile generation

VMC® Simulation is a module within the VMC® Suite providing simulation methods for the vehicle performance on arbitrary routes. The basic idea goes back to [1]. This section briefly reviews important properties of the approach to an extent, which is necessary to understand all features relevant for ECOTRAVID, and introduces some recent enhancements. To this end, we introduce some notation: $s \in [0, L]$ denotes the position s of a vehicle on the route with length L. v resp. a_x denote the vehicle speed resp. the longitudinal acceleration. $\alpha(s), \kappa(s)$ denote the slope and the curvature along the route. The basic equation of the longitudinal dynamics is

$$F_{dr} = F_{air}(v) + F_{roll}(s, v) + F_{slope}(s) + F_{acc},$$

where the different driving resistance forces are $F_{air}(v) = \frac{\rho_{air}}{2} \cdot c_w \cdot A \cdot v^2$,

$F_{roll}(s) = m_{veh} \cdot g \cdot f_{roll} \cdot \cos \alpha (s)$, $F_{slope}(s) = m_{veh} \cdot g \cdot \sin \alpha(s)$, $F_{acc} = m_{veh} \cdot a_x$ and F_{dr} denotes the total driving force, which keeps the vehicle traveling with acceleration a_x at speed v against air, rolling, slope, and inertia resistance. The parameters in the formulas are air density ρ_{air}, air resistance coefficient c_w, effective front area A of the vehicle, total mass m_{veh}, gravity g, and rolling resistance coefficient f_{roll}. The driving force F_{dr} is limited by the maximum friction between tire and road.

2.1   Calculation of speed limits

The speed of the vehicle is limited due to various constraints. We start with the limit $v_{max,DB}(s)$ due to legislation as stored in the VMC® database. This is multiplied with a driver and road type dependent factor $\gamma_{rt}(s)$ close to 1, which models the driver's willingness to follow the

legislation. In addition, we use another factor $\gamma_{slope}(s)$, which models speed variations due to slope (a bit slower uphill, a bit faster downhill). On top of the resulting limit signal, we add stochastic fluctuations based on an AR1-process $X_{driver}(s)$, which represents the driver's imperfection (see [2] for a description of the process). Next, we derive an upper traffic dependent speed limit $v_{max,traffic}(s)$ from the average spatial density $D_{veh}(s)$ of vehicles on a road segment in combination with a safe distance rule as follows. We define $D_{veh}(s)$ as a constant value per road segment and add random fluctuations $d_{veh}(s) = X_{traffic}(s) \cdot D_{veh}(s)$ to get a more realistic setting. Here, $X_{traffic}(s)$ is a stationary random process (log-AR1 process). From the traffic density, we calculate the distance to the vehicle ahead, which in turn leads to a maximum speed due to a safe distance rule. See [2] for more details.

Speed reduction due to cornering is modeled by $v_{max,curvature}(s) = \sqrt{\frac{a_{y,max}}{\kappa(s)}}$, where $\kappa(s)$ denotes the curvature at position s. The maximum lateral acceleration $a_{y,max}$ is the minimum of the desired lateral acceleration defined in the driver model and a vehicle dependent limit.

Finally, we randomly select stopping points and weighting time out of a list of all stop events stored in the VMC® database.

The minimum of all those limits serve as an upper bound $v_{max}(s)$ for the speed profile to calculate in the following. It reflects by construction all route and traffic restrictions as well as the driver's desired speed, which is the legal limit, modified with the driver's tolerance factor, the slope adaptation, and the imperfection model.

2.2   Vehicle model and speed profile

Up to this point, the physical restrictions from the vehicle e.g. due to limited power and the driver's desired acceleration have not been taken into account. Based on the capabilities of the vehicle and on the stochastically fluctuating desired acceleration and deceleration of the driver (again an AR1-process), a physically drivable speed signal $v_1(s)$ is calculated, which models traveling along the route in shortest time. Vehicle parameters used within that step are the maximum engine and braking power P_{max} and $P_{max,brake}$, the average power required by auxiliary consumers P_{aux}, as well as parameters for describing losses in the drivetrain between engine output and wheel. They describe the vehicle's driving capabilities, which we take into account according to the inequalities $P_{max} \geq P_{eng} = \begin{cases} r_c(v) \cdot F_{dr} \cdot v + P_{aux}, F_{dr} \geq 0 \\ P_{aux}, F_{dr} < 0 \end{cases}$ and

$P_{max,brake} \geq P_{brake} = \begin{cases} 0, F_{dr} \geq 0 \\ -F_{dr} \cdot v, F_{dr} < 0 \end{cases}$, where $r_c = \left(1 + \frac{\lambda - 1}{10^{\frac{v}{v_{max}}}}\right)$ is a simple speed dependent model of losses in the drivetrain containing two vehicle parameters λ, v_{max}.

In addition, the driver model controls the acceleration and deceleration events in the speed profile by the maximum desired deceleration and acceleration as well as parameters for another log-AR1 process for generating stochastic fluctuations.

Finally, a refinement step is applied to $v_1(s)$. We introduce another driver parameter F_u, which acts as a controller and balances the driving force against the deviation between actual and desired speed. The parameter describes the driver's characteristics, i.e., an aggressive driver aims for driving as fast as possible (following the speed profile $v_1(s)$) and a more "balanced" driver takes into account the required power resp. energy. The effect of the parameter is a kind of smoothing of the target profile $v_1(s)$. If $v(s)$ denotes the unknown refinement solution, then we solve the optimal control problem $J(v,u) = \int_{s=0}^{L} ((v(s)^2 - v_1(s)^2)^2 + F_u \cdot u(s)^2) \cdot ds \rightarrow \min$, where $u(s)$ is the driving force at the wheels.

2.3 Algorithms for handling traffic based on observed average speeds

As an alternative to the traffic model described above, we are able to handle observed average speeds on road segments. This kind of data is provided by e.g. the HERE data platform (see traffic pattern data product [3]). For a certain link (piece of road) in the HERE digital road map, an average speed is provided as a function of week time: 4 * 24 speed values (every 15 minutes) for each day of a week. This information can be requested for the nodes along a route, and one obtains a speed map with a spatial and a temporal axis. During simulation, we need to know at which time we arrive at a certain position. We introduce the speed map after having calculated $v_1(s)$ without traffic limitations as described above. Starting at the beginning of the route at the time of departure, we check the current speed against the corresponding speed map restrictions and reduce it if necessary. With the possibly reduced speed, we update the time of arrival at the next spatial discretization point and again check the speed from phase 1 at that position against the speed map and reduce it if necessary. In addition, we take into account the waiting time at enforced stops. We repeat these steps until we reach the end of the route. The updated speed signal is the input for the refinement phase as described above. In order to illustrate that approach, we plot the average speed map (gray scale = speed) and indicate the time of arrival at all positions in Fig. 1 (for one example route).
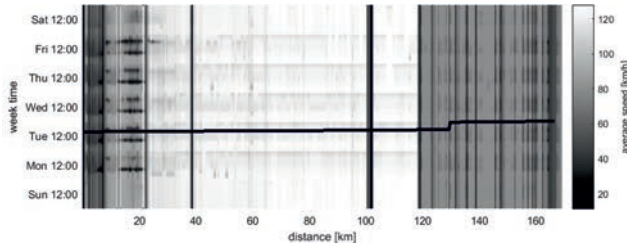
Fig. 1:   Speed map for one example route. The black line indicates the points where we
           evaluated the speed map restrictions due to the time of departure.

For illustration purposes, we synthetically enlarged the waiting time at one of the stopping
positions to 6 hours. This leads to the jump of the black line at position 130 km approximately.
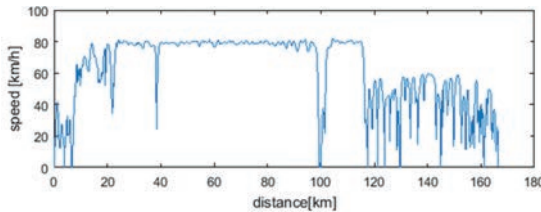The following Fig. shows the final speed signal.

Fig. 2:   The final speed signal for the example route.

2.4   Driving resistances, work shares, and fuel consumption

We use P_{eng} from the speed profile generation to estimate the instantaneous fuel consumption
$C_{inst} = 3600 \cdot \frac{P_{eng}}{\eta \cdot H_{fuel}}$ as well as the total consumption (reported per road segment) $C =
\int \frac{1}{3600} \cdot C_{inst} \cdot dt + \frac{P_{aux} \cdot T_{stops}}{\eta \cdot H_{fuel}}$, where H_{fuel} denotes the energy density of the fuel (a typical
value for Diesel is $4,3 \cdot 10^7 \frac{Nm}{kg}$) and η denotes the engine efficiency (average ratio of energy in
terms of fuel per unit time and power at the output shaft of the engine).

Based on the decomposition $F_{dr} = F_{air}(v) + F_{roll}(s,v) + F_{slope}(s) + F_{acc}$ of the driving force,
we are able to compute a corresponding decomposition of the mechanical energy at the wheel

required for driving and also consumption. This decomposition can be used by logistics companies to assess the benefit of potential improvements of the truck's equipment (e.g. better tires towards less rolling resistance or devices towards smaller air resistance).

3   Routing with consideration of energy consumption and truck restrictions

3.1   Considering truck restrictions in routing

This section summarizes the special restrictions for trucks applied in the routing algorithm. As a basis, the Open Source Routing Machine (OSRM) [4] is used. It is adapted to the specific needs of truck-trailer combinations to only compute drivable routes.

First of all, heavy goods vehicle restrictions are added to a classical car profile. This mainly means that road sections with bans for heavy through traffic are avoided. They cannot be completely removed from the network but are only allowed for usage when the prescribed destination cannot be approached on an alternative route without truck ban. Additionally, for every truck-trailer-loading combination, a simple vehicle model is conFig.d. Here, the outer dimensions, the total mass and the classification of goods are relevant. Large trucks and trailers are for instance not able to pass all ways going under bridges or gates. The total mass of the combination including payload is compared to the maximum weight allowed on roads and bridges. If the transported goods are classified as hazardous, also correspondent tags of the roads are evaluated and appropriate sections are removed from the network. Thus, sometimes shorter or energy saving routes can be travelled with empty trailers on the way back to a next loading point compared to those of the fully loaded trailer.

In addition to these restrictions, turning angles are considered in the enhanced routing algorithm. For U-turns or small angles, additional costs are added such that alternative routes are preferred, if available. They are not completely prohibited to be used since they might lie on the only way to reach the destination. For different road categories, the angles that are uncomplicated to drive are different, often due to the number and width of lanes. An investigation on still drivable turnings can for instance be found in [5] and some results are used to tune the routing algorithm. Other restrictions that are included if necessary are those of avoiding special road types based on certain types or tags. Toll roads could be prevented this way for instance.

3.2   Providing altitude information in routing graphs

The virtual drive engine is based on the VMC® database in order to have access to important road properties. This digital map data is based on OpenStreetMap (OSM) data which does not contain altitude information at the road nodes. However, the VMC® database provides

altitude information from satellite data and calculates road node altitude by interpolation and smoothing. The OSRM routing graph is enhanced in the same way to be able to build a consumption oriented cost function for routing, which takes the altitude differences into account. The concept how to use this information is introduced in the next sections.

A simple consumption-oriented route measure

In [6], a simple consumption-oriented measure for characterizing the altitude properties of a piece of road has been developed. We briefly summarize the main idea here.

Let s denote the distance parameter and $h(s)$ the altitude signal along a road segment of length L, then the derivative of the altitude signal $h'(s)$ is the slope and $UAD = \frac{1}{L}\int \max(0, h'(s))\, ds$ resp. $DAD = -\frac{1}{L}\int \min(0, h'(s))\, ds$ denote the normed upward resp. downward altitude difference of the road segment. If the result is expressed in $\left[\frac{m}{km}\right]$, then $UAD = 60$ means that within one kilometer, we climb 60m in upward direction. If $DAD = 0$ on this segment, then the average (positive) slope is 6%. If both $UAD, DAD > 0$, then the average positive slope is higher. For instance, let $UAD = DAD = 60$, then the segment starts and ends at the same altitude and the average slope (either upward or downward) is 12%.

These measures depend on the traveling direction. UAD, DAD swap roles if the direction is reversed. It is clear that a road segment with a high upward and low downward altitude difference consumes more fuel or energy than a flat or purely downward segment.

In [6], the usefulness of this simple measure has been demonstrated based on truck data from MAN. The approach is also validated based on data from the current measurement campaign.

Deriving a simplified slope signal

For the calculation of the slope share of the driving resistance, we need a slope signal along the road. We construct a simple slope angle function $\alpha(s)$ on the route segment, which is consistent to the altitude differences UAD, DAD.

We model $\alpha(s)$ as simple as possible and assume that we have an uphill part of length L_+ with constant slope angle α_0 and a downhill part of length $L - L_+$ with constant slope angle $-\alpha_0$, leading to $\alpha(s) = \begin{cases} \alpha_0, 0 < s < L_+ \\ -\alpha_0, L_+ < s < L \end{cases}$.

Inserting this ansatz into the formulas for UAD and DAD, we obtain simple terms for $\sin(\alpha_0)$ and L_+.

Pre-calculation of expected consumption under simplified conditions

According to the equations of longitudinal vehicle dynamics, we have the expression

$$W_{\mathrm{dr},+} = T \cdot P_{aux} + \int_0^L \max\big(0, F_{air} + F_{roll} + F_{slope} + F_{acc}\big) \cdot ds$$

for the work required in order to move the vehicle along a route, where $F_{air}, F_{roll}, F_{slope}, F_{acc}$ denote the air, rolling, slope, and inertia resistance, T is the traveling time and P_{aux} is the power of some auxiliary consumers (e.g. air conditioning). Since we don't know the vehicle's exact speed during routing, we assume a constant speed v_0 leading to $F_{acc} = 0$. In addition, we assume that travelling downhill does not gain energy (no recuperation).

These assumptions together with the vehicle's parameters for mass, air, and rolling resistance lead to

$$W_{\mathrm{dr},+} = \frac{L}{v_0} \cdot P_{aux} + \int_0^L \max\Big(0, \frac{\varrho_{air}}{2} \cdot c_W \cdot A \cdot v_0^2 + m_{veh} \cdot g \cdot f_{roll} \cdot \cos\big(\alpha(\mathrm{s})\big) + m_{veh} \cdot g \cdot$$
$$\sin(\alpha(\mathrm{s}))\Big) \, ds.$$

We now apply our simple slope model above and obtain after some re-arrangements

$$W_{\mathrm{dr},+} = \frac{L}{v_0} \cdot P_{aux} + m_{veh} \cdot g \cdot L \cdot \left(\delta_{veh,R}(v_0) + UAD^* - DAD^* \cdot \min\left(1, \frac{\delta_{veh,R}(v_0)}{UAD^* + DAD^*}\right) \right)$$

where $\delta_{veh,R}(v_0) = \frac{\varrho_{air} \cdot c_W \cdot A \cdot v_0^2}{2 \cdot m_{veh} \cdot g} + f_{roll} \cdot \sqrt{1 - (UAD^* + DAD^*)^2}$ and $UAD^* = \frac{UAD}{1000}, DAD^* = \frac{DAD}{1000}$

denote the altitude differences expressed in $\left[\frac{m}{m}\right]$.

The cost function

The OSRM routing algorithm expects the costs of a road section to be computed as length L multiplied with some individually computed factor R. The smaller R, the more is the section preferred. Normalizing the formula for the mechanical work $W_{\mathrm{dr},+}$ by $m_{veh} \cdot g$, we get a weighting factor R depending on some vehicle properties and on the altitude properties of the route represented by UAD^*, DAD^*.

In order to preliminarily validate the approach, we use simulation results for routes taken from the measurement campaign between February and June 2020. We concentrate on trips with high payload. In total we use 30 trips of approximately 3000 km length in total, divided into approximately 900 road segments. For each of the segments, we have the length in km, the

road type, the value of the cost function (with $v_0 = 50\frac{km}{h}$ for city roads, $v_0 = 60\frac{km}{h}$ for country roads and $v_0 = 80\frac{km}{h}$ on the motorway) and the consumption from the simulation.

In the following Fig., we plot the length of the segments over the consumption and calculate the linear correlation coefficient between both variables.
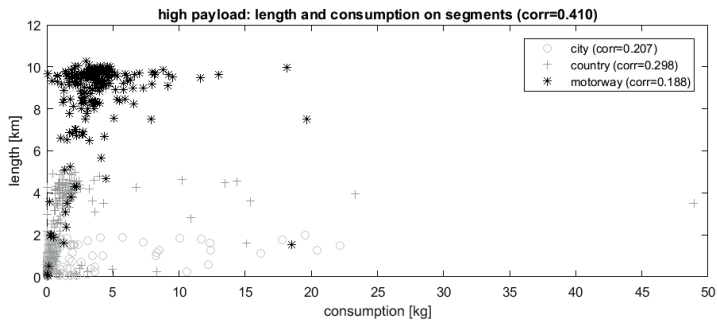

Fig. 3: Length over simulated consumption for high payload trips.

The correlation coefficients are between 0.19 (motorway) and 0.3 (country roads). The next Fig. plots the new cost function over the consumption and calculates the linear correlation coefficient between both variables.
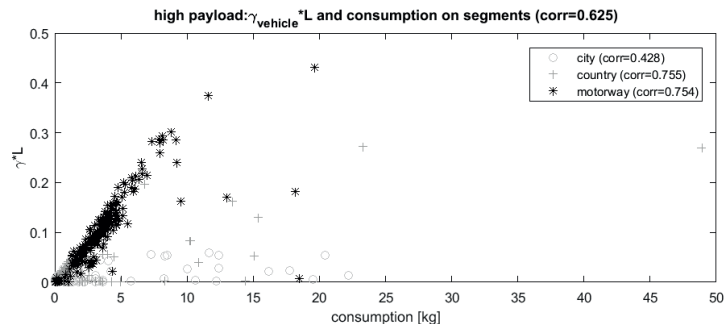
Fig. 4: New cost function over simulated consumption for high payload trips.

The correlation coefficients increase considerably from 0.19 to 0.75 on motorways, from 0.3 to 0.75 on country roads and from 0.21 to 0.43 on city roads. The improvement on city roads is

the smallest. This seems to be reasonable, since there, dropping the acceleration part of the energy demand leads to the largest gap between simplified calculation and real driving.

Nevertheless, the first results are promising. The increase of the correlation coefficients indicates, that the routes found according to the new cost function will be those, which lead to less consumption. Of course, this depends on the assumptions we made and needs more validation in further steps.

4   The measurement campaign

A measurement campaign offers a good opportunity to analyze vehicle and driver behavior under normal operating conditions in order to derive suitable model parameters. In the ECO-TRAVID project, 20 truck-trailer combinations are equipped with enhanced telematics terminals. These monitor, among others, fuel consumption, driver behavior like acceleration and braking events, tire pressure and temperature and the total mass of truck and trailer. In addition, the GPS-position of the vehicle and its speed are logged.

The data is split into single trips which are further processed with VMC®. A central step is the map-matching, which projects the GPS-traces onto the digital map. Once this is done, we can identify the road types travelled and compute altitude profiles along the route. Moreover, we decompose the data into segments of different road types and compute e.g. the fuel consumption for all segments individually. This type of analysis gives detailed insights into the performance of the vehicle. It serves as a benchmark for the estimated energy consumption for the virtual drives and is thus used to tune the simulation parameters.

As the measurements originate from real drives, several routes are travelled multiple times with different traffic situations and probably different drivers. Hence, a fairly complete picture of consumption and its dependencies is possible. For this purpose, the routes are automatically clustered. Since a fixed route is travelled inside one cluster, we have a fixed slope profile but still varying mass, speed influenced by traffic as well as other parameters such as wheel temperature and pressure or ambient temperature. This can be used very well to study the effect of the varying parameters onto consumption and for the calibration of simulation parameters.

Derivation of simulation parameters

The speed profile simulation as explained before requires several vehicle and also driver dependent parameters. Two of them are the *speed adaption factor* that models the relation between allowed and driven speed as well as its stochastic variations. On highway segments with an allowed speed of 80 km/h, we often observe a pretty constant speed value of 82 km/h with only small variations. On highways in France the legal speed limit is 80 km/h. Accordingly, we set the *speed adaption factor* to 1.025. The variance of the stochastic AR1-process $X_{driver}(s)$ can be set to a very small value .

Occasionally, there are larger deviations from mean speed 82 km/h. In order to Fig. out whether those are related to e.g. overtaking maneuvers, we check the engine power, which we calculate from the logged engine speed and torque. Fig. 5 shows a scatter plot of acceleration over speed for measurement segments, where the color indicates the engine power. Highest power is plotted last in order not to hide high power events. Obviously, sections of high power are rare at speeds above 82 km/h, even in cases where the acceleration is positive. High power sections occur mostly at speeds below 82 km/h. This shows, that overtaking maneuvers do not play an important role. The main effect we see here is a slope dependent adaptation of the speed. By additionally checking speed, acceleration and engine power for selected measurements based on time signal plots (not shown here), we can confirm that usually speeds above 82km/h are due to downhill driving at low engine power, while positive accelerations at high engine power are due to accelerating back to the desired speed after slowing down due to uphill driving.
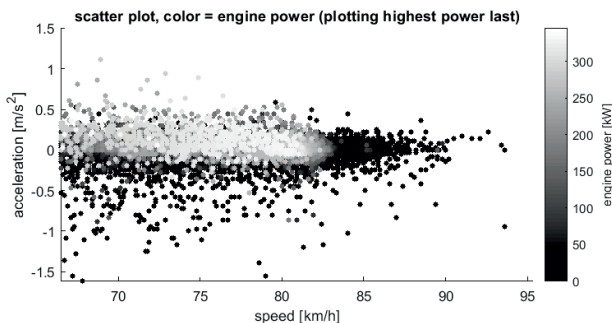

Fig. 5: Acceleration over speed, colored according to engine power

A very important simulation parameter is the engine efficiency η, which we use to calculate the instantaneous consumption (fuel rate) via $C_{inst} = 3600 \cdot \frac{P_{eng}}{\eta \cdot H_{fuel}}$ (see section 2), where P_{eng} denotes the mechanical power at the output shaft of the engine. Since engine speed and torque as well as the fuel rate are part of the measured data, we can try to identify the engine efficiency based on this formula. However, the result we obtain from a simple regression is $\eta = 0.49$, which seems to be much too optimistic. From the literature (see for instance [7]), we expect the efficiency of heavy duty Diesel engines to range between 0.4 and 0.45 at most. The reason for the deviation lies in the fact, that the engine torque, which is taken from the FMS system (see [8]) includes the torque developed in the cylinders required to overcome friction. From [7], [9], we find that friction approximately consumes 4% or more of the total energy. Taking this into account, the value of η decreases to $\eta = 0.45$ at most. Up to here, we did not use simulation results. If we use a preliminary set of simulation parameters and calculate the consumption via simulation for the routes we have in the measurements, then we observe that we need $\eta = 0.43$ to fit the calculated consumption to the measured one. Although the simulation parameters are not yet finally determined, this is already in good accordance with the literature data.

Other driver and vehicle parameters can also be derived with more or less effort from the measurements. Since this part of the work is still ongoing, we do not go into more details here.

5   Integration into the fleet management platform

Within the project the functionality described in sections 2 and 3 is being integrated into Trailermatics™, the fleet management platform of the French project coordinator Collecte Localisation Satellites (CLS). Trailermatics™ is a user friendly telematics road transport platform daily used by more than 400 logistic and transport customers, representing more than 25.000 road transportation vehicles. Fig. 6 illustrates some monitored SAMAT vehicles as part of the Ecotravid measurement campaign.

Fig. 6: SAMAT's vehicles monitored on the Trailermatics™ map module

The integration of the VMC® functionality into the CLS platform is done via web services. This allows an application under real conditions for the virtual drive engine. A final version with all available settings is currently under integration at the CLS side. The workflow of a transport order is shown in Fig. 7.
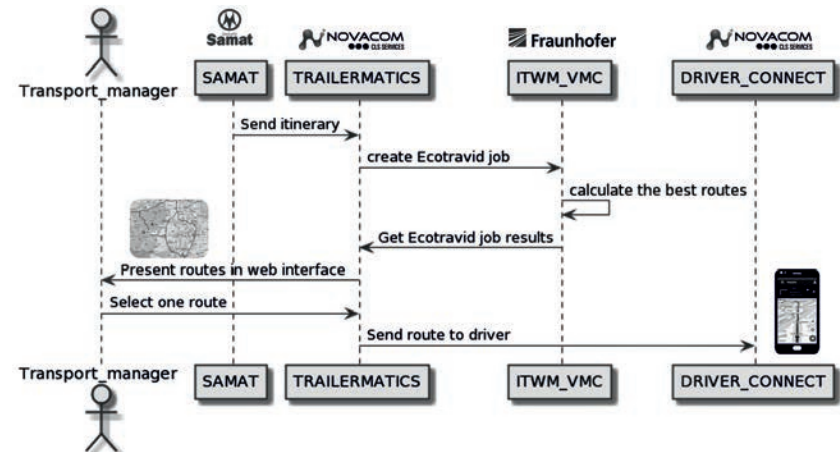

Fig. 7: Workflow of an Ecotravid transport order

The VMC® software is called from the "Planning module" of Trailermatics™. For each transport order the user interface provides the new functionality including specific characteristics of the trip (dangerous goods transportation, parameters of the vehicle as sizes, engine power etc.). The virtual drive engine calculates and proposes different alternative sets of routes, with different goals displayed in the form of a table (estimated fuel consumption, distance and duration for each alternative). The user (usually the transport manager) can select one or another and set-up his route plan for the trip, which can be sent to the driver's smartphone for GPS navigation. Then, the driver can follow the chosen route and effectively optimize the trip and fuel consumption. This last step can be done via the Android "Driver connect" application, which has been developed by CLS, allowing the transmission of the Ecotravid transport schedule to the driver. Finally, if the proposed Ecotravid itinerary has been followed by the driver, the trip can be analyzed through a set of Trailermatics™ features (real GPS track, speed, real fuel consumption etc.).

6   Conclusions

In this paper, we reported about the current status of the LIFE project ECOTRAVID. We sketched the main two-step idea of the approach as well as some preliminary results.

A key element is the realistic simulation of consumption for a prescribed route based on suitable models for vehicle, driver and traffic. In section 2, these models have been introduced.

Another step of the virtual drive concept requires an enhanced routing, which takes into account truck restrictions in order to avoid infeasible solutions. Besides taking into account the weight of the truck-trailer-combination as well as the type of goods to transport (hazardous material or not), we also try to prevent steep turning angles at crossings if another acceptable route is possible. In addition, we have seen how the cost function in a routing algorithm can be modified in such a way, that it is capable of considering not only shortest path or shortest time but also minimum fuel consumption. Since doing this based on the advanced virtual drive simulation techniques would be much too time consuming, we developed a consumption-oriented route measure, which can be used to modify the routing cost function. Moreover, it does not slow down the optimization since it can be pre-calculated. The key approach is to use the simple UAD/DAD values of a road segment. The details and a first validation has been given in section 3.

In section 4, we have introduced the measurement campaign, which accompanies the approach and is used to calibrate the models. Since this is still ongoing, we presented some preliminary results only. In order to assess the fuel saving potential, we are using the routes from the measurements as reference and try to find alternatives with less consumption. We currently apply our simulation capabilities to all of them in order to Fig. out, which of the reference routes are already optimal with respect to consumption (this of course has to be expected for a certain part of them) and which could be replaced by better alternatives. In a later step of the project, the findings of this simulation analysis will be checked against the results of real measurements.

Finally, we sketched in section 5 the integration of the virtual drives in the CLS planning and monitoring solution for logistics companies.

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Concept study of a commercial vehicle suspension with optional electric machines

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Abstract

The electrification of commercial vehicles does not only affect trucks, but also trailers can make a significant contribution to reducing CO_2 emissions. In principle, electrified trailers can reduce the fuel consumption of a commercial vehicle combination by up to 20%. However, there are significant implementation barriers, as the standard trailer suspensions do not have defined interfaces for the adaptation of electrical machines. Another problem is that with electrification, the trailer weight increases which reduces fuel savings again.

To remedy these problems, a trailer lightweight chassis was designed in a completed study. The chassis, which is designed as a frame structure, is about 50 kg lighter than conventional design. The operational strength of the frame structure has been demonstrated in Finite Element Method (FEM) calculations. Experimental stress measurements on a prototype confirm the calculation results. In a second study, the frame structure is further developed in such a universal way that an electric machine can be connected optionally.

Introduction

Greenhouse gases emitted by road transport are changing the earth's climate. Policies are responding to this [1]. For example, vehicle manufacturers are obliged to gradually reduce the fuel consumption of their vehicles. Important contributions to this are provided by lightweight design measures and the electrification of vehicles.

Conventional combustion engines are currently replaced by electric drives. At the commercial vehicle sector, the first thought is given to tractors, but electrification of trailers also brings considerable progress, because electric recuperation can absorb excess braking energy. In a

joint research project funded by the Federal Ministry of Economics, it was shown that electric recuperation can save significant fuel not only in delivery traffic, but also in long-distance transport. With the so-called *EVTrailer*, consumption savings of up to 20% could be demonstrated [2]. A comparable saving was also confirmed in another study by WABCO [3].

In addition to electrification, lightweight design is another effective measure to reduce CO_2 emissions, as this reduces driving resistance. Both rolling, acceleration and incline resistance fall proportionally with the vehicle mass. Vehicle weight can be reduced in two ways: either by design measures or by lighter materials. For example, the weight of a steel component can be reduced using aluminium, magnesium or CFK. However, these lightweight materials generally increase the material costs, which are a high proportion of heavy-duty vehicles. For economic reasons, therefore, most chassis structural components are still made of steel. Thus, the constructive lightweight design in the commercial vehicle sector is of particular importance because its potential has still not been exhausted.

The development potential of state-of-the-art suspensions is mostly exhausted, as they have been optimized since the 1960s. Progress in lightweight design is barely apparent [4]. In addition, this state-of-the-art arrangement is not designed to integrate an electric machine, as there is no connecting corridor through which drive shafts can be guided to the wheel hubs.

1   Lightweight suspension as frame structure (EVOAXLE - WIPANO Project)

Significant advances in lightweight design require new concepts. So, the well-known design principle of a frame structure was applied to a trailer suspension. As a result, the weight of a trailer suspension can be significantly reduced. It has been demonstrated that the weight of a trailer suspension can be reduced by about 50kg with the help of frame structures (Fig. 1).
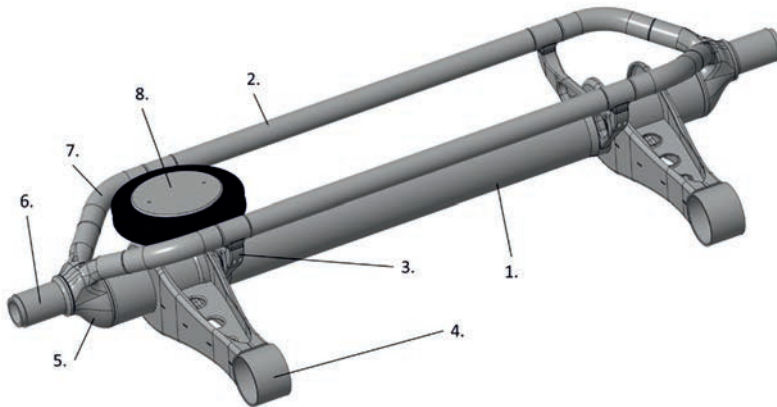
Fig. 1:   Frame structure of trailer suspension *EVOAXLE*

Such a structure consists of tensile and pressure struts (1, 2, 7), which skeletally connect the axle pins (6). The struts span a spatial structure, which branch in part in a technical manner. In the variant shown, the air bellows cylinders (8) were moved to the centre of the axle and are surrounded by annular struts (3, 7).

1.1   Stress calculation

The fatigue life of the structure should reach at least the same values as conventional chassis. The finite element method calculates the stresses and deformations. From the stresses, the service life is derived mathematically. The fatigue life is quantified by the number of cycles that are achieved without cracks.
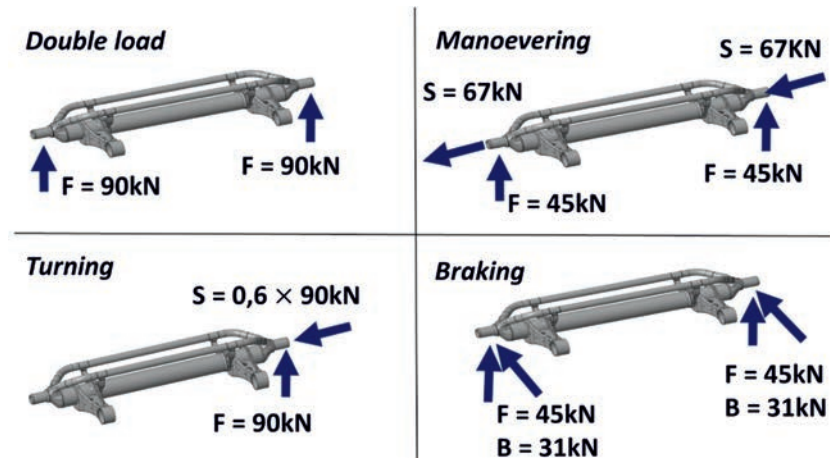
Fig. 2: Four load cases for calculating

The shown structure (Fig. 1) has a wheel track of 2040 mm and a spring track of 1300mm. The pivot points of the longitudinal trailing arms are 500 mm in front of the centre of the axle. The air spring bellows are positioned on the centre of the axle, with a lateral offset of 50mm. The entire arrangement weighs 95 kg. It is analysed in various driving manoeuvres. For this purpose, four different load cases are simulated (Fig. 2).

1.2   Four load cases

The *double load impact* simulates the crossing of a threshold (Fig. 3). Both wheels spring in the same way, whereby the vertical axle load is 2x90 kN. The highest comparative stress occurs in the annular strut and is 406 MPa. The expected service life is derived mathematically. The chassis is permanently able to cope with the double load impact or can withstand more than 1 million load cycles.
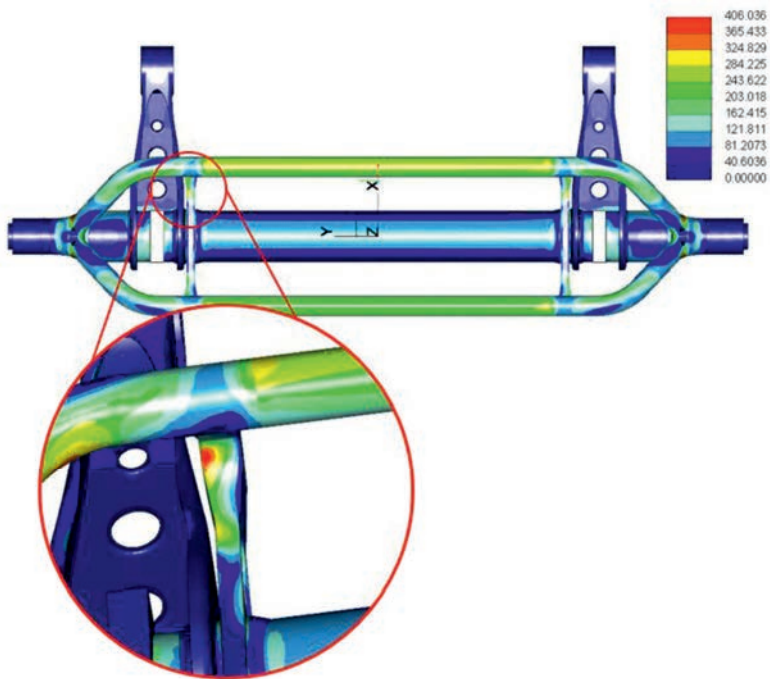

Fig. 3: FEM Result of calculation double load impact

In case of *turning*, driving at the tipping limit is simulated. The entire axle load is discharged via the outer wheel, whereby the inner-curve wheel is completely relieved. The tire side force (μ=0.6) is introduced via the outer wheel. The frame structure has the task of stabilizing the rolling inclination of the structure, whereby the rolling stiffness should be within defined limits.

The roll angle is 3,2 degree and maximum stress is at the pivot point with 740 MPa. Calculated, the structure withstands more than 100,000 load cycles, which is considered sufficient.
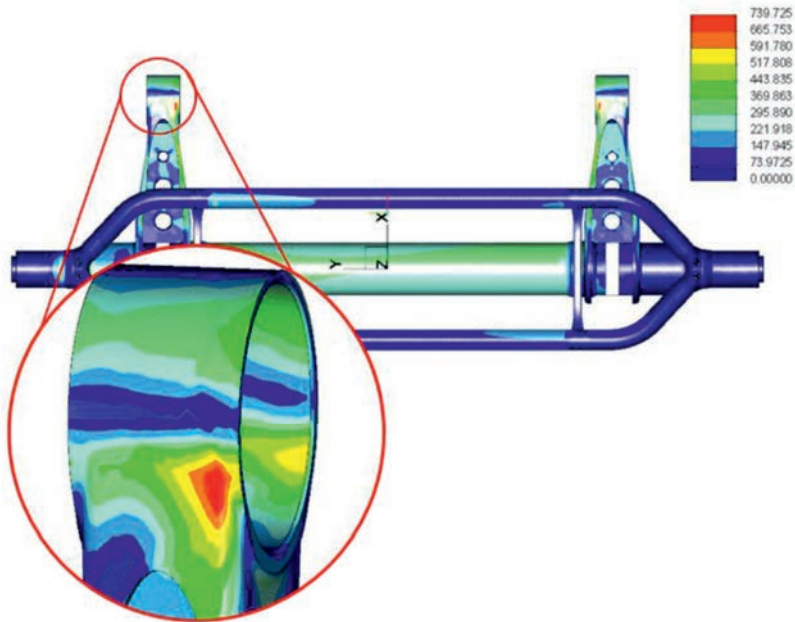

Fig. 4: Result of turning load case calculation

The *manoeuvring* load case simulates turning a three-axle semi-trailer on an extremely small curve radius. It is assumed that the tyres are pulled across the road and sometimes they are entangled in the roadway in a form-fitting manner. This results in the extremely high tyre side force, which is 1.5 times the wheel load. Manoeuvring usually causes the highest stress (785 MPa) and thus represents the most critical load case. The computational service life is more than 100,000 load cycles.
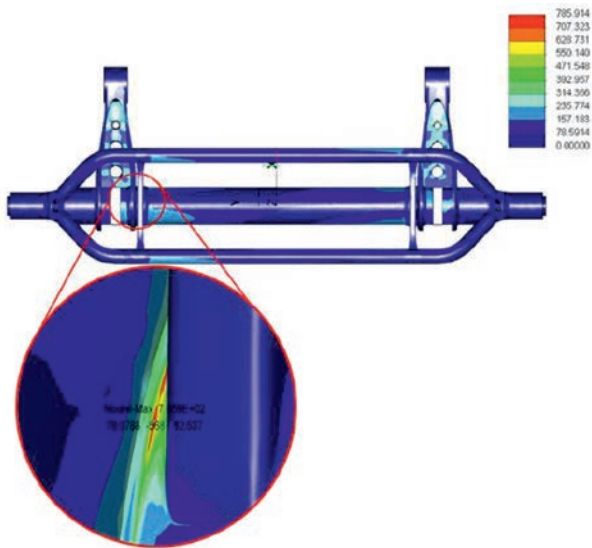
Fig. 5: Result of manoeuvring load case calculation

In the case of *brakes*, a full braking at the blocking limit (μ=0.7) is simulated. This manoeuvre causes relatively lower stress in the frame structure. The maximum stress is below 462 MPa.
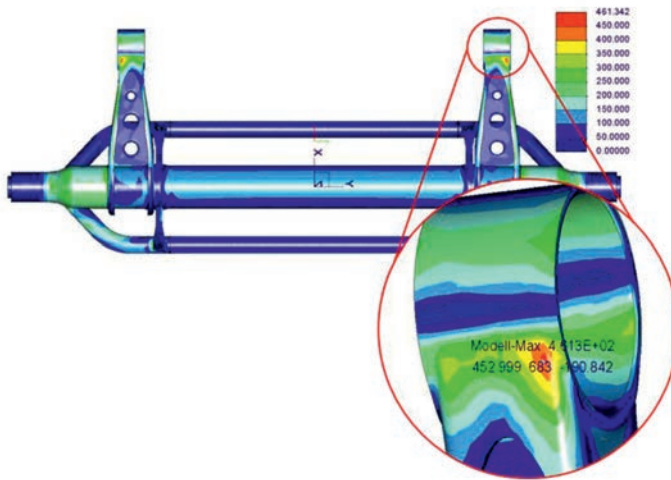
Fig. 6: Result of braking load case calculation

After successful completion of the calculations, a first prototype was built to carry out experimental stress measurement. The demonstrator shown in Fig. 7 served as an exhibit to be presented to a larger audience for the first time at the IAA 2018. The expert discussions brought some valuable suggestions for improvement, such as the manufacturing process, the ride height or the connection dimensions. These improvements were included and incorporated into the following study.

Fig. 7: Demonstrator

2   Electrifiable suspension *EVAXLE*

However, the weight savings shown by structural design are not sufficient to meet the future legal requirements for CO_2 emissions. Therefore, a modified structural design should be combined with a recuperating electric drive unit because the electrification of trailers is another option to significantly reduce CO_2 emissions. The current follow-up investigation EVAXLE is being prepared by the University of Applied Sciences and Arts Hildesheim/Holzminden/Göttingen (HAWK), JOST Achsen Systeme GmbH and Robert Bosch GmbH.

Currently, there is still the problem that conventional trailer axles are not designed to be connected to an electric machine. There are very fundamental problems, such as the lack of a mechanical interface to be able to flange an electric machine on it.

The *EVAXLE* study pursues three main development goals: First, defined interfaces should be available on the suspension in order to be able to mount optional electrical machines. Secondly, the suspension should be lighter than state of the art suspensions. Thirdly, the suspension should be cost-effective to manufacture so that the investment in a recuperating trailer is worthwhile.
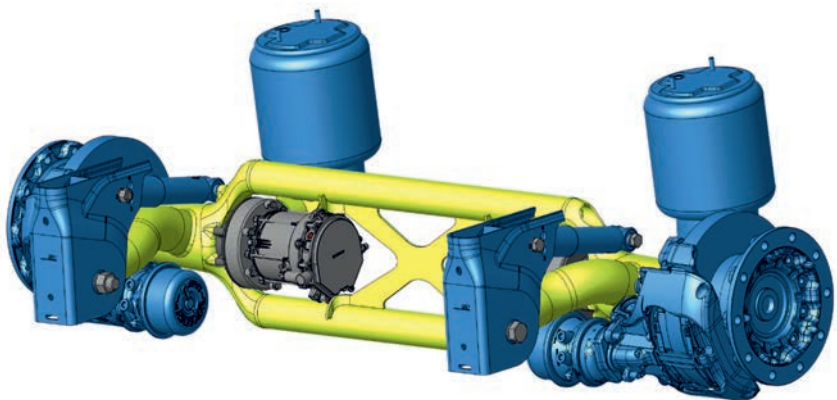

Fig. 8: Suspension EVAXLE

These goals are achieved with the suspension shown in Fig. 8. The essential feature of this design is that the axle body in the middle section consists of two cross struts, between which electric drive units can optionally be arranged. The electric drive unit consists of an electric motor and a planetary gearbox. Due to the light structural design, the weight of the suspension is only 372 kg (without brake cylinder and without electric machine). The suspension has standard connection dimensions and allows ride heights from 230 mm.

Fig. 9 shows the suspension without hanger brackets, air spring bellows and without dampers. The structural design of the axle body is extremely rigid and at the same time more torsional soft than conventional suspensions. Even with extreme torsions of the coupling link suspension, no external forces are introduced into the electric drive unit. Thus, the electric drive unit is not deformed during the reciprocal springing of the wheels.
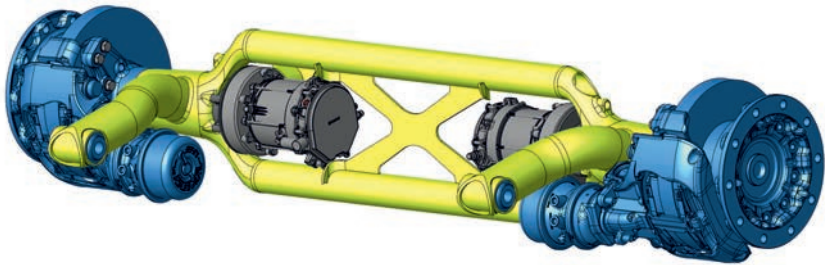

Fig. 9: EVAXLE with wheel ends an electric drive unit

Fig. 10 shows the structure freed from all attachments. The ZB axle body consists of several sections. The standard axle pins are connected to the axle carriers by means of a friction weld seam. The middle section of the axle body is formed by the two axle cross struts, which are connected to each other via a push plate.

To the front extend the trailing arms, which cross the axle carrier. The trailing arms are made of bent tubes, as the air bellows tailend. Both components are pushed into the axle carrier via a fit.
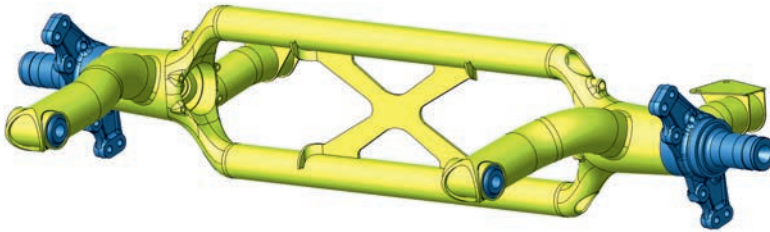
Fig. 10: Structural design EVAXLE

The manufacturing cost of this design should be lower than those of a conventional suspension. This cost target is supported by the reduced use of materials. The structure shown currently weighs 140 kg and is therefore lighter than conventional designs. It can be assumed that the weight can be further reduced during the project. It should be emphasized that despite the lightweight design approach, the operational strength is not reduced.

The axle body has a freely accessible interface on their insides to which electric drive units can be mounted. The suspension is basically designed in such a way that it can be operated either with or without an electric drive unit. The universal suspension offers the possibility of electrifying the trailer depending on the willingness to invest and the expected driving profile. It is also possible to install an electric machine in after-sales. Three-axle semi-trailers can be equipped with up to three recuperating axles depending on customer requirements.

The concept presented is intended to contribute to further reducing CO_2 emissions from heavy commercial vehicles. Lightweight structures in conjunction with recuperating generators show a way to make trailers even more efficient. Whether a freight forwarder makes the associated investments also depends on the business case. The presented suspension concept is intended to create an incentive for this through its lightweight and cost-effective nature as well as its flexible application possibilities.

3   Reference

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The chassis remains the backbone of road transport ➔ smart & light

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Abstract

The main drivers to shape the transport of the future are efficiency and safety. The fight against climate change accelerates by new legislation the switch to an electric drive train. In addition, automation at various levels is a driver for greater efficiency and safety. In the area of chassis technology, the so-called driving chassis is focus of several developments. Braking and steering systems become electrified and connected and thus essentially contribute to automation. The holistic view including the electric drive train offers further potential for efficiency and safety.

There are fewer innovations in the suspension area, which as a commodity business has only been driven by increasing cost pressure for years. Design to cost, standardization and improvements in the supply chain shape the development activities of the suppliers.

This presentation would like to draw attention to areas in which the suspension supports the future drivers of mobility: lightweight construction and smart chassis. Lightweight construction is becoming an enabler for range extension and more payload in vehicles with electric drivelines. The smart chassis solutions provide the necessary data for automation and digitization by integrating sensors into the suspension components.

The solutions shown are each characterized by a good combination of the use of new technical possibilities and economically optimized products. Intelligent links between the various domains in the chassis and the consideration of new framework conditions in electrified vehicles offer further potential.

The future chassis will continue to meet the requirements for robustness, reliability and economy, but will also be more important as enabler for electrification and automation and is contributing to the long-term vision of zero emission & zero accidents.

01
Introduction

ZF Vision on Next Generation Mobility
What is the Contribution of Chassis/Suspension Technology?

ZERO EMISSIONS   **ZERO** ACCIDENTS

Efficiency

Product and system solutions for the reduction of operational costs **(TCO)** as well as lower **CO2 emissions**

Safety

Assistance systems **(ADAS)** for the protection of road users, driver comfort and cargo integrity
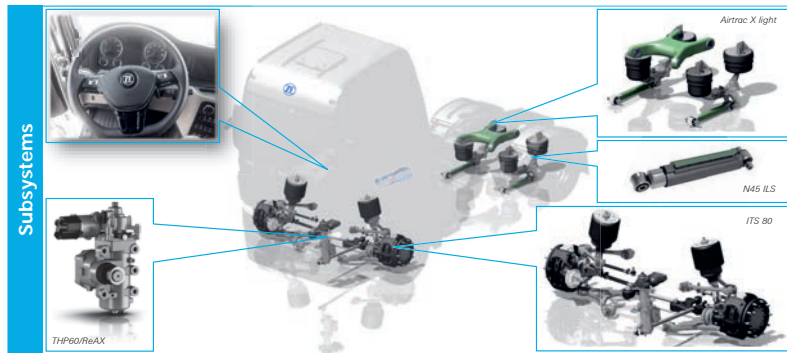
Digitalization

Connectivity and **software solutions** for efficient processes (fleet mgmt. predictive maintenance, ...)

Technology Demonstrator
Chassis System Integration

Subsystems

Airtrac X light

N45 ILS

ITS 80

THP60/ReAX

02
Future Steering

Synergies Steering & Suspension

Electro-hydraulic steering

THP80
P_{total} = 456W

-2,3 kg

THP60+ReAX
P_{total} = 375W

- Downsized steering actuator
- Energy and weight saving
- Interface for lateral control systems

Independent Truck Suspension

- ReAX provides line centering
  → Modification of kingpin inclination and caster angle
- Adjusted steering ratio (lever link system)
  → gear torque (-5.1% straight ahead, -17.8% right turn)

Technology synergy delivers potential for CO2 reduction and efficiency optimization
Reduced energy consumption: 20% for driving condition „cruise" & idle state
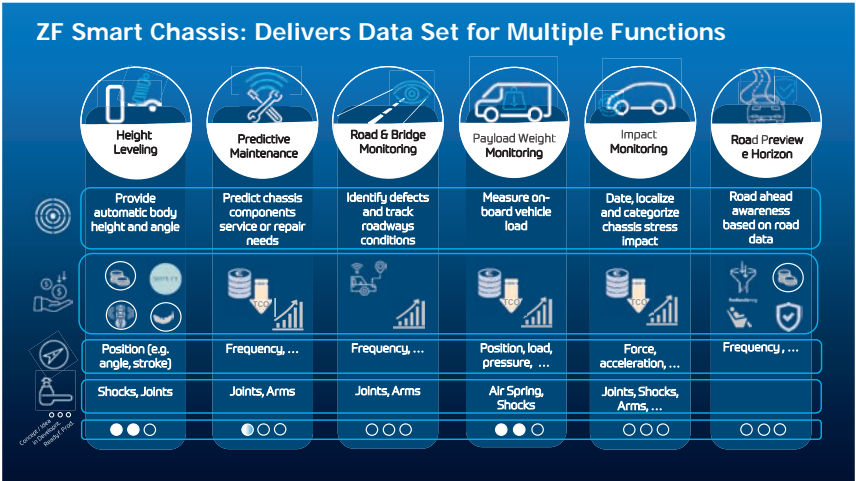
Precision By-Wire Control required for Automation

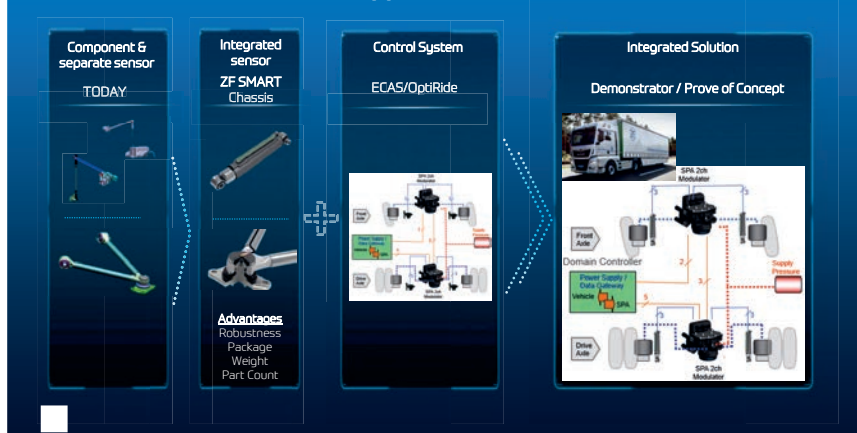By Wire:
- Drivetrain ✓
- Braking ✓
- Steering ✓

Steer-by-Wire
without Column

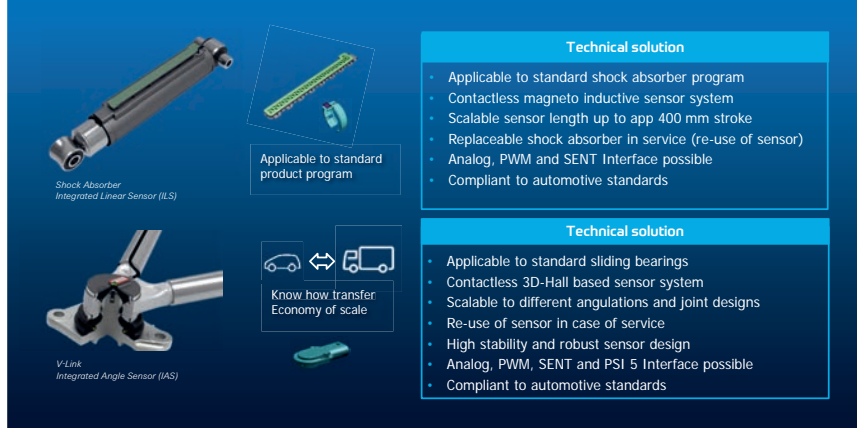→ New degrees of freedom for
chassis packaging

03
Smart Chassis

ZF Smart Chassis: Delivers Data Set for Multiple Functions

Height Leveling	Predictive Maintenance	Road & Bridge Monitoring	Payload Weight Monitoring	Impact Monitoring	Road Preview e Horizon
Provide automatic body height and angle	Predict chassis components service or repair needs	Identify defects and track roadways conditions	Measure on-board vehicle load	Date, localize and categorize chassis stress impact	Road ahead awareness based on road data
Position (e.g. angle, stroke)	Frequency, …	Frequency, …	Position, load, pressure, …	Force, acceleration, …	Frequency, …
Shocks, Joints	Joints, Arms	Joints, Arms	Air Spring, Shocks	Joints, Shocks, Arms, …	
●●○	●○○	○○○	●●○	○○○	○○○

ZF Smart Chassis: Holistic Approach Focus on Customer Value

Component & separate sensor

TODAY

Integrated sensor

ZF SMART Chassis

Advantages
Robustness
Package
Weight
Part Count

Control System

ECAS/OptiRide

Integrated Solution

Demonstrator / Prove of Concept

Smart Chassis Components - Integrated Sensors

Shock Absorber
Integrated Linear Sensor (ILS)

Applicable to standard product program

V-Link
Integrated Angle Sensor (IAS)

Know how transfer
Economy of scale

Technical solution
• Applicable to standard shock absorber program
• Contactless magneto inductive sensor system
• Scalable sensor length up to app 400 mm stroke
• Replaceable shock absorber in service (re-use of sensor)
• Analog, PWM and SENT Interface possible
• Compliant to automotive standards

Technical solution
• Applicable to standard sliding bearings
• Contactless 3D-Hall based sensor system
• Scalable to different angulations and joint designs
• Re-use of sensor in case of service
• High stability and robust sensor design
• Analog, PWM, SENT and PSI 5 Interface possible
• Compliant to automotive standards

Lightweight Advantages

Increase Payload

- 1:1 Increase of payload leading to higher efficiency

Range Extension

- Approximately additional 20km[1] range extension with 100 kg battery replacement

CO_2 Reduction

- Reduction in operations (VECTO):
  - 0.03...0,07l/100km/100kg
  - 0,08..0,18kg CO2/100kg / 100km
  - Approx. 1.800 kg CO2 in a vehicle lifetime [2]
- 85% less CO_2 emission[3] during production due to:
  - Smaller machines needed (100 W Robot instead of 9.5 kW press)
  - Lower temperatures needed (Forging steel → Bonding epoxy)
  - Lower heat capacity of materials

CO_2 Footprint

Source: ZF internal investigation, GaBi simulation, 2019
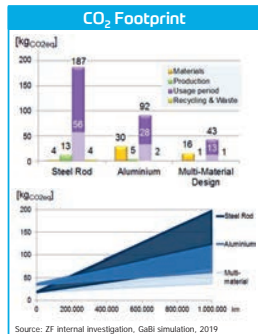
1) 40t truck   2) Runtime 1.000.000 km   3) Compared to products in serial production

Chassis Weight Reduction
Example: Air Suspended Rear Axle

ZF Airtrac

FRP solutions

Function integration → -30 kg

ZF Airtrac X

Weight reduction

V link	6	kg
2 torque rods	6,5	kg
2 stabilizer links	4	kg
total	**16,5 kg**	

Weight reduction

4p-link	24	kg
2 torque rods	6.5	kg
Total	**30,5 kg**	

Lightweight Design – Profile based Commodity Portfolio
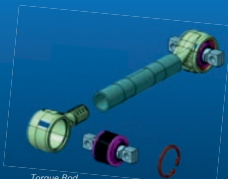
Torque Rod
Serial design
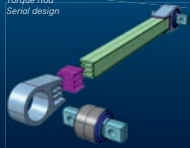
Torque Rod
*Fibre reinforced plastics design*

Design

- Platform approach for various CV profile structures
- 30 % - 50 % weight reduction (incl. bearings) compared to current parts
- Intensive unidirectional Loads
- No bending or torsion due to elastomer bearings or ball joint
- All fibers are oriented in load direction
- Bonding results in a very homogenous load introduction
- Optimized shape to avoid local stress hot spots

Process

- Structural bonding for joining composite profile and extruded aluminum load introduction
- Cost efficient continuous composite profile production using inexpensive raw materials
- Cost efficient extrusion of aluminum load introduction profile
- Low energy consumption processes

Lightweight Design – 4P-Link 3D Filament Winding Technology
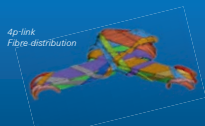
4p-link
Fibre distribution

4p-link: Winding patterns

4p-link: Process automation

Design

- 40 % - 50 % weight reduction (incl. bearings) compared with current part
- Design for separation of local multiaxial loads in different areas
    - 4 arms (bending)
    - 1 central Box (torsion)
- Local fiber architecture follows local loads applied and required stiffness
- Integral component made of one 6 km long fiber roving
- Light foam core used to define shape

Process

- Automated 3D filament winding of pre-impregnated fibers
- Combination of robots used for automated winding - generating local fiber orientation as needed
- Cost efficient raw materials
- Integrated quality assurance during production
- ZF specific material design for 3D filament winding

05
Summary

The Chassis remains the Backbone of Road Transport

Electrification & Automation require:
- Lightweight materials that deliver energetic advantages
- New designs that offer packaging advantages for BEV & FCEV
- Integrated smart actuators which enable safe automation
- Integrated sensors that improve uptime by preventive surveillance

As a key enabler for **Electrification** and **Automation**, the future chassis will contribute to the long-term vision of Zero Emission & Zero Accidents

The future chassis will be electric, robust, lightweight, compact, smart & connected

Intelligent Automated Driving Features for Refuse Collection Vehicles

Hybrid automated diving (AD) solution with intuitive human machine interaction for efficient municipal application and extended operational design domain (ODD)

DI Dr. techn. **Thomas Mauthner**, DI **Gernot Hasenbichler**,
AVL List GmbH, Graz, Austria;
Bernardo Henriques M.Sc., AVL SFR, Regensburg

Abstract

Compensating the lack of skilled truck drivers by implementation of smart automated Driving features – This is one of the main challenges for future safe and efficient trucking business, which also affects the area of logistic and municipal business areas. AVL in cooperation with Mitsubishi Fuso Truck and Bus Corporation (MFTBC) realized a prototype hybrid Autonomous Driving (AD) solution with partial automation and responsibility share between operators and AD vehicles, targeting a feasible cost-efficient alternative to SAE level 4 systems.

1. Introduction and Problem Statement

The lack of skilled drivers for commercial vehicles affects also the logistic and municipal business areas, such as refuse collection. Fully automated vehicles show promising solutions for compensating this shortage but are not yet available with enough maturity to cover driving tasks under all conditions at reasonable costs [1]. Furthermore, many municipal tasks do not request full SAE level 4 autonomy [2] but rather require a seamless and non-distracting interaction with workers operating with and around the vehicles. Recent standards like Low-speed automated driving (LSAD) ISO22737:2021 [3], shaping the context for vehicle requirements and dual-mode operation with designated drivers within specific operational design domains (ODD). In literature, one can find several concepts and studies on defining human machine interfaces on between ADAS/AD systems and drivers e.g. [4,5] or on teleoperation of automated vehicles [6]. Although important approached to enhance acceptances and usability of AD systems, they are not solving the problem of missing drivers.

Instead of operating with designated drivers either in-vehicle or remote, we developed a hybrid AD solution with dynamic driving tasks performed partly automated by the vehicle and partly manually controlled via remote device (see Fig. 1), from an accompanying operator represents

a feasible cost-efficient alternative for the near future [9]. Thereby the operational design domain of the AD system can be increased significantly while keeping technical complexity and hardware costs down. The idea is to emphasize this hybrid AD approach in sharing driving responsibility between the automated vehicle and the "working" team outside the vehicle including extension to future use cases.

Fig. 1: Operator interacting with AD vehicle via smart device.

This article describes AVL's approach for the development of hybrid AD features enabling higher efficiency in refuse collection. Based on the MFTBC eCanter platform, and in cooperation with MFTBC, AVL developed the eCanter Sensor Collect demonstrator, fulfilling use cases and scenarios relevant to the industry as identified with MFTBC.

2. Methodical Approach for Problem Decomposition
With limited reference projects from the industry, the context and development strategy were elaborated within several concept workshops to define the main AD features. With the MFTBC eCanter, a fully electric platform was chosen at project start to target future-proof zero emission solutions for municipal and urban operation.

Already in the early project phase, all partners realized the importance of user acceptance for success, which drove the need for early prototypes and iterative function development. The automation of the existing eCanter platform with actuators and controller hardware was enabled with support from several AVL departments including prototyping, mechanical and E/E

engineering as well as vehicle design and workshops. Therefor enabling real world testing of functionality from the beginning.

Following AVL's ADAS/AD model-based system engineering (MBSE) development approach, we systematically analysed the MFTBC target scenarios, use cases and requested system capabilities, always with respect to cost-effectiveness of the potential solutions.

Main challenges were:
1) Distribution of driving and control tasks between vehicle and remote operator
2) Minimizing the interruptions for the operator allowing them to focus on their primary tasks
3) Intuitive human machine interface concept for the hybrid AD approach

Everything was embedded into the AVL development process, ensuring decomposition of scenarios into requirements and traceability throughout the development cycle following an automotive standards-compliant approach. This approach ensures maximum efficiency in the transfer from prototype vehicle to serial development.

3. Description of the AD feature and use cases

The refuse collection process was decomposed in two parts, as illustrated in Fig. 2. First the vehicle reaches the collection area at high velocity. Next, the refuse collection procedure takes place at low velocity, repeatedly moving the vehicle along a road, stopping at collection points, and loading the refuse into the vehicle.

The high velocity part takes place in an unstructured urban scenario, which implies high dynamic constraints in an unpredictable and diverse environment. An autonomous vehicle manoeuvring in these conditions is required to have a high level of safety. Development efforts and operational risks would be disproportionate to the benefits and optimization potential.

On the other hand, the low velocity part allows the definition and utilization of pre-recorded routes or HD map information in the collection area, with limited dynamics.
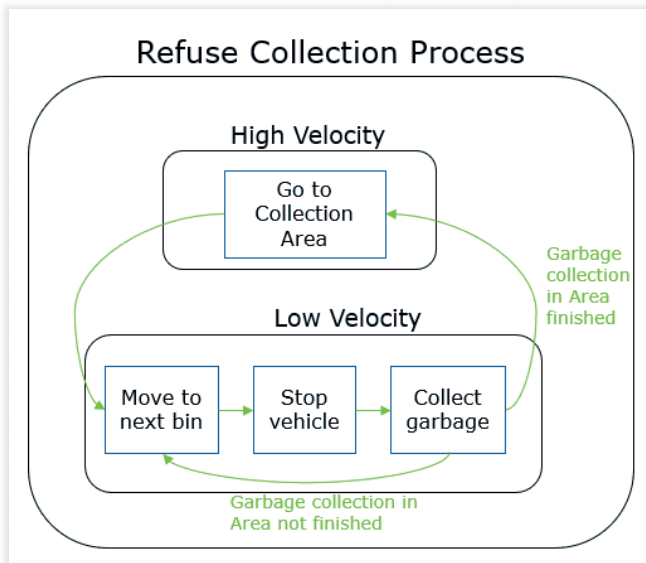
Fig. 2:   Division of the waste collection process into two speed ranges to identify optimization
           potential

We designed a solution in which the operator keeps control and responsibility of the whole
operation, planning the actions and collecting the refuse while being assisted by the vehicle
which takes over the driving task at low velocities, thus removing the need for a driver. To
cover different urban topographies, both forwards and backwards motion must be possible.

The low velocity part can be defined by two AD feature modes (see Fig. 3). In Follow-Me mode
the operator walks in front of or behind the vehicle. The system detects their position and
follows the operator at walking velocity while keeping a safe distance and respecting the pre-
defined path constraints. In Stop-Here mode, the vehicle continues driving at walking velocity,
respecting the pre-defined path, and stops at the marked position defined by the operator be-
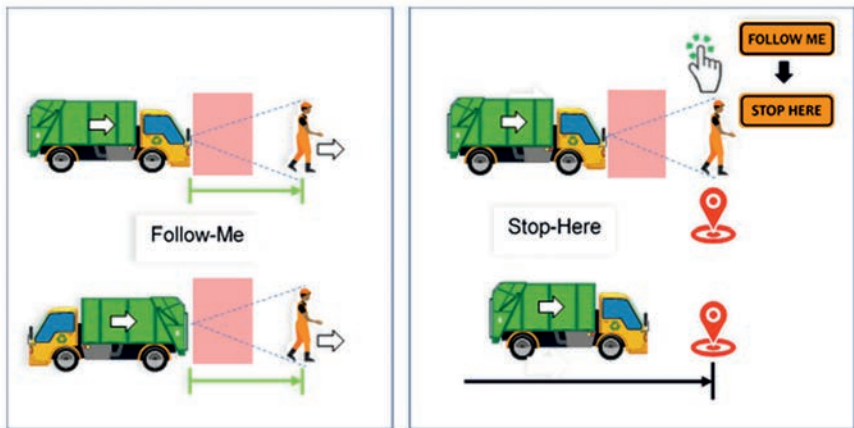fore they leave the corridor to gather a trash bin.

Fig. 3: Operational AD driving features.

Both modes allow the vehicle to deviate within a pre-defined corridor in case of detected ob-
stacles blocking the optimal route. The solution focuses on creating a symbiotic system defined
by the vehicle/operator interaction, where the operator assumes full control and easily orches-
trates the actions and motion of the vehicle forwards and backwards in both feature modes,
with minimal overhead.

4. Solution for hybrid AD municipal vehicles

Following AVL's process, the use cases are formally decomposed into logical functions. In turn
these are decomposed to function components as presented in Fig. 4:

- Obstacle detection: based on Lidar data, static and dynamic objects are detected.
- Operator assignment: the operator is assigned as a unique object.
- Operator tracking: all detected objects must be tracked over time, all around the vehi-
  cle. The operator is of special importance as he must be differentiated from other ob-
  stacles.
- Following GNSS path: a pre-defined path is recorded and saved as a set of waypoints
  defined by positions and orientation. They are used to set the lateral motion of the
  vehicle.
- Dealing with obstacles: When encountering obstacles, the path planning adopts a local
  deviation in order to pass the obstacle. If the vehicle is unable to generate such a de-
  viation, it will come to a full stop and notify the operator.

- Operator/Vehicle interface: this handles the inputs from the HMI device carried by the operator. This is the gateway of the operator to control the behaviour of the vehicle and orchestrate the whole process. At its core is a state machine, where all states and transitions are modelled.
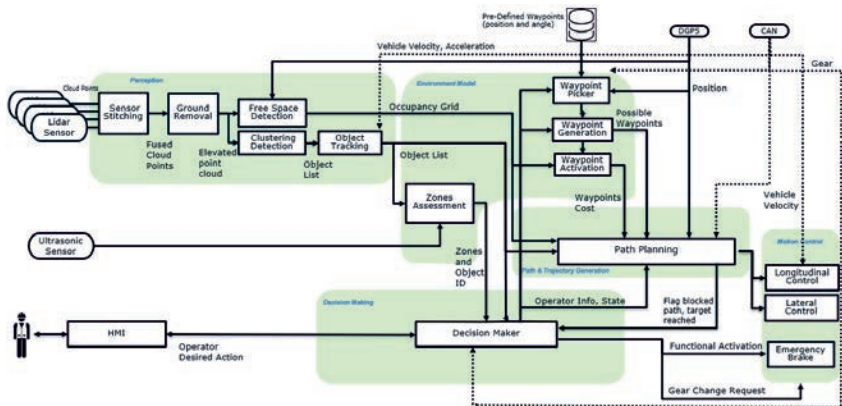

Fig. 4: Main software architecture blocks.

5. Human Machine Interface

The human machine interface is the set of strategies used to allow the operator to control the vehicle. It can be separated into different parts. First the use of the space around the vehicle is modeled to allow the operator to control the motion of the vehicle using his own body place-ment and therefore keep his attention on the surrounding. Then an electronic device is carried by the operator to pass commands, activate operation modes and deactivate/shutdown the vehicle for safety reasons.

5.1 The use of space

The space around the vehicle can be segmented in the areas as represented in Fig. 5, the vehicle zones definition. Note that the exact shapes can be calibrated to represent anything from an ellipse to a rectangle.

The sensor range is limited by the physical limitation of the sensor setup. The observation zone is the space around the vehicle where the operator is expected to be moving, it must be cali-brated to allow the operator to collect the garbage bins while being tracked reliably.

The Follow-Me zones are located at the front and rear of the vehicle, they allow the operator to set the vehicle in motion by moving further away from it creating a distance. The vehicle in turn tries to close the distance, hence following the operator. To obtain a smooth behaviour, the operator is not only tracked for his position but also for his velocity, which can be used to as a target set point for the vehicle.
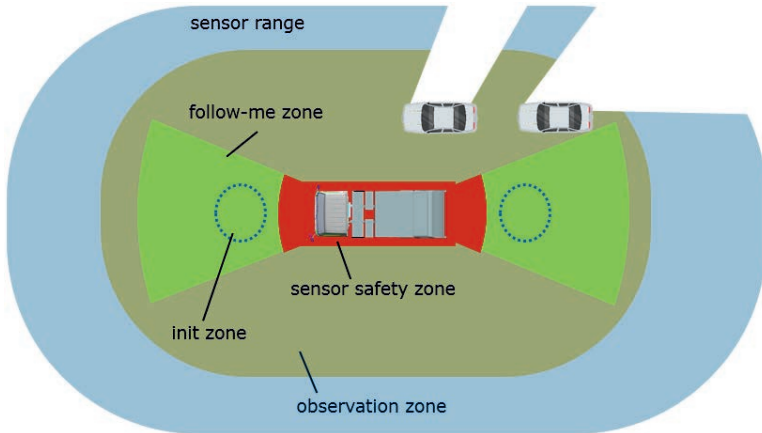

Fig. 5: Vehicle zone definitions.

The initialization zones are located at the front and rear of the vehicle and define a limited space in which the operator can be assigned in combination with the use of the electronic device. This is a key feature of the safety process, as the operator takes responsibility for the environment by confirming he is the correct detected object to be tracked; the operator must ensure not only his readiness to initiate the process , but also that the surrounding area is safe for himself and the vehicle. The vehicle is then set in a forward or backward motion based on the initialization side, upon confirmation by the operator.

The safety zone is also a key element of the safety concept; it delimits a proximity space around the vehicle that shall not be breached while the features are activated.

5.2 The Electronic Device

The feature modes (Follow-me and Stop-Here) are modelled in a state machine as shown in Fig. 6. The device is carried by the operator and allows him to control the state transitions. A minimalistic approach was chosen here; to allow the operator to keep his focus on the surround and on the vehicle itself, the transition options are presented; the operator can only choose

among the possible modelled transitions. The HMI server located onboard the vehicle ensures a stable communication between both. The state machine is embedded in the Decision Maker function on the ASW.
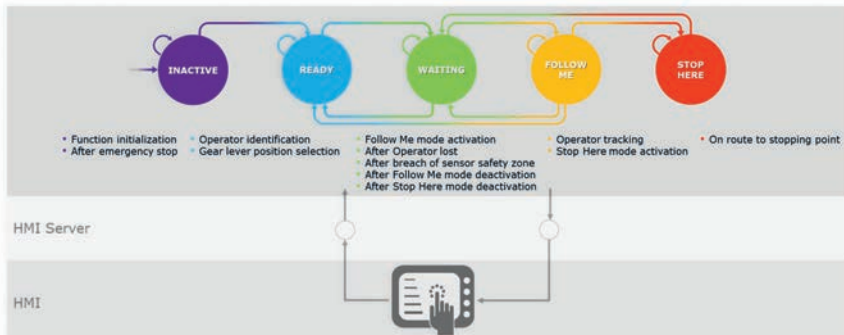

Fig. 6: Automation state machine.

The inactive state represents the state in which the vehicle can be driven manually; no automation is active. The transition to ready turns on the systems and initializes all perception functionalities, namely the object detection and tracking.

In ready state, the objects around the vehicle are tracked and assigned to the zone definitions. Once an object enters an initialization zone, the transition to waiting is proposed to the operator, displaying the driving direction. At this moment, the operator must ensure he is indeed the object located in the initialization zone and that no errors are present. The system only allows for one initialization zone to be occupied for safety reasons.

The confirmation by the operator via HMI device allows the transition to state Waiting. Here the operator can revert to the previous state by releasing the operator, or transition to one of the operation features.

5.3 Driving Cycle

The following example presents how the operator is guided through the state machine by being presented with only two options at any given time. This ensures his attention is not

compromised by unnecessary actions. In Fig. 7, a driving cycle is illustrated on the HMI in which the operator activates both Follow-Me and Stop-Here features.
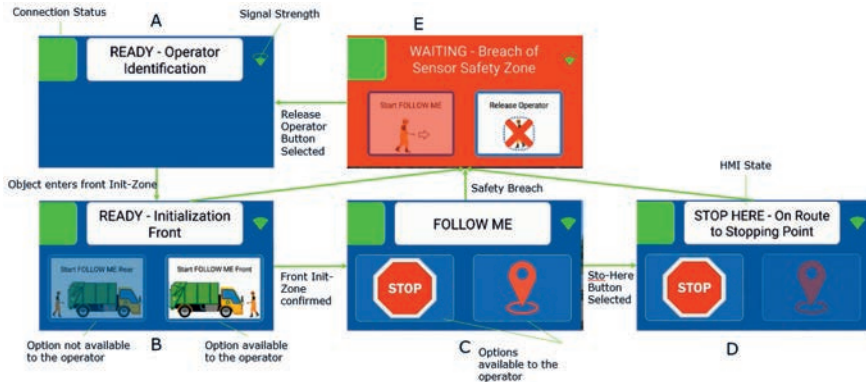

Fig. 7: HMI display for the operator during driving cycle.

The operator is presented with the connection status and the signal strength at all time. Additionally, the visualization relies on three areas. The state is clearly presented and stated at the top of the screen. Bellow, the (maximum two) options are displayed. Note that no longer valid options are greyed out. This is the case when the operator is located in the front initialization zone: the rear one is deactivated to ensure that the system is not initialized with the wrong object being tracked.

In case of a breach of the safety zone, the operator's attention is driven to the device by a strong vibration and the dominant colour red informing the operator that while in movement he or something else was found too close to the vehicle. An emergency stop is also triggered.

First the operator turns the system on (A) and walks in front of the vehicle entering the front initialization zone (B). Once the front initialization is confirmed with the correct button, the Follow-Me mode remains active (C) until Stop-Here mode is activated (D). When an object is detected too close to the vehicle, the system interrupts the motion and notifies the operator (E).

6. Vehicle Automation and Safety Considerations

Based on logical functions, requirements are broken down towards specific vehicle, perception and safety capabilities. Vehicle modifications including sensors, actuators and safety equipment are depicted in Fig. 8. The sensor concept was first developed within simulation (Vires-VTD) and validated accounting for the vehicle geometry and use cases.
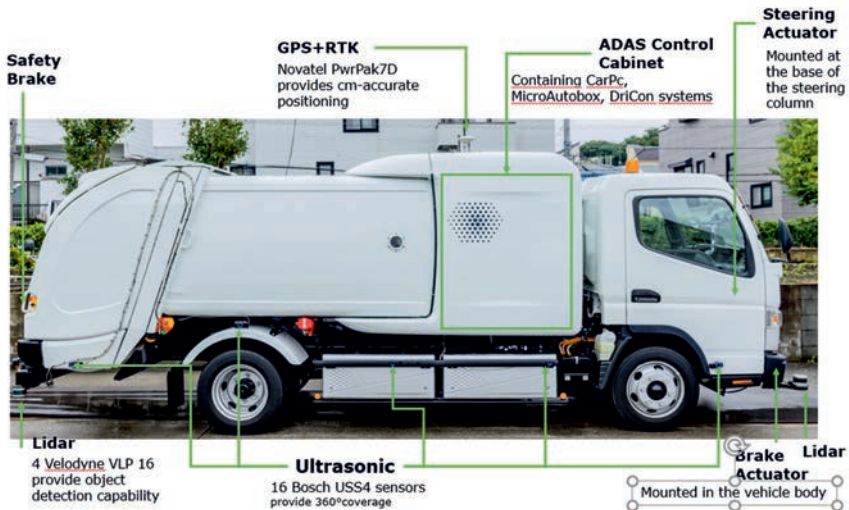

Fig. 8: Refuse collection vehicle fully equipped.

Due to the close distance between vehicle, operator and obstacles, the safety considerations shaped to a large extent the design of the sensor concept. Lidar sensors are the main source for detection of objects and tracking them. Four sensors are placed at the corners of the vehicle and offer a full 360° coverage of the vehicle's surroundings. To ensure a multi-mode safety zone surveillance, ultrasonic sensors are also used in close range to the vehicle.

To ensure working safety for developers and test engineers working in close distance to the prototype vehicles, additional prototype safety features were implemented following basic Functional Safety Analysis. Safety driver override capabilities and remote controls for emergency brake actuation were considered as main countermeasures, supporting software functions controlling safety zone breaches, HMI controlled stops and connection loses. Vehicle

actuation and interfaces were implemented on AVL DriCon™ hardware ensuring real-time control and in-built safety features too.

Finally, a GNSS with RTK correction and built-in IMU fusion ensures centimeter-accurate localization. Utilizing two receivers on the vehicle allows for a high-precision heading angle estimation.

The vehicle implementation was carried out equally considering the design and functional requirements, thanks to the cooperation of highly specialized departments at AVL and MTBFC.

7. Functional Results

The deployment of the vehicle into an are must be carefully planned since it relies on a pre-recorded route. It is therefore important to have the driver surveying the route, ensuring all safety conditions are met, and recognizing the locations where his attention is most needed (intersections, garage exists, pedestrian crossings, etc.). The recording is performed with the same vehicle, at the target velocity and attention is given to keep a safety distance to static obstacles This will ensure that once in automated functioning, the vehicle will reach all desired locations.

The recorded route must then be analyzed and processed. Of special importance are the intersections resulting in branch points and connection points as seen in Fig. 9 (left), in which the operator has the option of leading the vehicle either left or right. To do so, he must know the route beforehand and use the space. By sticking to either side the vehicle interprets what the desired route is. This allows the operator to focus on the intersection itself, instead of controlling an HMI device to pass the desired route.
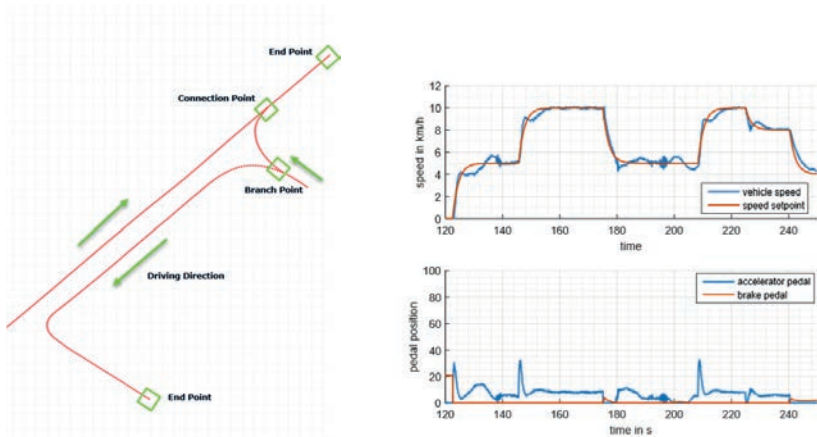
Fig. 9: Left: route recording and processing. Right: smooth longitudinal control.

The recorded route or route segments are then post processed and unified. Smoothness of the route is taken into account and all overlaps are eliminated creating clearly identified and unique branch and connection points.

The implementation of the functions in the vehicle were done in a distributed system between the CarPC and the MicroAutobox. For the CarPC, ROS was selected as middleware since its numerous libraries and toolboxes ease the calibration process and the visualization of the signals using RViz. In Fig. 10 the operator stands in the front initialization zone. The system recognizes the object-operator and represents it with a blue rectangle; the occupancy of the front initialization zone is also correctly represented in red.
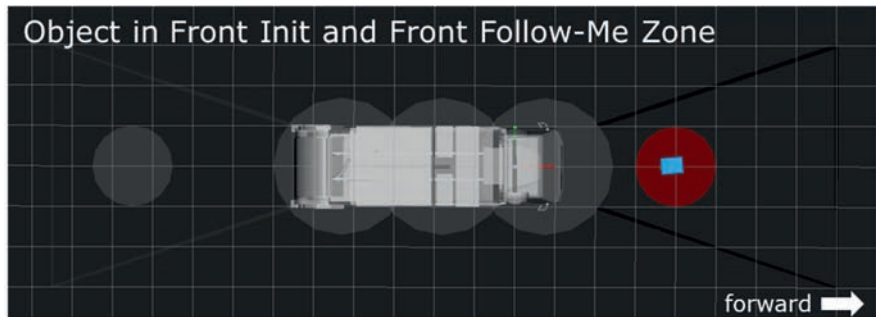
Fig. 10: Operator initialization depending on different zones defines the vehicle driving direction.

The motion control is split in longitudinal control and lateral control. Considering the low speeds of the vehicle and the relatively generous radius of curvature, the Stanley controller well known in the literature [7] was chosen.

The longitudinal control posed a bigger challenge due to the difficulty of keeping a vehicle moving at a very low speed keeping distance constant to the operator. Additionally, there is a clear requirement of reaching certain points at target velocities. The solution passed by designing a feedforward control, modelling the forces on the vehicle, the conversions to torque and to pedal position. The complex modelling was supported by the AVL tool VSM [8]. The results can be seen in Fig. 9(right)**Fehler! Verweisquelle konnte nicht gefunden werden.**, where the vehicle output follows well the setpoint values for both accelerating and braking motions.

8. Summary

Developing hybrid AD system solutions, with dynamic driving tasks performed partly automated by the vehicle and partly manually controlled via remote control from an accompanying operator, shows to be a promising strategy for future AD applications. Thereby the operational design domain of the AD system could be increased significantly while keeping technical complexity and hardware costs down. Moving decisions for complex situations from system to operator require a structured analysis of human machine interfaces and iterative testing, user-acceptance benchmarking and development.

One important step considering the implementation of hybrid AD features is a thoroughly performed feasibility phase, investigating certain feature realization and consequently comparing against cost-efficiency. User interaction and acceptance needs to be evaluated constantly during the project to ensure a successful potential market introduction.

Fast prototype implementation of complete features is crucial and must be realized on vehicles in early project phases. Especially for benchmarking the operator interaction with the automated system, the perceived safety of the operator working in close distance to the vehicle is important for acceptance. AVL's portfolio covering all necessary steps from system design, prototype build-up, software development and testing facility is a key enabler for efficient realization of AD solutions.

Open questions for future research and development projects will be to analyze efficient solutions to select between automated driving, local remote-control by operators and teleoperation from back office. Such triangle might be the optimal solution for keeping the system complexity low while extending the ODD to a maximum and optimizing the utilization of human drivers.

With such split of responsibilities additional questions will rise on how to solve legal issues within those shared operation tasks. Furthermore, we must deeper investigate all safety relevant cases of hybrid AD operation.

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Towards the standardization of a high speed truck-trailer data connection

Dipl.-Inform. **Konrad Feyerabend**,
Dipl.-Ing. (TU) **Andreas Goers**, ZF Group,
Commercial Vehicle Control Systems, Hanover, Germany

Truck Trailer communication today

Europe & ROW

North America

On Brake Connector (ISO 7638)
• CAN Bus 125kbit/s according to **ISO 11992-2**
• 100% market penetration (Europe)
• EBS (Brake by wire)
• Running Gear (suspension, axles, tires)
• Trailer Geometry Data
• Trailer DTC

ISO 7638
Brake Connector
Layout

On Light Connector (ISO 12098)
• CAN Bus 125kbit/s according to **ISO 11992-3**
• est. 10% market penetration
• All other than Braking and Running Gear:
   • General Purpose (Engine, Speed, Lights)
   • Military (IR lights)
   • Automated Commanded Steering Function
    (objects in lanes)
   • Trailer VIN data

ISO 12098
Light Connector
Layout

On Trailer Connector (SAE J560)
• Power Line Carrier (PLC) 10kbit/s
  according to **SAE J2497**
• 100% market penetration (mandatory)

PLC Messages
• ABS and brakes
• Stability control
• General trailer information

SAE J560
Connector Layout

Source: Connector images by Ehsnils CC BY-SA 3.0, wikimedia.org

Industry Drivers of the Evolution – Example Bandwidth Requirements

Feature
Evolution

e. think. act.

**Very high bandwidth
> Gbit/s**

360° high resolution
surround camera,
uncompressed

**High bandwidth
Gbit/s**

360° 2D Surround
(camera) view,
compressed

Cargo Space Camera

360° 3D (radar /lidar /...)
data

**Medium bandwidth
100 Mbit/s**

Rear view Camera

Detailed surround objects

Full sensor and actuator
data sets

Bandwidth
required
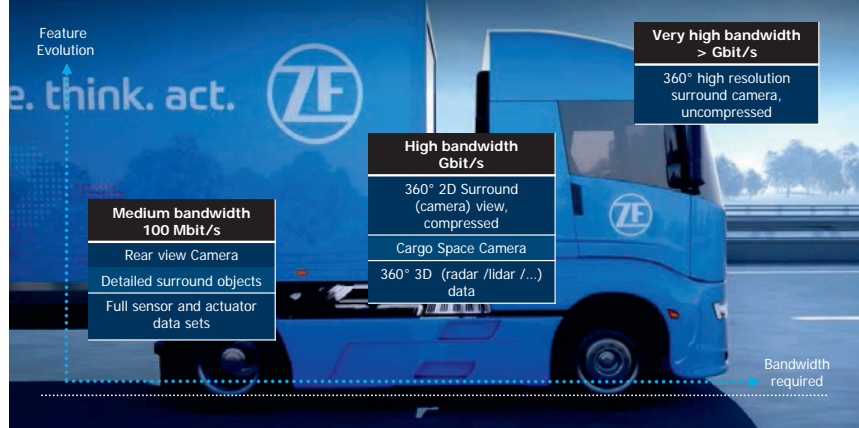
Truck-Trailer Link Usage Example: ZF Advanced Reversing Assist

Agenda

01 Truck Trailer Communication Today

02 **Ongoing Research Activities and Their Findings**

03 Standardization Planned

04 Protocol Stack Considerations

05 Outlook and Conclusion

European research activities

FAT – VDA Research association automotive technology

WG 9: „Fast broadband data communication between Truck and Trailer as prerequisite for highly automated commercial vehicle driving"

Setup

- Working group started in 2018
- Joint work of truck and trailer manufacturers and suppliers
- Focus on wired transmission since wireless cannot support safety, latency and jitter

Scope of work

- Capture and classify requirements
- Analysis of available high speed transmission technologies
- Feasibility to reuse **existing Light and Brake connectors**
- Function and robustness tests with different technologies

Creating a multi brand standard for a complete vehicle road train network with high bandwidth for the next decades

ISO 7638
Brake Connector
Layout

ISO 12098
Light Connector
Layout

Source: Connector images by Ehsolls CC BY-SA 3.0, wikimedia.org

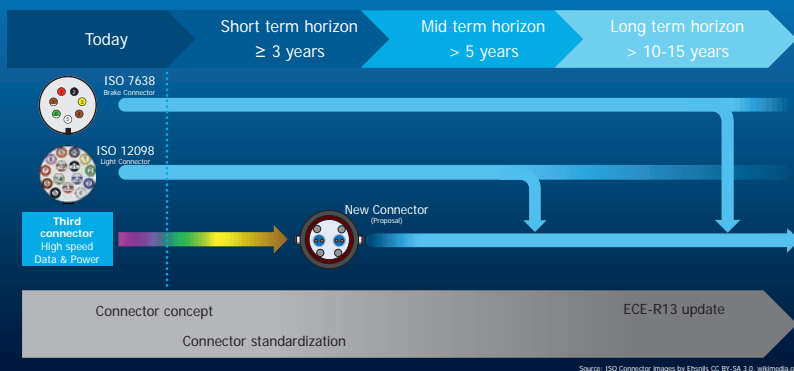## FAT – VDA Results and Recommendations

- Existing connectors and cables
  - **Need modification** even for the lowest requirement class 3 (100 – 750 Mbps)
  - Are **NOT** capable for requirement class 2 (1 Gbps)
- Similar effort expected to standardize class 2 and class 3 requirements
- Most Automotive Ethernet standards are limited to 9 m cable length
- IEEE Standard 802.3 bp 1 Gbps provides 40m channel specification (type B) which is perfect for CV market

- 1 Gbps @ 40m requires new type of connector and cables → **3rd connector**

Vision

A new connector that replaces all existing connector (Light and Brake) functionality long-term

The report is published (German language) and can be downloaded for free:
FAT-SCHRIFTENREIHE 340 - VDA

High speed Truck-Trailer Link → The Vision

| Today | Short term horizon ≥ 3 years | Mid term horizon > 5 years | Long term horizon > 10-15 years |

ISO 7638
Brake Connector

ISO 12098
Light Connector

Third connector
High speed
Data & Power

New Connector
(Proposal)

Connector concept

ECE-R13 update

Connector standardization

Source: ISO Connector images by Ehmiîs CC BY-SA 3.0, wikimedia.org

Related Research Activities

SAE

TMC (Trucking Maintenance Council)
TMC S1: „Next Generation Truck-Trailer Interface"
TMC S7: „Next Generation Trailer Electrical/Electronic Architecture"

- Identified need for higher speed truck-trailer communication

- Immediate need to introduce more bandwidth

- Also looking into new connector concepts for the North American market

Adjacent Industries

AEF (Agricultural Industry Electronics Foundation) also selected 1Gbps @ 40m for HS-ISOBUS

TCN (IEC standard: Train Communication Networks) addresses dynamic reconfiguration of connected vehicles

Common use of Automotive Ethernet standards

Agenda

01 Truck Trailer Communication Today

02 Ongoing Research Activities and Their Findings

03 **Standardization Planned**

04 Protocol Stack Considerations

05 Outlook and Conclusion

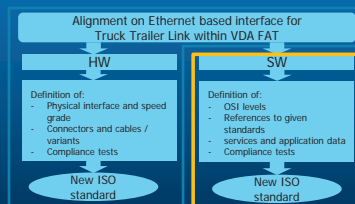## Standardization as key enabler of future technologies

ISO

Parallel standardization paths
As soon as Ethernet technology was the aligned interface,
the **protocol standardization** was initiated

Advantages of a separate **SW protocol standard**

- HW independent
  - Different connectors possible
  - Same protocol → same ECUs reusable worldwide

- Alliances with similar organizations
  - SAE (Society of Automotive Engineers)
  - AEF (Agricultural Industry Electronics Foundation)

Alignment on Ethernet based interface for
Truck Trailer Link within VDA FAT

HW	SW
Definition of: - Physical interface and speed grade - Connectors and cables / variants - Compliance tests	Definition of: - OSI levels - References to given standards - services and application data - Compliance tests
New ISO standard	New ISO standard

Active and passive support of the standardization is welcome
- ✓ Proposals and contributions
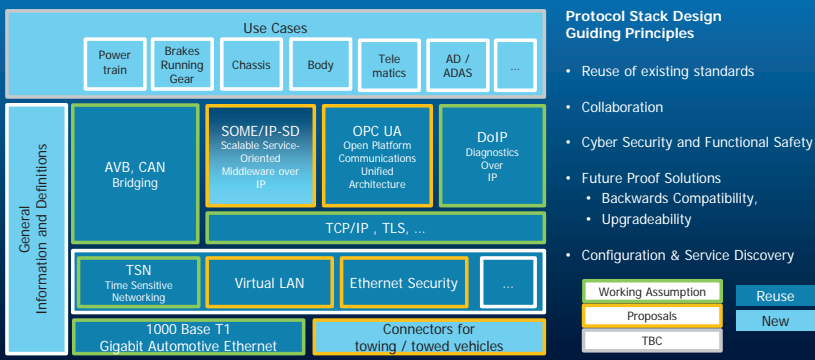- ✓ National ISO representation – support for the initiative

Region specific distinctions

	ISO	SAE / North America	Alignment
Wiring, Physical Layer	Agreed: Gigabit Ethernet 1000 Base T1, shielded	Proposed: Gigabit Ethernet 1000 Base T1, shielded	(✓)
Protocol Stack	New work item proposal (see next slides)	Discussion just started	(✓)
Truck and Trailer Connectors	Proposal: New connector • 2x power • 2x high speed data	Several proposals: Extending existing SAE J560 connector	(?)

Agenda

01 Truck Trailer Communication Today

02 Ongoing Research Activities and Their Findings

03 Standardization Planned

04 **Protocol Stack Considerations**

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Truck-Trailer Link Protocol Stack
State of Discussion in the Committees

Use Cases

| Power train | Brakes Running Gear | Chassis | Body | Tele matics | AD / ADAS | ... |

General Information and Definitions

AVB, CAN Bridging

SOME/IP-SD
Scalable Service-Oriented Middleware over IP

OPC UA
Open Platform Communications Unified Architecture

DoIP
Diagnostics Over IP

TCP/IP , TLS, ...

| TSN Time Sensitive Networking | Virtual LAN | Ethernet Security | ... |

1000 Base T1
Gigabit Automotive Ethernet

Connectors for
towing / towed vehicles

Protocol Stack Design Guiding Principles

- Reuse of existing standards
- Collaboration
- Cyber Security and Functional Safety
- Future Proof Solutions
  - Backwards Compatibility,
  - Upgradeability
- Configuration & Service Discovery

Working Assumption		Reuse
Proposals		New
TBC		

Protocol Standards Under Consideration

Physical
- IEEE/ISO/IEC 8802-3-2021 - Telecommunications and exchange between information technology systems

Network & Topology
- IEC 61375-1:2012 Electronic railway equipment - Train communication network (TCN) - Part 1: General architecture
- IEEE 802.1Q – Virtual Local Area Network
- IEEE 802.1AB – Link-Layer Discovery Protocol (LLDP)
- IEEE 1722 – Layer 2 Transport Protocol for Time Sensitive Streams
- Time-sensitive Network (TSN) Standards (see next slide)

Security
- IEEE 802.1X Authentication and Authorization

Application and Service Communication
- IEC/TR 62541-1 OPC Unified Architecture – Part 1: Overview and Concepts
- Scalable service-Oriented Middleware over IP (SOME/IP)
- ISO 17215 – Road vehicles: Video communication interface for cameras
- ISO 13400 – Road vehicles: Diagnostic communication over Internet Protocol (DoIP)
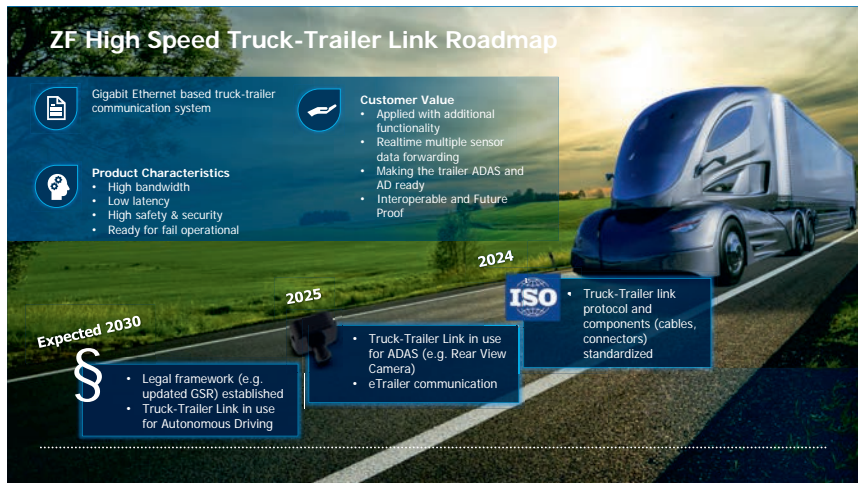
◆IEEE

ISO

IEC

Considered TSN Standards

Category	IEEE 802.1 Standard	Description
Time Sync.	AS-2011	Timing and Synchronization for Time-Sensitive Applications (gPTP)
	AS-2020	Enhancements to 802.1AS-2011
Traffic Shaping	Qav-2009	Forwarding and Queuing Enhancements for TSN
	Qbu-2016	Frame Preemption
	Qbv-2015	Enhancements for Scheduled Traffic: Time-Aware Shaper (TAS)
	Qch-2017	Cyclic Queuing and Forwarding (CQF)
Availability & Reliability	CB-2017	Frame Replication and Elimination for Reliability (FRER)
	Qca-2015	Path Control and Reservation (PCR)
	Qci-2017	Per-Stream Filtering and Policing (PSFP)
System Configuration	Qat-2010	Stream Reservation Protocol (SRP)
	Qcc-2018	SRP Enhancements and Performance Improvements
	Qcp-2018	YANG Data Model

Agenda

01 Truck Trailer Communication Today

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05 **Outlook and Conclusion**

ZF High Speed Truck-Trailer Link Roadmap

Gigabit Ethernet based truck-trailer communication system

Customer Value
- Applied with additional functionality
- Realtime multiple sensor data forwarding
- Making the trailer ADAS and AD ready
- Interoperable and Future Proof

Product Characteristics
- High bandwidth
- Low latency
- High safety & security
- Ready for fail operational

2024
- Truck-Trailer link protocol and components (cables, connectors) standardized

2025
- Truck-Trailer Link in use for ADAS (e.g. Rear View Camera)
- eTrailer communication

Expected 2030
- Legal framework (e.g. updated GSR) established
- Truck-Trailer Link in use for Autonomous Driving

Conclusion

1. Truck-Trailer Communication needs significantly higher bandwidth in future
   - Redundant Gigabit Ethernet recommended

2. Research and Standardization
   - Good progress on physical layer and connectors
   - Protocol Stack started

3. Your input & support is required
   - Truck and trailer OEMs
   - Future users
   - Suppliers

Automated and networked city buses

Optimized, demand-oriented service through intelligent use of data

Nicole Rossel, **Martin Sommer**, **Eric Sax**,
Karlsruhe Institute of Technology, Karlsruhe

Abstract

Developments in the sector of trucks and busses are influenced by the rising availability of various kinds of data. In order to be effective, on the one hand this fact will be assessed in terms of the impact on the operation. On the other hand, the automation of vehicles will be enabled by the application of big data analytics and artificial intelligence (AI). In general, the availability of large amounts of data generated by automated and networked city buses in service will influence several areas of public bus transportation. Interactions with motorists and cyclists, constricted traffic space due to road works or dense crowding at bus stops are just a few examples of the daily challenges during the operation of city buses in urban areas. In addition, the potential of new data driven technologies will influence the daily operation and maintenance of the buses, which will be shown on the example of automated doors and HVAC[1] control.

1 State of the Art and Motivation for data driven technologies

1.1 Automated Driving

One of the greatest challenges in automated driving (level 4 and level 5 according to SAE[2]) is the predictability of situations. This concerns the planned route of the ego vehicle, but also the dynamics of other road users and pedestrians. Looking at the ego-vehicle, the route results from the starting point and the desired destination. It is a source of valuable data to have a line network plan, defined stops and thus a reduced number of variants like you have for city busses. If you also know how environmental data (e.g. weather, traffic, etc.) will affect the route, you can use this information to derive advantages. Iterative learning on the route brings you much further along in the automation task than with an initial, unsophisticated approach. In public transportation, these influencing variables can be captured with constantly improving probabilities by a fleet that is on the road 365 days a year and that also passes on knowledge

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1 HVAC: Heating, Ventilation, Air Conditioning
2 https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic

from the first journey of the day to the subsequent ones. This knowledge can be used to optimise the driving task and the auxiliaries as well.

1.2 Flexible transport volume

In order to ensure high-performance and efficient local transport, it makes sense to adjust the transport volume depending on the current demand. Sethuraman et al. [1] showed in their analysis the effect of bus platoons on the traffic flow and the energy consumption. By combining several vehicles into a group, the so-called platoon, a more continuous flow of traffic is ensured in the inner-city. The challenge and at the same time the potential is to save the driver in the following vehicle(s). Platooning becomes particularly attractive when buses from different lines form a platoon in high traffic and high demand areas and separate again in less demanded marginal areas or intersections.

1.3 Efficient use of human resources

Fuel costs are counterbalanced by personnel costs. In middle Europe these costs form more than 50% of the annual costs in public bus transportation. If a system exists which is able to assist the driver during his job, the driving itself is not so exhausting anymore and the driver is able to drive for a longer time. As a result, the throughput can be maintained or even increased with less human resources.

1.4 Environmental Impact

For reasons of environmental protection and the health of the inhabitants, more and more cities are attaching importance to a transport infrastructure with the lowest possible environmental impact. Public transport can make a decisive contribution to this by data driven energy reduction and intelligent and individualized mobility offers.

1.5 Vehicles with alternative drive systems

Since trams and underground trains in inner-city areas are already locally emission-free, the electrification of city buses offers the greatest potential for reducing the environmental impact. To achieve this, the vehicles that have so far run predominantly on diesel will be replaced by locally emission-free alternatives step-by-step. Currently, research is focusing primarily on battery and hydrogen-powered vehicles. In order to ensure the most efficient operation with longest range, the performance indicators of an electrified powertrain for the vehicles must be further improved and the operation strategy can be optimised again based on fleet data.

1.6 Predictive maintenance

Further saving possibility is given by predictive maintenance. A significant economic loss is caused by poor timing within the substitution of spare parts. Up to 50% of them are substituted too early or too late. A replacement too early has economic disadvantages as spare parts are

not used until their end of life. Waiting too long for the inspection and replacement might have more cost-intensive consequences such as a breakdown on the route. This challenge can be solved by an approach of big data analytics and a prediction of the state of one component or system during the on-going operation.

1.7   Control-over-the-Air

New, high-performance data transfers (5G ff.) allow vehicle parameters to be updated "over-the-air". Soon, not only will this be possible for updates, but also functions located in a "cloud" will control the vehicle directly. In the foreseeable future, this scenario will not take place for safety-critical functions, but comfort applications are already implemented as prototypes today.

2   Automated and networked city buses to optimize operations and demand-oriented service

As addressed in chapter 1, automated driving will be an important topic in the city bus sector. Through the use of this technology several of the topics mentioned in chapter 1 can be bundled together to achieve the maximum benefit. In the following the focus is on the impact of the amount of available data of the automation and networking of vehicles and the resulting opportunities.

2.1   Automated driving on the base of big data and its impacts

The challenges of automated driving are particularly the automation of the vehicle´s longitudinal and lateral control. In order to accomplish this, environmental data of the vehicle is needed. This data can be generated by sensors that observe the vehicle's surroundings, like Camera systems, Radar, Lidar or Ultrasonic sensors.

Additionally, environmental information can be received via vehicle-to-everything (V2X) communication. This can be, for example, information about traffic jams, hazard zones or road works.
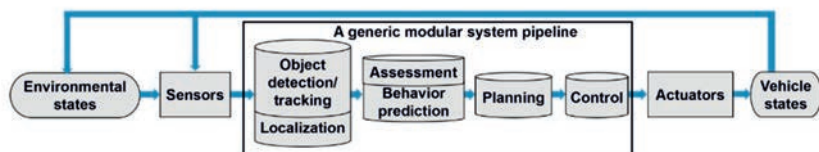

Fig. 1: Components of an automated driving system [2]

As seen in Figure 1, after recording the environmental data and states, further functions are required. This includes a reliable object detection, localization, behaviour prediction and a

trajectory planning. In the following, the control values for the actuators are determined by control functions. Together with the monitoring of the vehicle status, these steps form the tasks that need to be solved for automated driving. [2]

Depending on the degree of automation of these steps, different levels of automated driving are defined by the SAE[2]. Level 4 of this definition means that a driver is no longer needed to fulfil the driving task in limited or all conditions. Level 5 will even replace the driver constantly. Unfortunately, the current legal requirements forbit driverless vehicles on public roads. But starting with restricted areas such as depots as analysed in [3] or bus rapid transit (BRT[3]) the first test fields are found[4].

Within the context of vehicle automation, the current focus is primarily on the automation of the driving task itself. But especially in the sector of city buses, however, the driver is responsible for several additional tasks during the operation of the vehicles apart from driving. Checking the functionality of important components such as brakes, interior and exterior lights and the doors are, for example, tasks to guarantee a safe and reliable operation. Another important task is the monitoring of the interior. If there is an emergency or a dangerous situation in the bus, the driver has to react in an appropriate way to ensure the safety of the passengers. To manage the transition to a fully driverless service and thus to achieve an economic advantage, these tasks must also be automated.
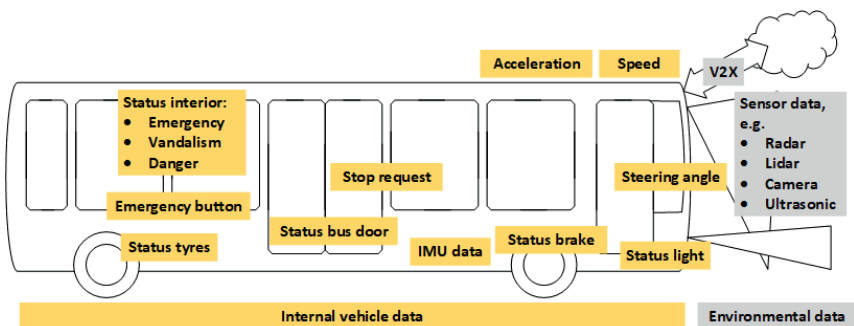

Fig. 2: Important vehicle data needed for a full automation

In the first step, the data required for this automation must be available. As shown in Figure 2, this necessary data is part of the internal vehicle data. For a reliable operation, this data must

be captured in addition to the environmental information. This can be done by using additional sensors or by evaluating existing vehicle protocols on the communication busses.

Together with the sensors needed for automation of the driving task, a large amount of data is available for further application and evaluation. As shown in [5] within the automation, the implementation of over 200 sensors is required in current and future vehicles. Thereby an amount of 4.000 GB will be generated every day and is available for further processing.

However, some of the required data cannot be acquired directly by means of sensor technology and must be generated first through the use of suitable algorithms. An example of this is the monitoring of the interior, which can be recorded by camera systems, but the decision whether there is an emergency must be taken by an evaluating software based on machine learning algorithms. Simple systems can only distinguish between functional and defective. But if this vehicle data is made available with the help of big data analytics or Artificial Intelligence (AI), efficient monitoring can be ensured and thus a significant added value could be created. In [6] the coordination of automated vehicles und the individual vehicle control systems are mentioned as two main applications of big data analytics. But the majority of current approaches, such as [7], relate the use of big data to the automation of the actual driving task. To demonstrate the use in further automation steps with a concrete application, in subchapters 2.3 and 2.4 we will address the potential for diagnosis, in form of predictive maintenance, based on the data that will be available.

2.2 Optimization of daily operation by networking city buses

Through the use of wireless technologies, a communication between several vehicles (Vehicle-to-Vehicle, V2V) or between vehicle and infrastructure (Vehicle-to-Infrastructure, V2I) could be realized. In case of passenger cars this communication can result in increased safety and better traffic flow. [8]

This also applies to city buses, but here a further important factor must be considered: Already today, it is common for public transport vehicles to communicate with the control centre during the circulation. By networking every bus of a fleet, the information obtained about the status of the individual systems can be transmitted to the control centre. Anomalies, operation profiles, sensor and protocol data make it possible to generate a comprehensive overview of the operating status of each individual bus in a fleet. If necessary repair or maintenance work is known before the arrival of a vehicle, the operating procedures and spare parts procurement can be optimally prepared at the depot. This results in time and cost savings. For the use of electric buses, this data exchange also supports an efficient charging management, as the charging status of each bus can be transmitted before it enters the depot. This means that the vehicles

can be allocated to the charging stations depending on this status and can also be charged in the most battery-friendly way possible to ensure a long battery life.

2.3 Predictive maintenance through artificial intelligence and big data analytics

The current maintenance system used in the automotive industry is based on a preventive approach, where components are either replaced within a schedule (time-based) or with the help of diagnostic data (condition based) (see Figure 3).

With the development of big data related techniques (e.g. sensors, IoT) and the ever-increasing size of this data, data-driven predictive maintenance (PdM) has become gripping for the whole industry. Predictive maintenance takes place after equipment diagnosis is performed. By reading sensor data and other diagnostic information, predictive maintenance attempts to analyse the condition (remaining useful life, degradation pattern, health status, etc.) of the equipment and to predict what type of maintenance is required to minimize costs and increase the equipment's lifetime [9][10][11].
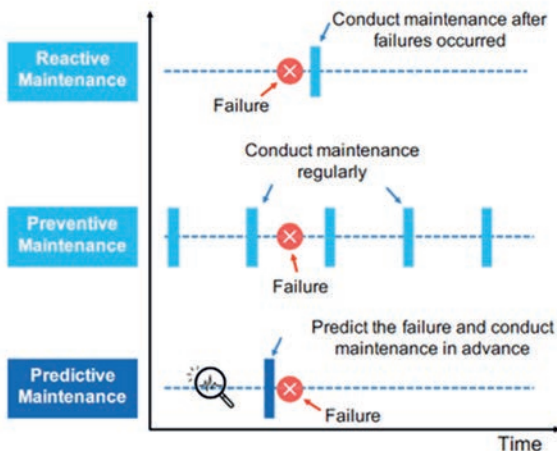

Fig. 3:   Maintenance plans of Reactive Maintenance, Preventive Maintenance and
          Predictive Maintenance [8]

To extract useful knowledge and make appropriate decisions from the available data, machine learning (ML) techniques have been regarded as a powerful solution. Figure 4 shows a proposed system architecture that integrates the emerging advanced technologies to create a functional system that allows the implementation of data-driven PdM.

The system functionality is initiated with the "Data Acquisition" module, where the data from several sources is collected via "wireless sensor networks" and stored in a data warehouse. Then the data will be fed to the "Data Pre-processing" module, where data cleaning, data integration, data transformation and feature extraction are conducted. The output of this module will be used as the input of "Data Analysis" module, where advanced data analytics and machine/deep learning are used to perform the knowledge generation.

The "Decision Support" module will visualize the result of the 'Data Analysis" module and provide an optimized maintenance schedule. Finally, the "Maintenance Implementation" reacts to the physical world according to the maintenance decision and implement maintenance activities to achieve a certain purpose.

2.4 Example: Predictive Maintenance based on a bus door

We applied data-driven predictive maintenance on bus doors in a measurement setup and used the previously described process from data acquisition to decision support as our red line. For data acquisition the bus door was equipped with an inertial measurement unit (IMU) at each door wing for a measurement of the acceleration and by integration the velocity and position. Additionally, the motor current and the operation of the door buttons were recorded.
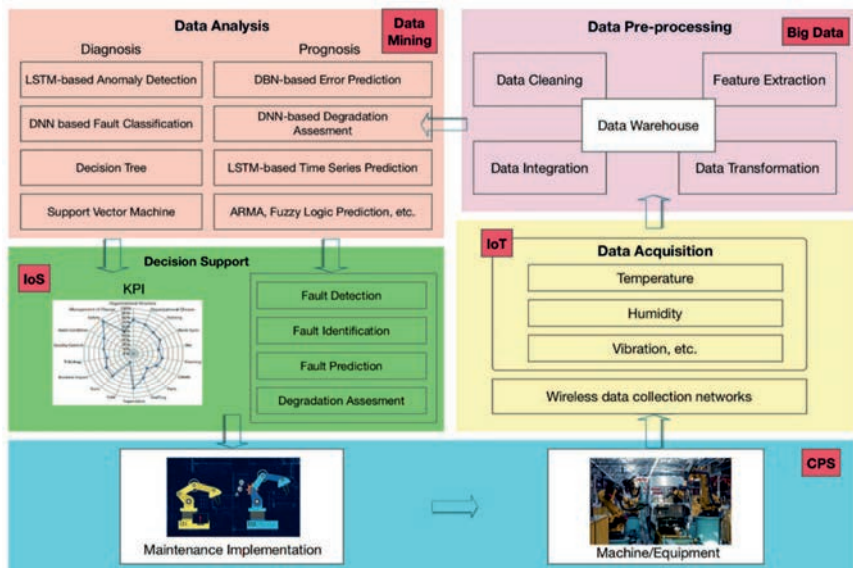

Fig. 4: System architecture for cloud-enhanced PdM (adapted from [12], [13])

Altogether the data summed up to 51 signals and within two weeks 1.7 TB of data were available for data pre-processing and analysis. For the purpose of anomaly detection, error classes had to be defined. These error classes included:

- adjustment of the preload on the rotary column
- wood late in the door
- iron weights on the door wings

The error classes enabled the application of One-Class, Two-Class and Multi-Class classification algorithms (see Figure 5), whereby in the following only the results of Multi-Class will be discussed.

The ML algorithms Decision Tree (DT), K-Nearest-Neighbor (KNN) and Support Vector Machine (SVM) were implemented for the Multi-Class Classification (s.

Table 1). Each error was correctly identified and the lowest False-Negative-Rate was achieved with the SVM performing best.
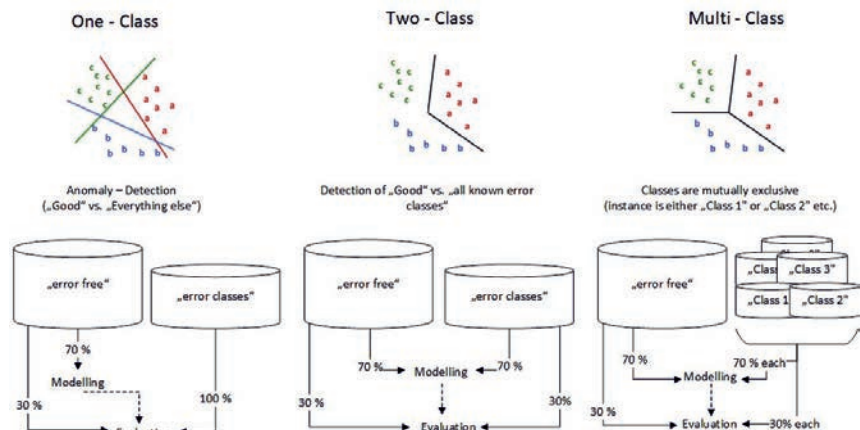
Fig. 5: Data driven classification for the bus door use case

The last step of the system architecture in Figure 4, namely the decision support, was implemented by the use of clustering algorithms which helped displaying the results and finding parameters that had the biggest impact on the results of the classification algorithms.

Table 1: Average True Positives and False Negatives of Multi-Class Classification algorithms over all error classes of bus door data

Algorithm	True Positive	False Negative
Time Embedded DT	80.2 %	19.8 %
Time Embedded kNN	85 %	14.6 %
Time Embedded SVM	87.7 %	12.2 %

3 Deployment in vehicle fleet operation - potentials through federated learning

Networking the vehicles with each other can create additional synergies. For example, information about traffic incidents registered by one vehicle can be quickly passed on to the entire fleet in order to adjust routes and thus ensure better availability and reliability of the busses.

As well, the promising results of this bus door example emphasize not only the potentials of data-driven predictive maintenance. In addition on the next level, namely the vehicle fleet level, the topic becomes even more exciting as we do not only learn parameters of a single bus door but rather the parameter set of many bus doors. The resulting system has the potential to become more robust to strongly varying data and is able to precisely predict bus door failures in order to prevent broken down buses.

3.1 Predictive Maintenance in a fleet

The knowledge of a fleet can also increase the performance of predictive maintenance. In a so called cross-fleet analysis [14] each vehicle is equipped with an extensive log capturing real-time measurements from the various vehicle sensors and the emerging data will be pushed to a central server.

Some of the benefits of a cross-fleet analysis of this data are:

- New types of faults can be identified by comparing the similarities between vehicles' diagnostics data
- Monitoring the normal behaviour of many similar vehicles (e.g. drivetrain, dimensions) is simplified. Consequently, outlier data, which is usually more difficult to obtain, will be easier to identify and extract
- Collecting and sharing knowledge related to investigated situations in order to infer new results that can be used to resolve further similar situations [15]
- Constraints and dependencies of unexpected behavior can be identified

Through the use of Federated Learning, along with this vast collection of data, extensive predictive maintenance models can be built. The mechanics of how to select the data to build these models (i.e., brand-based, location-based, network-based) is still an open question, but the impact a federated learning approach will have on predictive vehicular maintenance in a fleet is indisputable [16].

Large vehicle fleets generate large amounts of data, which on the one hand are suitable for continuously training machine learning methods and on the other hand open up exciting analysis possibilities. These can improve vehicle systems such as the energy management regarding drivetrain, the HVAC system (s. next chapter) and even the scheduling of the charging/refueling process of city buses.

Furthermore, city buses in particular can benefit from an analysis of vehicle data on the fleet. Due to the fact that the bus route is known before the start of the journey and the vehicles usually travel the same routes, continuous experience values can be built up in a central cloud and each vehicle can have access to this database.

Federated Learning is a technique that fits such a fleet learning use case in many ways. The technique has been developed by the Google research department [17]. The idea behind federated learning is to leave the training data for machine learning algorithms distributed on different devices (or vehicles) and to learn a shared model by aggregating locally-computed updates. This basically means that the learning task is solved by a loose federation of participating clients which are coordinated by a central server. Each client has a local training dataset and this dataset is never sent to the server. The current global model at server-side shares its parameters θ but only receives updates (denoted by H_i in Figure 6) of the local models and thus never has access to the local raw data.

3.2   Example: Control-over-the -Air for HVAC in fleet operation

The HVAC function of a city bus can profit immensely from the implementation of federated learning. The HVAC function is strongly influenced by disturbance variables such as passengers entering the bus or door openings at bus stations. These disturbance variables drive the energy consumption of the HVAC function to a level where it may account for up to 40% of the total energy consumption of the bus during extreme outside temperature [18].

A data-driven HVAC function which continuously learns how to handle the disturbances or is even in the position to know when people enter the vehicle and when the door will be opened might be able to reduce the impact of the HVAC system on the overall energy consumption.
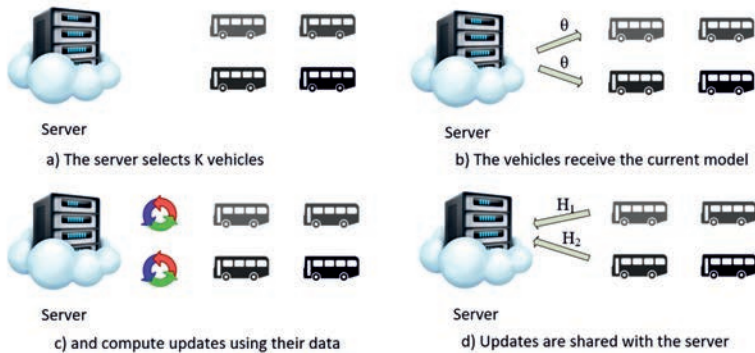

Fig. 6: Basic principle of federated learning (one communication round)

From the technical point of view this can be designed with the development of a Neural Network Model Predictive Control (NNMPC) and the federated learning approach. The central server holds the control algorithm for a whole fleet, where only parameters for different bus types (length etc.) need to be adjusted. Thus, the central server has the potential to control the HVAC system of many vehicles in the fleet and learn its internal neural networks from the operation of each vehicle. This creates an intelligent controller whose performance increases over time in terms of energy consumption and passenger comfort.

3.3   Potentials for energy savings in electric buses

Optimised, predictive control of heating/ventilation/air conditioning (HVAC), for example, saves fuel, electricity or increases range. The auxiliaries especially at cold winter days use more than one third of the battery energy for heating in an electric bus. A weather and demand prediction based on learned reference models relying on fleet data will tremendously increase the efficiency. Holidays of workers and pupils, that influence the door opening and heating of the cabin by persons, will be learned in the fleet database yearly but as well daily, because the bus on the route before can send data about the current demand directly to the cloud where the data model of the day is adjusted. This way the auxiliaries get more and more efficient but as well cycling of the battery especially in a hybrid bus with a range extender (diesel or hydrogen) will be optimized.

Furthermore, a longitudinal assist that helps to save energy of the powertrain including knowledge about topology, traffic signs and speed limits will lead to acceleration and braking models learnt in the fleet. This assist can be an indication in the cluster or a forced feedback paddle in still human driven vehicles.

A study [1] shows that traffic flow can be improved by forming platoons (s. chapter 1.2). At the same time, as an example for the influence of platooning on energy consumption it can be shown that there are around 10% cumulative energy savings in the case of a bus platoon with two vehicles, a 1m intra-platoon distance and a driving cycle with signal priority [1].

3.4   Swarm Intelligence for automated driving by use of data analytics

Mixed traffic from conventional vehicles without assistance systems, from vehicles that are partially automated to fully automated vehicles, will shape the picture on our roads in the fore-seeable future. We will therefore not experience level 5 fully automated driving overnight, but rather we are on a roadmap. Especially in city buses, the supporting longitudinal acceleration to optimize consumption, the automated bus stop approach to protect the rims and tire walls, the automated depot, the special lanes as in the BRT and, last but not least, the bus platooning will gradually pave the way to fully automated driving. Platooning becomes particularly attractive when busses from different lines form that platoon in high traffic and high demand areas and separate again in less demanded marginal areas or intersections. The fleet plays an important role here as well. The fleet is a swarm and artificial intelligence includes the intelligence of swarms as well. Think about demand driven public transportation, platoons that are constructed and decoupled by knowledge in the swarm. Depots can be organized based on self-learning algorithms like in an anthill and busses organize the services, charging and end position autonomously, which is no science fiction anymore.

4   Summary and Outlook

The availability of high performing hardware such as electronic control units, sensors and wireless communication components enable static and real-time analysis of big amounts of data. It this contribution is shown how these potentials can be used to improve public transportation based on city buses. From automated driving to auxiliary management data can be used to optimize comfort and pay tribute to environmental saving.

In addition, from an economic point of view and with regard to the availability of drivers, vehicle automation opens up further options. But in this context, it is important to consider the tasks that a driver performs today and what a gradual elimination would mean. In the field of vehicle automation, the automation of the driving task of longitudinal and lateral dynamics is currently in the foreground. However, especially in the automation of public transport, there are further possibilities and necessities to replace the classic tasks of the driver, to achieve added value

for the passengers and to increase economic efficiency. This can be achieved, for example, by increasing the availability of the vehicles.

Currently, research and development in the field of automated driving in public transport is mainly focused on smaller vehicles, so-called shuttles or people movers. Due to their limited passenger capacity, these are rather unsuitable for use on particularly busy lines or at peak times. In order to guarantee efficient public transport in urban and suburban areas, it therefore makes sense to also consider the automation of proven concepts with larger vehicle capacities. If these points are considered in the development and deployment process of new vehicles and vehicle technologies, the resulting systems will be accepted, high-performing, sustainable and as a consequence an important corner stone in the mobility of the future.

5 References

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Health & safety in public transport

Better climate and optimized hygiene in times of COVID-19

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Abstract

The COVID-19 pandemic has had a massive impact on public transport since the start of 2020. Intercity bus and coach transport has come to an almost complete standstill and there have also been significant changes evident in local transport. From an environmental perspective, any shift toward private transport should be minimized as far as possible.

To make the transport of people as safe as possible despite the present infection risk, innovative solutions must be found in the shortest possible time in consideration of medical, technical and psychological aspects. An agile working group within the development department of Daimler Buses has been set up to address this issue. The participating development engineers are dealing with a new range of topics relating to the SARS-CoV-2 virus in a constantly changing environment that is characterized by uncertainty.

On the basis of scientific findings, the focus is on further optimizing the already excellent indoor air quality in buses.

Combined with additional hygiene measures, an innovative and rapidly implemented filter technology for vehicle air conditioning systems results in an even higher level of safety in buses.

1. Effects of COVID-19 pandemic on public transport

When the news from China about a newly discovered virus first appeared in the media world at the beginning of 2020, nobody could have foreseen the serious impact this would have on the life of society and the economy within Europe and around the world. For public transport and the coach industry in particular, this slump was unforeseen and had a major impact, especially given that, before the pandemic – primarily on account of the debate on climate change and the associated goal of reducing people's reliance on private vehicles – there were signs of very positive developments in these business areas.

Bus travel has come to an almost complete standstill. Even in the brief phases during which incidence rates were at lower levels, regulations within Europe and also within Germany have

not been uniform. At this time, long-distance travel seems almost impossible since each (federal) state that is to be traveled through has its own – sometimes very different – requirements for travel companies. The sometimes widely different specifications for maximum occupancy of vehicles, for example, represent an almost irresolvable problem for the companies. In addition, not all destinations can be called at without restriction. Strong fluctuations in incidence rates and the associated restrictions make travel planning and booking almost impossible. Declines in excess of 90% in some cases in bus rentals and long-distance bus journeys mean that many bus companies have had to deregister their entire fleet.
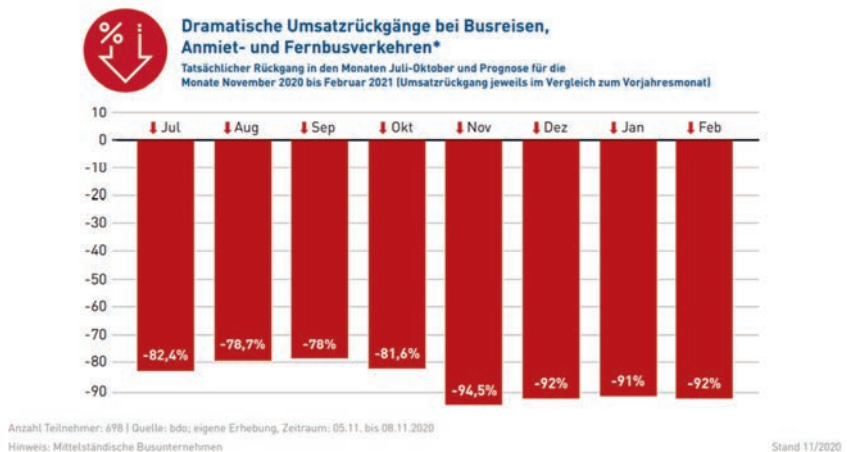
Fig. 1:   Sales decline for bus journeys and long distance bus services,
          source: bdo.org – Der Politikbrief 01/20

Not quite as dramatic, but still clearly noticeable is the simultaneous decline in public transport. In the months following the rapid slump at the beginning of 2020 as a result of the first lockdown, occupancy rates in public transport evened out at between 10 to 50% less than the previous year.

The above mentioned declines in demand are also reflected, virtually unfiltered, in the sales figures of bus manufacturers. This has had a significant impact on employees at the manufacturers, as well as the suppliers, for example, through to 2021.
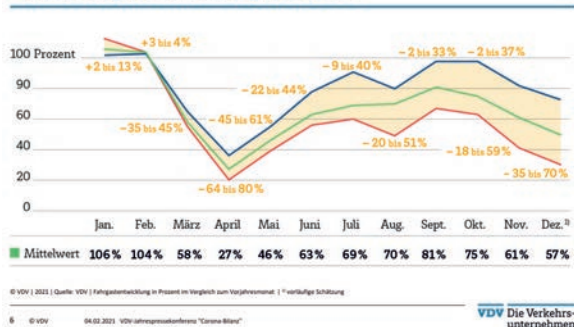
Fig. 2:   Fall in the number of passengers at public transport in Germany, source: VDV

In addition to a general decline in mobility, which can be explained by the lockdown at the beginning of the pandemic, the rise in people working from home, and psychological components related to traveling on public transport, there has also been a shift towards private transport. While increased bicycle use is also helping to reduce CO_2 emissions, an increase in the number of people choosing private vehicles over public transport has a negative impact on CO_2 emissions and, increasingly, electricity consumption. To counter the long-term negative impact of a permanent shift in modes of transport, it is of great social interest to enable the safe use of environmentally friendly buses as quickly as possible.
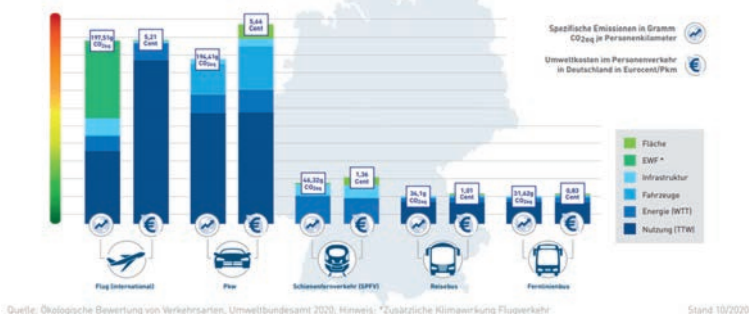

Fig. 3:   Ecological assessment of different modes of transport, source: Umweltbundesamt

A clear picture of the expectations of the public transport vehicle operators quickly emerges. Manufacturers are expected to provide rapidly deployable, simple and affordable solutions. It is important to the companies that the vehicle manufacturers provide clear and communicable information on the general technical conditions – and related passenger safety. However, the top priority for all companies is the protection of their employees, not least the bus drivers, who are exposed to an increased risk of infection due to the time they spend inside the vehicle and the continuous passenger flow. For this purpose, protective glass is requested around the driver's area, which separate the driver from the passengers.

Hand sanitizer dispensers have also been high on the list of requirements since the start of the pandemic. These should make it as easy as possible for passengers to sanitize their hands when boarding or alighting the vehicle.

In the first stage of the pandemic, when uncertainty about the transmission routes of the SARS-CoV-2 virus has not yet been sufficiently scientifically investigated, vehicle manufacturers and service providers are increasingly asking for disinfection options for the entire interior. The request is for complete fogging of the interior with disinfectants to eliminate all potential hazards.

All these demands and requirements need to be addressed as quickly as possible on the basis of current scientific findings and also to take a look at the associated risks. Recommendations by bus manufacturers for customers to use virus-combating measures that in retrospect turn out to be harmful to people or vehicles must be avoided at all costs even in the initial uncertainty of the pandemic. To illuminate these questions in full, a task force has been set up at Daimler Buses within the development department. Supported by Daimler Research and other external research institutions, it will define and implement suitable measures for bus operation.

The objectives are clearly defined:
- Analysis of the actual infection risk inside buses
- Rapid market availability of new, effective hygiene measures
- Affordable costs for bus operators
- Minimizing of risks for drivers, passengers and vehicles
- Retrofitting of existing vehicles
- Strengthening of passenger confidence in buses and public transport
- Active support for the entire bus industry by communicating the facts

2. Complex measures for an increased level of passenger safety in public transport

Before a solution can be identified, the general conditions first require clarification. In the case of a viral pandemic, it is important to identify the primary routes of transmission so that targeted measures may be employed to protect against this.

To paraphrase the Chinese general, military strategist and philosopher Sun Tzu from 500 BC: "To defeat your enemy, you have to know your enemy".

To tackle the significant challenge of procuring the necessary medical knowledge, the task force of engineers consulted with a number of experts, including doctors from occupational health, the public health department and aerosol researchers.

Suitable protective measures shall be implemented on the basis of the scientific findings on the routes of transmission. The three main routes of transmission for respiratory viruses, which include the SARS-CoV-2 virus, are:

1. Smear infection via surface contact
2. Droplet infection
3. Transmission by aerosols

Suitable protective measures can be found for all three transmission routes. The main focus, however, is indoor airborne transmission through droplets and aerosol particles. The Robert Koch Institute stated early on: "Transmission of SARS-CoV-2 via contaminated surfaces has not yet been proven outside the healthcare system." [1]

Since viruses on surfaces can survive for a certain time, but acute infections of the SARS-CoV-2 viruses have not yet been detected via surfaces, and the new virus thus behaves differently than, for example, many bacteria, the focus in the first step is more on the two airborne transmission routes.

To ensure that long-distance bus journeys or journeys on public transport can take place as safely as possible, the cooperation of all stakeholders is required despite the measures initiated by Daimler Buses.

The vehicle manufacturer can develop the necessary technical components and implement them in accordance with the applicable laws and automotive standards, and provide important basic information on how to deal with the prevailing technical conditions.

[1]   Source: RKI, epidemiological description of SARS-CoV-2 and COVID-19
       https://www.rki.de/DE/Content/InfAZ/N/Neuartiges_Coronavirus/Steckbrief.html;jsessionid=DDA
       3E6BF22B43E46BB98EA21ACED280C.internet101?nn=13490888#doc13776792bodyText2

To minimize the risks of transmission and reassure passengers of the cleanliness and safety of the vehicle, the vehicle operator must ensure the regular, thorough cleaning of the vehicles in accordance with the manufacturer's information.

The passengers themselves have to take a little more responsibility for themselves and the rest of their party. This includes consistent adherence to the hygiene rules established during the pandemic (e.g. the 'hands, face, space' rule).

The first item to help passengers comply with the hygiene rules to which everyone has become accustomed when shopping is a hand sanitizer dispenser. This tool helps reduce smear infections via the hands. Even if the risk of infection via surface contact is classified as low, the installation of a hand sanitizer dispenser signals to the passenger that safety is being taken into account.

For all buses of the Mercedes-Benz and Setra brands, sensor-controlled hand sanitizer dispensers are available at the entrance areas, which can be retrofitted as well as ordered for new vehicles. The sensor control and dispenser placement directly at the entrance areas permits contactless hand sanitizing when boarding or alighting.

To protect the driver from droplet infection, protective screens made from safety glass, acrylic glass or polycarbonate are available for all vehicles. These separate the driver's cabin from the passenger compartment and enable low-risk interaction between the driver and the passengers, for example when purchasing tickets. Protective screens are available – also as a retrofit kit – for all vehicles from coaches to public buses, which are the focus of this measure due to the high passenger flow.

It is important for safe bus operation that the driver follows the correct procedures and takes into account the technical characteristics of the vehicle. In this regard, there is a recommendation for correct operation of the air conditioning or ventilation system. According to this, the vehicle can be completely purged with fresh air within a few minutes before the start of the journey or after breaks. In addition, the driver should be alerted to the fact that driving with windows and hatches open may disrupt the flow control function of the vehicle's air conditioning and ventilation system. This will significantly slow the rapid air exchange in the vehicle or severely restrict the filtering of the air inside the vehicle.

An information catalogue is available for customers for correct handling of the vehicle and, above all, the ventilation system.

Recommendations to the driver for the optimal purification of the passenger compartment with fresh air.

Daimler Buses offers sophisticated air conditioning technology for buses which, when operated correctly, provides for a permanently high level of fresh air in the interior. With this information* you can make full use of the technical capacity of your air conditioning system.

Before setting off:

→ **Purification of air in vehicle** – engine is running, doors and driver's window closed, HVAC system deactivated (ventilation mode), blower set to at least 50 percent.

→ **After a maximum 4 minutes** (air has been completely exchanged) **activate HVAC AUTO mode.**

→ **Check that the ventilation grilles are clear** (boot, under the spare wheel).

While driving:

→ **Keep the driver's window and roof hatches closed while driving.**

→ **Drive in AUTO mode, only use the SMOG and REHEAT button if the situation requires it** (tunnel, traffic jam, misted windows).

→ **To avoid the SMOG button in traffic jams,** maintain sufficient distance from the vehicle ahead.

→ **Increase the rate of air exchange by setting the blower to a higher speed.**

Breaks while on the road:

→ **Open the driver's window, roof hatches and both doors to ventilate the bus** – the vehicle must be supervised and the air conditioning system deactivated.

After the journey:

→ **Purification of air in vehicle** – engine is running, doors and driver's window closed, HVAC system deactivated (ventilation mode), blower set to at least 50 percent.

→ **After a maximum of 4 minutes** (air has been completely exchanged), **activate HVAC AUTO mode.**

Fig. 4: Recommendations to the driver, source: Setra.de

In addition to the measures supporting compliance with the familiar hygiene rules, other technologies are appearing that have not previously found their way into automotive engineering in this form.

One example is the use of a photocatalytic system for interior air disinfection. The tungsten trioxide photocatalyst releases free radicals and electrons via an LED light source. These react with the air flowing past and destroy the organic pollutants that may be contained within it, such as viruses, bacteria, or fungal spores. The purified air can then be returned to the passenger compartment.

This technology is already used effectively in the field of medicine. Automotive supplier Ellamp S.p.a., together with Daimler Buses, has made this technology available for use in buses. Daimler Buses considers another technology more efficient for the purification of air inside the main passenger compartment. For the smaller volume restroom on coaches, however, the system is a useful addition for reducing the microbial load of the interior air. The system is available for Mercedes-Benz and Setra buses equipped with restrooms.
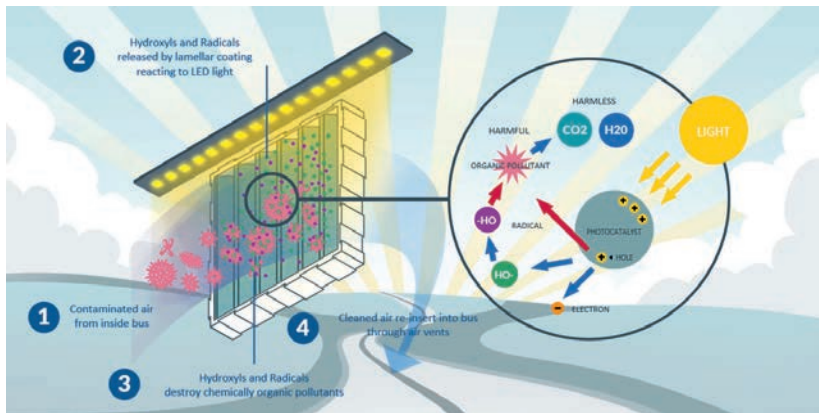
Fig. 5:   Schematic functional description of photocatalysis, Source: Ellamp.it

The technology for cleaning surfaces and interior air with UV-C light is also considered effective. With this technology, however, the complexity of the system and correspondingly high installation costs prohibit its use in commercial vehicles. For the purification of the interior air with UV-C, the irradiation intensity and exposure time of the air flowing through the radiation source must be calibrated specifically for the air flow of the air conditioning system. Since modern bus air conditioning has a very high air flow rate of up to 4000 m³/h with correspondingly high flow velocities, the installed radiated power of the UV-C light source must be correspondingly high, which does not meet the customer's requirement for a cost-effective solution.

In the case of direct surface irradiation, it must be ensured at all times that neither humans nor animals can come into contact with the radiation, as this is likely to cause considerable damage to health. The cleaning effect in this case extends exclusively to contaminated surfaces that are not in the radiation shadow. In addition, with regular use of UV-C irradiation, damage to the plastic materials used in the interior cannot be ruled out by Daimler Buses and its material suppliers. Since, like the Robert Koch Institute, the Federal Institute for Risk Assessment (BfR) is not aware of any cases of transmission of SARS-CoV-2 viruses via surfaces [2], the effort is not in proportion to the benefits of combating the COVID-19 pandemic.

[2] Source: Federal Institute for Risk Assessment - Bundesinstitut für Risikobewertung (BfR)
   https://www.bfr.bund.de/de/kann_das_neuartige_coronavirus_ueber_lebensmittel_und_
   gegenstaende_uebertragen_werden_-244062.html

The same applies to antimicrobial coatings of interior surfaces. These do have a laboratory-proven effectiveness. This effectiveness is limited in real-life driving conditions by the formation of a layer of dirt caused by dust and the application of greases when touched by the numerous passengers. Regular cleaning is therefore essential to maintain effectiveness and ensure that the effective antimicrobial components of the surface come into contact with the applied pathogens. For bus operators and drivers, the use of antimicrobial surfaces does not significantly reduce cleaning effort. From laboratory studies, it is known that cleaning with soap-containing detergent is already sufficient to eliminate existing virus contamination, which further reduces the benefit of using antimicrobial surfaces in real-life conditions. In internal tests of retroactively applied antimicrobial coatings, researchers found a significant impact on the visual and tactile surface quality of the interior materials.

3. Risk reduction of aerosol transmission by new filters in the HVAC system

Scientists communicated to the public the scientific finding that the SARS-CoV-2 virus spreads mainly via aerosols in the air very early in 2020. The viruses can adhere to passing aerosol particles that are exhaled when breathing, speaking or singing. Many enveloped viruses such as corona viruses require a transport medium such as droplets or fine aerosol particles to transmit them to other people. While contaminated droplets sink to the ground very quickly due to their mass, aerosol clouds can remain in a room for a very long time. Air currents caused, among other things, by the motion or body heat of people present, can spread these aerosol clouds throughout the room.

An important goal in the interests of making a journey by bus as safe as possible for all passengers is the maximum reduction of viral load in the interior air of the vehicle. The indoor air quality in a vehicle is significantly influenced by three properties:

- Air flow in the vehicle
- Air exchange rate
- Filter quality for fresh and recirculated air components

Almost without exception, the air flow of Daimler Buses vehicles is determined by air conditioning or ventilation systems. The filtered fresh air is introduced into the vehicle in the roof area via air ducts and flows into the passenger area via air nozzles above the passenger seats or forced air outlets. In city buses, the used air is released into the open air via roof fans and the frequent opening of doors. The proportion of recirculating air, which is controlled automatically depending on ambient conditions, is taken in again by the air conditioning system in the area of the inner ceiling, cleaned by a recirculating air filter and mixed with the fresh air that has been taken in from outside.

In intercity buses and coaches, fresh and recirculating air are also introduced into the vehicle via the roof area. The air is released into the luggage compartment via vents in the floor area for replacement and flows out of the vehicle in the area of the underbody in front of the front axle. The passenger compartment is thus flooded with air from top to bottom. There are therefore no areas where the interior air is left standing or uncirculated. All vehicle types also have an additional fresh air supply, which is mainly used to ventilate the driver's cabin with filtered air in the area of the instrument panel.
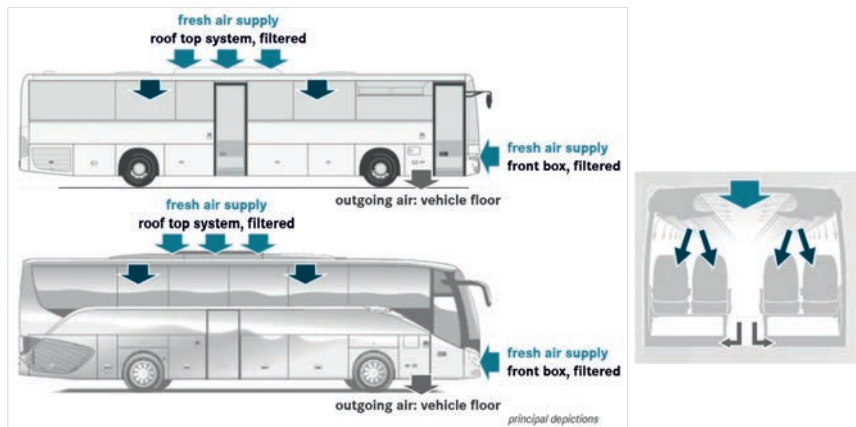
Fig. 6:   Principal depictions for airflow at raised floor coaches, source: Daimler Buses

The air supply for vehicles with air conditioning is controlled in the temperature range 8-26 °C by automatic mode with a maximum volume of fresh air. This corresponds to approx. 80% of use cases for buses in Central Europe. Below 8 °C and above 26 °C, additional recirculation air is used to heat up or cool the passenger compartment.

Only at outside temperatures above 35 °C and in driving situations where the driver intervenes manually via the smog button (e.g. when going through tunnels or in a traffic jam) does recirculation air operation take place.

Due to the directed and continuous flow of air through the interior, in conjunction with fresh air volumes of up to 4000 m³/h, the passenger air is exchanged every 1 to a maximum of 4 minutes at most operating points. In comparison, the minimum standard for residential buildings is a complete air exchange every 120 minutes. The combination of directional air flow and a high fresh air exchange rate in the passenger compartment in Daimler Buses thus reduces the risk of an increased aerosol concentration at values significantly below other familiar everyday

situations such as spending time inside buildings. Also, the fresh air exchange rates in buses are the highest of all modes of transport due to their modern air conditioning and ventilation systems.
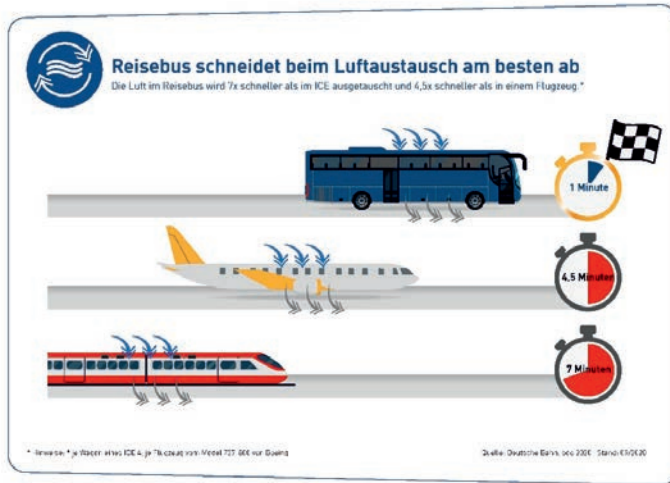

Fig. 7:   Air exchange at different modes of transport, source: bdo.org

To further increase the maximum exchange of fresh air in certain climate zones and to provide passengers with an even better supply of fresh air, Daimler Buses offers its vehicles the option of further increasing the temperature window for maximum fresh air supply. Depending on the vehicle type, the control range for maximum fresh air content is extended by 33% to 40%. Since this can be achieved via software parameterization, this represents a simple and fast way of further optimizing the fresh air supply. However, due to the slightly increased air conditioning requirements of the fresh air, a moderate increase in fuel consumption cannot be avoided.

New high-performance interior air filters represent the most important tool for reducing the risk of infection from airborne respiratory viruses. Progressively structured high-performance particle filters with an antiviral functional layer were developed in cooperation with the supplier Freudenberg Filtration Technologies SE & Co. KG within a very short time and tested in Setra and Mercedes-Benz vehicles. Due to the multi-layer structure of the pleated filters, they are able to filter even the finest aerosols. The filter performance in respect of the very smallest particles from 0.3 µm in particular was improved significantly compared to the class G3 dust

filters commonly used in buses. Freudenberg Filtration Technologies has proven in laboratory tests that the filter efficiency is already above 99% for particles of 0.3 μm and above. SARS-CoV-2 viruses themselves are slightly smaller, but the aerosols to which viruses are able to attach for emission are above this size. If virus-laden aerosols are trapped in the filter, the air flowing past dries out the virus envelope and the viruses are naturally deactivated. In addition to the fine filtering and the described dehydration of aerosols and viruses, the new filters have a functional layer based on a fruit extract that deactivates captured viruses on contact.

The effectiveness of the filter technology has been confirmed by the independent OFI Institute [3] according to ISO 18184:2019 with the judgment "excellent effect". For this purpose, the filters were subjected to extensive physical and microbiological testing over a period of 4 weeks at the institute in accordance with OFI guideline ZG250-1 and certified with the OFI CERT.

The progressive high-performance particle filters with antiviral function can be identified by the blue color of the final filter layer and are used on fresh air filters, recirculating air filters, and driver's cabin filters.
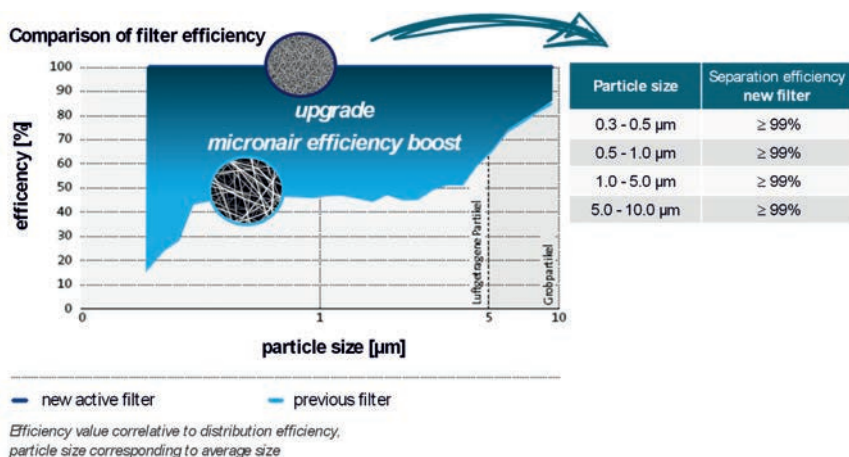

Fig. 8:   Comparison of filter efficiency of micronair filters vs. standard G3 filters,
          source: Freudenberg Filtration Technologies; Daimler Buses

These interior air filters have already been installed in all Setra and Mercedes-Benz series buses produced since January 2021 and can be retrofitted into almost all existing models of these buses.

[3]   Source: Österreichisches Forschungs- und Prüfungsinstitut, A-1030 Wien

The advantage of the filter technology is that the technical complexity and effort required for installation is extremely low and equivalent to a regular filter replacement during the vehicle service. The new filters cost only 15% more than the previously used G3 filters. Long-term tests on the first vehicles equipped with the antiviral high-performance filters have also demonstrated that there is no need to alter the change intervals of the new filters. The shortening of the change interval from 6 to 3 months for the market launch has now been abolished.

The difference to filters manufactured to the HEPA (H13/H14) standard (DIN EN 1822), which are used in hospitals, in the food industry or cleanroom laboratories, is a significantly lower filter pressure drop and lower sealing effort in the area of the filter combined with a longer service life. In particular, the air flow and air conditioning performance are significantly reduced with a HEPA filter; and the HEPA filter also does not have any decisive advantages, especially in terms of separation of the aerosol particle sizes to which SARS-CoV-2 viruses can attach.

These newly developed filters can therefore also be used without negative effects in the ventilation systems of buses that are not designed for a HEPA filter.

For vehicles mainly in the city bus sector that are not equipped with an air conditioning or ventilation system, Daimler Buses now offers a specially developed system. This air purification system based on a recirculation system in conjunction with the same antivirally effective high-performance filters is specially designed for conditions in the bus and can be retrofitted in existing vehicles.

4. Scientific validation of the measures based on new research findings

Through numerous reports in newspapers and magazines that appeared from July 2020, the task force at Daimler Buses became aware of the research work and results of the Hermann Rietschel Institute of the Technical University of Berlin. A cooperation was agreed for a preliminary determination of the dispersal of aerosols in buses and to validate the procedure using antiviral high-performance filters. The research team led by Prof. Dr. Martin Kriegel is one of the leaders in Germany in the field of aerosol research. Firstly, an analytical calculation of the possible aerosol concentrations in the vehicle was conducted on the basis of the prevailing conditions in the bus with consideration of far-field aerosol transmission. The calculation was performed for three common coach application scenarios with stays in the vehicle of 60, 150 and 240 minutes with an occupancy rate of 70%, which corresponds to an occupancy of approximately 39 people for a standard coach. If an infected passenger is on

board the vehicle, potentially virus-laden aerosol emissions are assumed to be 25 particles when breathing and 300 particles when speaking.

As a general technical condition, the function of the air conditioning system is calculated in automatic mode with a fresh air content of 80 % and a fresh air supply based on an average blower speed.

It is known from other respiratory pathogens that a certain number of viruses must be inhaled for infection. Since not every aerosol emitted also carries viruses, an infection at 3000 inhaled aerosol particles is assumed on the basis of the findings from other viral diseases. There is a dependency between the number of aerosols in the passenger compartment, inhaled aerosols and thus the risk of infection for the duration of the stay in the vehicle.

The result shows that even after a journey time of >200 minutes, there is only a very low risk of infection in the vehicle as the amount of aerosols possibly loaded with viruses inhaled by passengers remains very low. This is still true even if the person speaks continuously and thus emits significantly larger numbers of particles. Compared to a mechanically ventilated office, which is already considered a relatively safe place to spend time due to the ventilation, less than half of the aerosols are inhaled by the passengers in the coach. Prof. Dr. Kriegel's assessment of the situation is therefore that: "compared to other daily situations, the situation in coaches with a fast exchange of air is not particularly critical for passengers, as long as the 'hands, face, space' rules are observed. There is only a very low risk even when an infected person is part of a group." [4]

The newly developed high-performance filters have already been included in the calculation. The calculation shows that the filter efficiency of >99% in the aerosol-relevant particle size range of >0.3 μm means that even the 20% recirculation proportion use in the application scenario has no relevant influence on the maximum possible length of stay and risk of infection inside the coach. This insight can subsequently be scaled to a scenario with pure recirculation operation. This makes it possible to prove mathematically that when using the antiviral filters from Daimler Buses "... the aerosol concentration is very low - also during recirculation air operation. The assumed critical value of 3000 aerosols that could lead to an infection are not reached – even after four hours in the coach." [4]

[4] Study on risk of infection in buses, Hermann Rietschel Inst., Technical University of Berlin, https://blogs.tu-berlin.de/hri_sars-cov-2/2020/10/26/untersuchung-des-ansteckungsrisikos-im-reisebus/
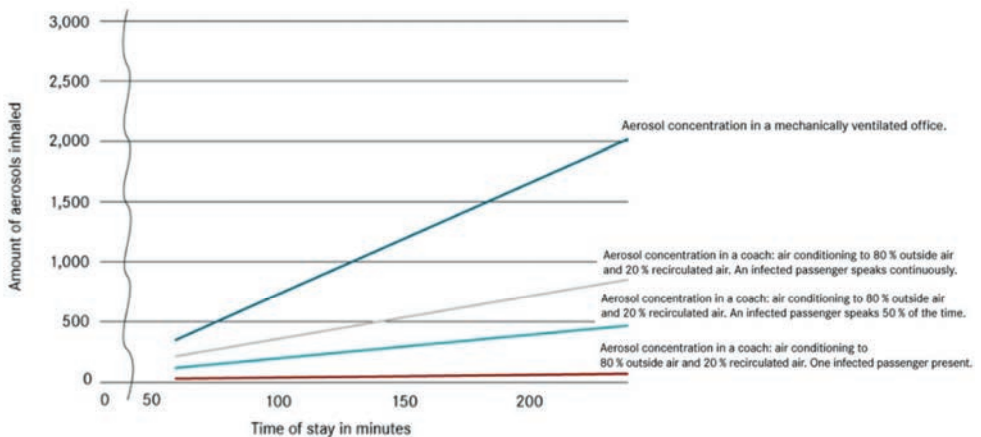
Fig. 9: Risk by aerosol-transmission at buses, source: Daimler Buses, TU Berlin

A joint data model is being set up by TU Berlin and Daimler Buses for the subsequent investigation of aerosol dispersal in the immediate near field. This will provide a computer simulation of the dispersal behavior of aerosol particles in the immediate vicinity of several infected passengers on board a coach. The interim results currently available already look promising. The final and scientifically evaluated results were not yet available at the time of manuscript submission, but will be communicated by Daimler Buses and TU Berlin in 2021.

The Robert Koch Institute also refers to the Federal Environment Agency's statement on indoor air hygiene, which was prepared by well-known experts:

"For infection control purposes, vehicle interiors should be supplied with the maximum possible air exchange and fresh air proportion. This applies equally to fresh-air intake through open windows as well as to the use of ventilation and air-conditioning (HVAC) systems."
"A maximum possible supply of fresh air is one of the most effective ways to remove potentially virus-containing aerosols from indoor spaces." [5]

[5] Statement by the Indoor Air Hygiene Commission (IRK) of the Federal Environment Agency
   https://www.umweltbundesamt.de/sites/default/files/medien/2546/dokumente/irk_stellungn
   ahme_lueften_sars-cov-2_0.pdf

"To reduce the risk of SARS-CoV-2 transmission, the IRK recommends that, where possible, in rooms containing people, either only supply air from outside (100 % fresh air) or, in the case of HVAC systems that use recirculating air content, provide the systems with additional filtering (HEPA filter)." [5]

Finally, subject to the results of the study by the TU Berlin, it can already be stated that the bus adheres to the recommendations for indoor air quality on the basis of a technically advanced air conditioning and ventilation system.

The ventilation system minimizes the risk of infection by airborne virus transmission

- Through a directed air flow in the passenger compartment

- Through a high fresh air exchange rate

- Through a newly developed, antivirally effective high-performance particulate filter

MAN Truck & Bus SE – Shaping the future of mobility

Autonomous vehicle studies – The societal benefits of future mobility concepts and the creative potential fields of application for tomorrow's world

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Abstract

The MAN BUS Design department is visibly reshaping the concept of mobility as part of TRATON SE's strategic focus and its transformation.

New solutions and outlooks are required if we are to experience the opportunities and possibilities offered by autonomous mobility. The MAN Design department examines the requirements and transformation options for the buses of the future from the perspective of users and passengers.

We carry out projects to develop amazing scenarios that lead to an increase in utility value and represent a completely new perceptible impression of quality for our autonomous buses of the future. Mobile spaces that inspire people and turn our understanding of public transport and travel on its head, allowing us to experience the mobile paradigm shift up close and personal.

As our cities are transformed into living spaces that are more pleasant to live in, and with the digital mobility revolution taking place right now, competitors are becoming stronger as they add smart, new mobility services to their portfolios. A major pillar on which our cities are built is public transport, and when it comes to travel we will be increasingly reliant on coaches in addition to planes and trains.

We take the significant demand placed on us by society very seriously, in order to provide our partners in society with an entirely new generation of city buses and coaches, and digital solutions.

In terms of buses, good design makes this aspiration tangible for people, both directly and indirectly. Fresh, intelligent use of space plays a decisive role in the spatial effect, using light, materials, acoustics and intuitive display concepts. The aim is to give every passenger, each

with their own individual needs, the best possible choice of transport by providing the appropriate spatial and vehicle architecture.

In the future, we will offer bus-travel solutions that perfectly transform the current opportunities and challenges into a new bus-travel experience.

The first generation of autonomous buses is an opportunity to avoid being perceived simply as a necessary "mobility evil" in cities and regions, and to be seen as the most appealing and sustainable mobility option, the best option, and one that people want to use rather than have to use.

Fig. 01: NEOPLAN-Grandtour-X 2040, top view of exterior

The world in transformation

More and more people around the world live in cities. Cities are the burning glass for our social needs and the result of the way in which we live our lives in this world. At the same time, cities are becoming more crowded and cramped. Global traffic volumes will more than double by 2050, according to a recent study by the ITF. Prior to the Covid-19 pandemic, a threefold increase had been expected. The appeal of city life is increasing, as are commuting distances. Frequency of travel between cities is becoming greater all the time, short flights less and less attractive due to their overly great, detrimental ecological footprint. Sustainable solutions are core aspects of future mobility concepts. Developing appropriate solutions is a major challenge for transport solution providers. Important questions arise from this:

What is the most sustainable form of mobility, while preserving the individual's right to free choice of mobility?

What form could a worthwhile, sustainable future of mobility take?

And how will we get around in the future and what part can mass transport providers play in this?

Let's peak behind the curtain a little together and look at some possibilities, concepts and visions relating to this!

Not only is technology changing at great speed in the industry right now, but it is also the case that "Tomorrow's customer requirements will not be the same as today's," says Göran Nyberg

"My objective for the future is clear: to lead the Group towards a sustainable and successful future. The global transformation in the industry will take about ten years, with or without Volkswagen," says Herbert Diess

A "business-as-usual scenario" no longer exists

We have our eye on the strategic goal of becoming a "Smart Innovator". That is why MAN is focussing on creating a portfolio that will make a difference in tomorrow's world: Making our mobility concepts humane and sustainable, considering, optimising and reducing emissions and noise. In doing so, we are helping to reduce the ecological footprint to the bare minimum.

We will gradually electrify our drive systems in order to lessen the extent of climate change. Advances in artificial intelligence, particularly in situational awareness, may soon see the driver replaced with a learning, global and neural network. This will make individual mobility more sustainable, much safer and more convenient.

The new strategy at MAN focuses on zero-emission drives and achieving CO2 neutrality by 2050. As a consequence, this could mean that we essentially stop selling combustion engines from 2040 onwards. Decarbonisation of transport is also a feasible goal for us in the foreseeable future in terms of mass transport. Sustainability is an inherent aspect of our strategy.

Halfway through the year, the rights of future generations to an unspoilt and liveable environment were strengthened in an impressive way. The European Union signed off on a legal requirement known as the "Clean Vehicle Directive". This is a clear commitment to ensuring that emission levels are greatly reduced. The rights and entitlement of future

generations to an unspoilt environment have also been strengthened by the German Federal Constitutional Court. The court has ruled that the current generation must not engage in economic activity with the environmental resources available at the expense of the next generation.

As such, the path towards zero-emission mobility has been clearly set out. The objective has now changed from "low emission" to "no emission"!

Today's sustainable decisions are paving the way to the new opportunities and scenarios of tomorrow. Linked to this is the transformation of our cities into more attractive living spaces; a process that has already begun. The transformation of transport and people's ability to get around is being accelerated and supported by the advancing digital mobility revolution. The competition for new, smart and sustainable mobility options has grown. As a result, cities are increasingly dependent on efficient, attractive public transport in order to meet the demand for a more humane, comprehensive mobility system. We are committed to becoming an even more appealing mobility partner for everyone over the next decade by turning out buses that are characterised by cost-efficiency, reliability, greater availability, safety and heightened appeal due to greater attractiveness and no emissions.

Fig. 02: Sustainability at MAN Truck & Bus SE

Off to a good start with the MAN Lion's City E

Our latest Lion's City E has seen us get this new era off to a successful start. It embodies the spirit of the age with a degree of success that has taken even us by surprise. A very successful starting point on a demanding, never-ending journey of optimisation.

In addition to its reliability and innovative technology, the MAN Lion's City E is now also fairly miraculous in terms of range. During the efficiency run that was carried out, the electric bus managed 550.8 kilometres in realistic everyday conditions, despite moderate weather – without any charging stops! This is significantly more than the guaranteed battery range we could promise customers previously. It shows the potential of the Lion's City E and the forthcoming e-mobility in the public transport sector.

The two electric buses from MAN, the Lion's City 12 E and the Lion's City 18 E, make it easy for cities to switch to electric vehicles. They can be integrated into the existing routes, ranges and timetables without much effort.

It is not only the inner, technical aspects of the new electric bus that one can be proud of: The elegant, modern smart edge design allows it to make a fresh, eye-catching and compelling impression and the vehicle's design is already award-winning. The iF International Forum design panel awarded the Lion's City E the 2021 iF Gold Award in the category "Automobile/Vehicle/Bike". "The MAN Lion's City E rounds off the new generation of city buses as the emission-free version boasting an award-winning design. With the launch of the 18-metre version, we're delighted that we can now offer all transport operators and city authorities a highly efficient vehicle for high-frequency routes with a first-rate design befitting its urban environment," said Rudi Kuchta, Senior Vice President, Sales Bus.

Fig. 03: MAN Lion's City E, 2020

Fig. 04: IF-Design Award GOLD MAN Lion's City E, 2020, BUS Design Team MAN TRUCK & BUS SE

Trends and drivers

Digitalisation, autonomous driving and alternative drives are the big drivers of the current change in the commercial vehicle industry. The way in which we address mobility and transport today will significantly determine the future viability of cities and the quality of life of their citizens. In order to implement the requirements more effectively, we must learn to understand the challenges and future trends. Topics that society, ourselves as manufacturers and every individual in society are able to notice right now and that will have a far-reaching and profound impact on our lives.

Cities are becoming less car-friendly

With the growing trend of placing more emphasis on citizens' quality of life, cities are becoming less car-friendly. More attractive streets, buildings and squares are being built to meet people's

needs – wide pedestrian zones instead of motorways, lots of green spaces and small building structures instead of concrete jungles.

Increased demand for public transport

In general, there will be an increased demand for mobility per capita in terms of public transport.

Extensive range of public transport services

Different protagonists, i.e. the familiar, established ones and new mobility solutions will provide the needs-based and planned forms of urban, public mobility services.

Personalisation

In future, public transport services must offer personalised mobility solutions that are tailored to the individual needs of each passenger. Digital and publicly tailored touchpoints are used to tailor content even more precisely to target groups.

Sharing economy

To an increasing degree, we are moving towards a new lifestyle of sharing goods and services, something that is finding greater acceptance and appreciation.

Autonomous driving

Autonomous mobility services are creating an entirely new business area. Public transport vehicles, which mainly operate on fixed routes, drive in a completely autonomous manner.

Level 4 (automation level 4: In a certain state, the driver can hand over the entire driving task to the system. The driver is not required at all in these situations, neither for supervision nor as a backup).

On-demand services

They serve as a supplement to enhanced fixed network services that are operated on a scheduled or simply high-frequency basis.

Post-data protection lifestyles

The use of digital services has resulted in user transparency. This new constant threat to privacy has become widely accepted. That being said, a new lifestyle has emerged based on the organised management of one's data footprint. Digital services that allow customers to decide for themselves how much of their data they want to share are now part of the repertoire of modern society.

The future of work

The world of work will be greatly influenced by highly individual working styles in future. Constant presence at work during regulated working hours is increasingly being replaced by flexible, location-independent working models and project-based tasks.

Sustainability

Ethics are playing an increasingly significant role in consumer decisions. Solutions and companies that have subscribed to such standards and have proven to be authentic have become very popular with consumers.

Footprint

The ecological footprint of each and every product is coming under increasing critical scrutiny. CO_2, space requirements, noise and the entire life cycle from the origin of the first screw to its return to the circulation process are perceived as components of this.

Governments, cities, people, passengers

The mobility of the future

To better understand the framework of the autonomous city bus and coach environment of the future, we need to take a little look into the future state of mobility and the new market players of the current decade. What new forms of mobility will be available in the future and what vehicles will be needed for them?

A very influential factor will be the user-oriented mobility service industry, which will be geared towards individual needs close to the market; the sharing economy will become a big driver.

The current digital transformation of mobility is affording providers as well as users far better opportunities to create space for mobility services that are more people-friendly and environmentally-friendly. Digital transformation provides the ideal communication tool, connecting people's individual mobility needs with the mobility units available, thus creating a new level of efficiency and sustainability.

To an increasing extent, "Mobility as a Service" will dispel people's fear of losing a piece of freedom by giving up their own car. On the contrary, it will lead to a more customised degree of needs-based mobility. At the weekend, you could hire a convertible or quickly book a seat on a coach; during the week, public transport could be used with a mix of ride-hailing, and with micro-mobility on the increase, simply riding your bike or getting around on foot, which is already the most popular form of mobility today, are also options.

This new form of networked mobility, with its range of autonomous vehicle options, can be used much more efficiently, independently and in line with individual needs. This decade is a paradigm shift in our understanding of mobility, opportunities and new business areas that will emerge from this digital transformation.

What form of mass transport is the most sustainable and quickest to implement in the plans currently under consideration? The quickest way to implement this is by opting for concepts that can make immediate use of the equivalent analogue infrastructure and render it applicable to the next decade by means of a digital network. Examples are autonomous buses and vehicles that provide a seamless, fully accessible mobility service at a high frequency, offering a compelling, consistent and engaging travel experience.

The sharing economy could render owner-oriented mobility largely obsolete and could lead to a tenfold reduction in the number of cars parked on streets.

We could see a shift away from huge, unused fleets of vehicles, like the transformation in production systems 30 years ago when large-scale stockholding was abandoned. An end to private cars that sit unused in public spaces for about 160 hours only to be used for an average of 8 hours a week. Will "just in time" mobility be one of the paradigm shifts in mobility that take place in this decade? Cities will gain a lot of street space and public space, and will be able to offer a new quality of life.

The denser settlement areas become, the greater the scope for merging of routes and improvements in the efficiency of local public transport. We manufacture buses and create mobile spaces that need to be available to all people at all times. Public transport is a public service that can cater for a wide range of people, age groups and social classes. Currently, however, the focus remains on the efficiency and functionality of transport.

The most important aspect of the mobility revolution is the ability to give people independence and a choice of mobility, so that mobility sovereignty is not restricted. That the sharing economy gives users a better range of choices, greater individual mobility and, what's more, as a very positive side effect, a greater amount of public space is created for everyone.

Old and new city districts are transformed into diverse ecosystems with traffic that is barely noticeable. Mobility that takes place in the background in an integrated, more service-oriented manner, while the pulse of mobility continues to beat at a high frequency on the main traffic arteries.

And then there are also the much-cited flying drones that are allowed to fly in specific flight corridors as air taxis, drones etc. Using these as a means of mass transport would be unsuitable and would be akin to a swarm of locusts. An unsightly relocation of traffic that would not improve the urban situation.

Perhaps the biggest change will be this new concept of micromobility: Smart vehicles, small parcel service robots that bring parcels directly to their recipients or wait for them, mobile shopping bags like "Gina" by Piaggio, etc. or autonomous electric scooters without a human driver on their way to the next stop. But the best methods are the old-fashioned ways of getting around, namely by bike or on foot.

The urban realm – a burning glass

Cities play a crucial role in developing the sustainability of our mobility. Fifty-four per cent of the world's population lives in cities. 75 per cent of the world's energy consumption takes place in our cities, and around 80 per cent of the gas emissions that cause global warming come from our cities, and the trend is rising everywhere.

Every day, around 10 billion trips are made in cities alone, representing around 64% of all trips – and the total number of kilometres travelled in cities worldwide is expected to almost triple by 2050 (Rode et al., 2014; Van-Audenhove, Korniichuk, Dauby and Pourbaix, 2014).

Electric buses in particular reduce noise and emission levels in cities. For example, each electric bus in Hamburg cuts CO2 emissions by up to 80 tonnes per year and consistently benefits customers and passengers. About 750,000 internal combustion buses, which are over 11 years old on average, are still operating in the EU.

In 2020, the total European market for electric buses was more than 2,000 vehicles – with a definite upwards trend. By way of comparison: The Chinese company Sengseng already has 16,000 electric buses.

"With the Lion's City E, we are focusing on an exclusively battery-powered vehicle. In our view, this is both economically and ecologically beneficial for public transport customers. For example, with a battery-powered drive system, about two thirds of the electricity actually ends up on the road – with hydrogen buses, only one third is utilised. In addition, the forthcoming range of up to 400 kilometres means it is no longer necessary to switch between two different types of technologies in the urban mobility setting," says Rudi Kuchta, Senior Vice President Sales Bus, MAN TRUCK & BUS SE.

Public space is one of the most valuable resources a city has, and yet it is an asset that is largely hidden at present. Private transport takes up the greatest amount of space per user. For example, the space required by a car with the braking and safety requirements at 50 km/h factored into the equation is already over 100 m2. Converted to mobility users, the same user in a bus at 20% occupancy only takes up around 15 m2 of public space. One pedestrian takes up about 1 m2; if you calculate the space taken up by private transport during rush hour, for example, the problem and the potential of the "environmental footprint" are self-explanatory.

If 50 car commuters travelling at 30 km/h in a convoy that is already more than a kilometre long opted to travel by public transport instead, they would free up an immense amount of

space for a city, and cut CO2 and noise emissions to a huge extent. If public transport, cycling and walking were the only forms of mobility, 50% of the streets in a city would be parks. The space requirement per mobility unit is even more crucial, and in this respect the bus has an unbeatable positive balance, which could solve the inner-city traffic problem immediately and in one fell swoop. The path to this goal can only be set out with a measured balancing act of "push and pull" factors. On the one hand, with alternative mobility concepts and with public transport services that make buses so appealing, accessible and easy to use that they become the first choice when transport is required. On the other hand, with regulation, promotion and effective communication of social added value versus individual needs.

Fig. 05: The space requirement for each mobility concept is multiplied many times over by the speed that is possible in each case

Connecting the metropolises

Kicking back and arriving refreshed, sleeping through the journey or piecing together the journey to your destination – there are already many ways to travel by bus across the country from one metropolis to another, each meeting the different personal needs of the traveller.

From centre to centre point

Reorganisation of urban or public construction space results in completely new spatial proportions when it comes to bus design. The internal combustion engine in buses has been

the formative factor in the vehicle package up to this point. As is the case with the passenger car, there are also new ways of apportioning and arranging the vehicle volume in a user-oriented way within a bus.

The degree of travel comfort is defined by the elements of the environment that can be adjusted or customised, such as the seats, entertainment, air-conditioning and service facilities. Other significant factors are the utilisable freedom of movement, enhanced and newly conceivable user experiences, such as a bar, enhanced hygiene facilities, interaction with other passengers, privacy etc. Hardly any other form of mobility on the road allows for as much variance as a coach. The expansion in possibilities for a new vehicle architecture provides the scope to factor greater room for the individual needs of passengers into the design and to create new worlds of experience.

Fig. 06: The vehicle volume of BEVs can be apportioned in different ways
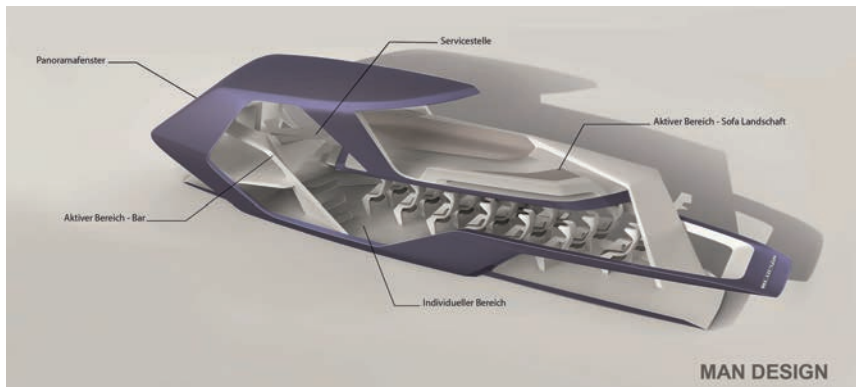
Fig. 07: Disruptive needs-based interior analysis with different focal points of use and areas
of use for passengers

The human dimension

From a design perspective, our aim is to present a comprehensive mobility experience. The aim is to do away with the compulsory character of efficiency when travelling by bus and to transform the journey into a new mobility experience. This means that the bus is arranged in such a way that all passengers, young or old, mobility impaired or healthy, poor or rich, feel at ease. All barriers are removed so that everyone is able to find their ideal spot, regardless of whether the passenger is making a one-stop journey or sitting on the bus for 40 minutes or 10 hours. With the aid of user reports and during projects with universities, we reflect on the needs of users and the passengers' views in relation to the bus as a technical object, and, furthermore, the entire "travel experience" of the users – the booking process, the place of boarding, the journey, changes in the means of travel, "first mile/last mile", etc.

On the one hand, buses will always be designed to be an efficient vehicle that transports as many people as possible. On the other hand, we have the option of configuring this 24 - 45 m² mobile space in such a way that the space is perceived in a completely novel way. We are experimenting a lot with ways to enhance mobile public space. The following questions arise in this regard: How can new materials promote qualitative perception, how do we design a seating layout that on the one hand facilitates social interaction among groups of young people, tourists for example, and on the other hand provides privacy, and a sense of calm and

tranquillity? Therein lies the challenge for the future of mass transport. On the one hand, ensuring efficient and safe transportation for as many people as possible and, on the other hand, ensuring that passengers have a very positive experience for the duration of their journey. Buses are democratic, diverse mobile spaces for all people, reflecting the diversity of our society and its individual demands.

They not only inspire us to respond to the ever-increasing global demand for clean, safe and sustainable solutions, but also play an active role in how we think about mobility as a whole by forcing us to think in terms of complex systems.

Fig. 08: Floor layout of the MAN Lion's City, previous development approach, people's range of movement determined by technology

Studies on the future

Collaborations with international design universities and the creation of MAN design concept studies are a source of inspirational challenge. They help us to refocus our outlook on things and to question our approach time and again.

Fig. 09: The city bus, a mobile space that creates more space rather than taking it away

A look into the future of city buses

MAN LEO is an autonomous, electric city bus concept for cities in the year 2035. The aim is to improve the quality of life in cities to the greatest extent possible. This is achieved by combining the current advantages that city buses have over other urban transport means with innovative technologies and a new design experience. The end result will be a far more desirable public transport experience. This will lead to greater uptake of public transport and thus to more efficient, ecological and people-friendly transport and cities.
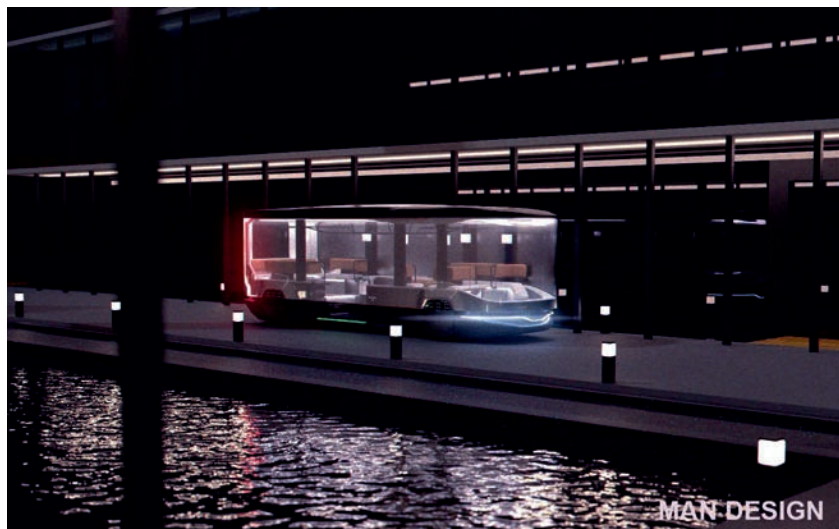
Fig. 10: The autonomous city buses of the future will be an integral part of the cityscape, thereby becoming part of the city

Fig. 11: Smart interiors provide more space and an area to embrace mobility and city life

Fig. 12: Topological investigations into the vehicle structure will result in new "lightweights"

Fig. 13: A homelike atmosphere is created by incorporating new materials

Studies into the coaches of the future

Travelling through Time and Space 4.0, the "NEOPLAN GRANDTOUR EXPERIENCE" project, a study on the future

The vehicle has an interior space that is split into three sections covering an area of 50 m². Transformable seat modules offer a high degree of comfort and, above all, variability. Communication and entertainment via a virtual bar as well as augmented and virtual reality options give passengers the opportunity to decide how they want to spend their time on board. In this way, a long journey can be transformed into an unforgettable experience. The concept is based above all else on variability, made possible by "programmable materials", and maximum travel comfort thanks to a special and exclusive spatial concept which is representative of the NEOPLAN brand.

Fig. 14: The generous architecture creates "rooms" for passengers that meet their needs, such as a lounge area

Fig. 15: Colours & trims add flair, ambient lighting provides structure and order

Fig. 16: A study of the interior, new architecture and boarding concepts offer greater scope for
new travel experiences and managed flows of passengers
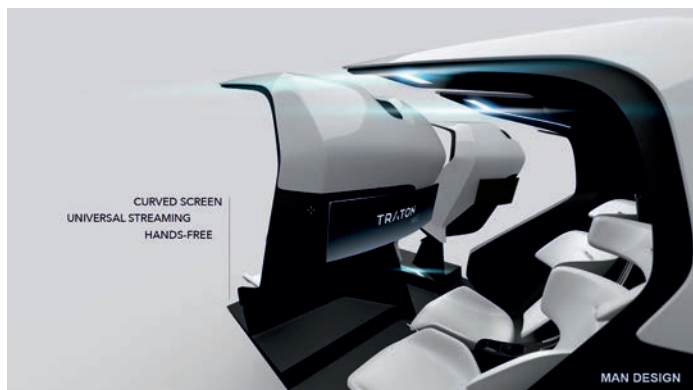
Fig. 17: Sitting on the bus in tomorrow's world: Greater variance of individual user experiences
and digital connectivity options

Fig. 18:   Travel as a way of life, the journey is the destination – The bus adapts to the travelling party, the user behaviour and the destination.

Fig. 19:   New layouts on the electric coach facilitate new travel experiences and outlooks

Fig. 20:   User- and travel-oriented division of areas of use. The vehicle layout is arranged on
            this basis.
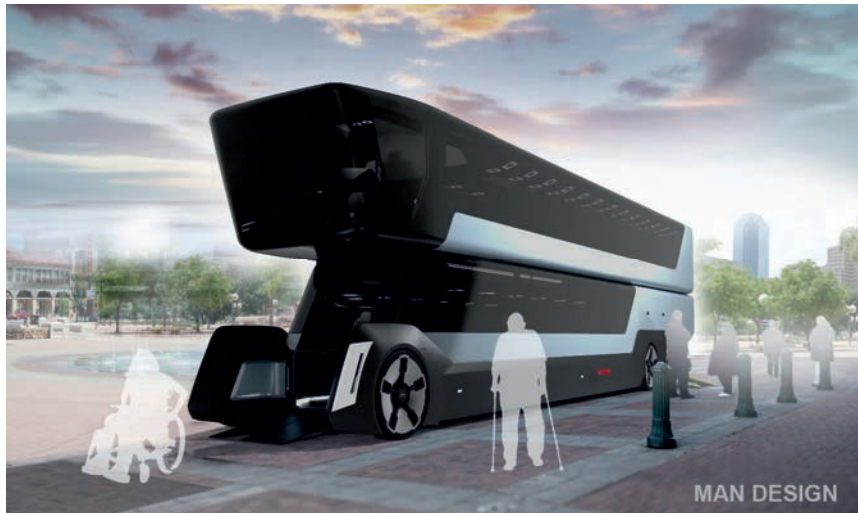
Fig. 21:   Inclusivity, equality. Omission of the driver's workplace creates new access possibilities, accessibility can be further optimised. As a result, passengers with limited mobility can sit in the first row.

Simply Connected

The central, configurable control system for full interlinking across systems for trucks, busses and light commercial vehicles

Dr. **Oliver Treichel**, XTRONIC GmbH, Böblingen

Abstract

1. simply connected to the vehicle's body components
2. simply connected to the vehicle's control units
3. simply connected to your cloud
4. central, configurable ECU for full interlinking across systems

Commercial vehicles

Commercial vehicles differ in one central point from normal vehicles like passenger cars. But first there is also one central, common property of both, the mobility. Vehicles have the central purpose to drive from A to B, to transport the driver and the passengers. In commercial vehicles there is the additional focus on transporting goods or tools, added to the back of the vehicle. The tools can be loaded or integrated to vehicles' body. The mostly used commercial vehicles can be divided into the sections of trucks, sometimes called heavy duty vehicles, busses, in most cases based on truck chassis, and light commercial vehicles, in most OEM organizations placed in the neighbourhood of the car products.

Since the 80's there is a strong development of electronics, leading to software driven developments, controlling the functions and automating the features of the vehicle. Today a vehicle contains more than 100 different ECU's, interlinked by a vehicle internal bus communication. The communication, based on digital protocols, allows the driver, as well as the technician, a central usage and analysis of the vehicles data flows and features. It allows on today the driver a comfortable, efficient and safe usage of the vehicle, as a tool for mobility. The marriage of vehicle data flows with the opportunities of a cloud infrastructure is now offering a new horizon of merging information, resolving the borders of the real, physical world. The merge of data is getting unlimited, and the visions of new features and business models are still rising. The well-known trends of Internet of Things (IoT) in the industrial sector, the

smart home in our private life and the smart car in everyday mobility were the motivation and impulse for our innovative connectivity platform development.

Commercial vehicles' bodies can be characterized as a combination of multiple systems and components. There are still simple components, like sensors, with analog outputs beside complex systems, already using digital communication protocols for control, diagnostics and user interfaces. It mirrors the market structure given by the OEMs, Body builders and suppliers of systems and components. In this context the trailers can be understood as a special kind of flexible vehicles' body.

In the meantime we are facing a huge amount of applications in the field of commercial vehicles. The OEM's are mainly focussing on the topic of "mobility". Beside this there is an even much more diversified market of body builders, adding and integrating special commercial features to the vehicles' back, the body, to meet user's requirements. Examples are concrete mixer, crane, tank, firefighter, ambulance, parcel service, handcrafter. This list can be extended until infinity.

The official categories of vehicles are:
- Category M: vehicles carrying passengers
- Category N: vehicles carrying goods
- Category L: 2- and 3-wheel vehicles and quadricycles
- Category T: agricultural and forestry tractors and their trailers

Vehicles that belong to category M or N are classified as:
- light-duty vehicles (passenger cars and vans), or
- heavy-duty vehicles (trucks, busses, and coaches)

In the following the focus is on the categories M and N in the context of commercial vehicles.

Simply connected to the vehicle's body components

The analysis of today's bodies' components shows the following key characteristics:

1. Analog sensors are used to measure e.g. temperatures
2. Digital Sensors are used to detect a certain status, e.g. lock control, gas alarm
3. Digital Switches are used to realize a simple on/off control, e.g. key switch, push-button

4. Systems are offering a LIN or CAN communication to control their features and to do diagnostics, e.g. cooling, heating, air-conditioning systems
5. Systems, which have their origin in smart home or IoT, are offering an Ethernet (IP) interface for interlinking, e.g. cameras
6. Sensors with a wireless communication-interface are using Bluetooth or Wifi standards, e.g. beacons
7. Components' behaviour is controlled by using pulsed signals, e.g. actuators, dimmable LED

These different control concepts of the components and systems led to a jungle of control units, supplier standards, dedicated user interfaces, redundant devices and the need of specialized experts to handle all this. Even the user is faced to a complex puzzle of user interfaces. This puzzle is even not prepared to be easily integrated into a big picture or to be optimized for the user.

Assuming that a central control unit will be the solution for this, we've transferred the above conclusion into requirements for a central control unit, which is able to:

1. Digitalize analog signals
2. Read digital signals
3. Write digital signals
4. Communicate with LIN and CAN based protocols
5. Communicate with IP based protocols
6. Communicate with BT (Bluetooth), BTLE (Bluetooth low energy) and Wifi based protocols
7. Create PWM (pulse width modulation) signals

A central control unit, you can call it also gateway, we call it XCU (XTRONIC control unit), requests immediately a universal language in order to overwhelm this multi-language jungle in the body or trailer.

The core of the XCU solution is a generic model hierarchy which integrates the complete functionality into a single concept:

- Usage models (lights, sensors, climate controls, …)
- Management models (traceability, parametrization, test support, …)

- Behavior models (Conditions, rules, scheduling, …)
- History models (Storage, …)
- Processing models (KI pipelines, Predictions, …)

For embedded devices, this model hierarchy is configurable with a system configuration that is loaded at runtime. On servers and client devices, this model hierarchy is built at runtime from received messages. In the XCU, the embedded PC is responsible for monitoring local messages and requesting missing data via UDS and other protocols. The locally built model hierarchy is then synchronized to the cloud server.

The main challenge in the local network is the configuration-free collection of data from different sources. This data must then be padded with a semantic meaning to build the generic model hierarchy. The approach was to create a generic framework, based on generic services. This generic language allows now the easy integration of different kinds of e.g. cooling systems, based on different suppliers' portfolio. The central control unit allows now to talk with all body's components in one common language. We call this generic language Appicals™, which had been developed during the last years.

During the development of Appicals, we had these key concepts in mind:

- Resource-optimized to implement it directly in the microcontroller
- Interface agnostic to work over CAN, IP, Serial, Bluetooth
- Configuration-free from a client point of view

Appicals is a middleware solution to connect embedded devices, smart devices and virtual devices over arbitrary networks. It uses discovery and description mechanisms to tell clients about available functions and capabilities with minimal communication overhead.

The comm framework, which is the lowest layer, defines protocols to exchange byte arrays up to a few hundred bytes between nodes using an IP-like address:port scheme. With this functionality, Appicals becomes interface agnostic.

The middle layer, SixML, defines the inner structure of the aforementioned byte arrays and defines the methods and events that are used in the various process steps like discovery, description or control.

The highest layer structures device functionality into instances of generic services like DigitalInput, RelativeInput or Consumption. This simplifies the development of support functions like automation, history or user interfaces.

Services can be sorted in the following categories [1]:

- Core-Services
- IO services
- Device services
- Media services
- PIM (Personal Information Management) Services
- ZoneManagement services

Since Appicals is interface agnostic, the already mentioned BT interface can now be used for one central user interface on a smart device, where all status information and control features are available via Appicals. With this a wireless communication is given in the vehicles nearfield (distance up to 40m, depending on the environment). The Bluetooth communication supports the simultaneous control by up to two smart devices.
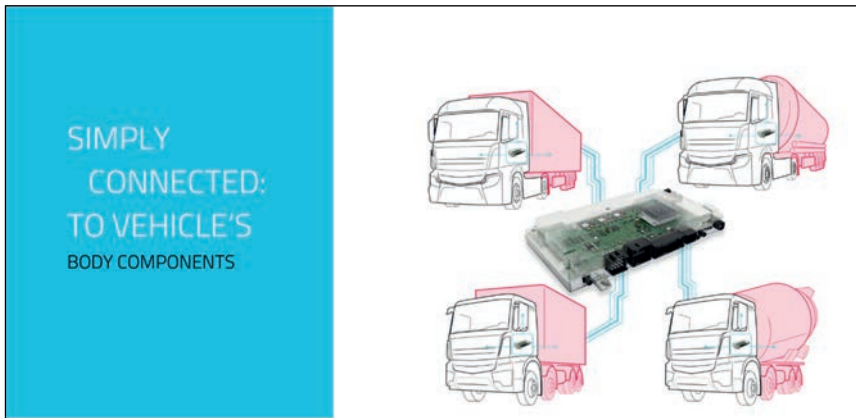
Fig. 1:   Simply connected to body's components

Simply connected to the vehicle's control units

The vehicle itself is the mobility platform of the body. It can be seen as a complex system with a digital interface for communication. Most OEM's offer a CAN interface for the body, which allows the reading of vehicle status information, e.g. ignition, velocity etc., as well as the writing of commands to the vehicle, to control its accessible features, e.g. door locks, horn etc.. From body's view the vehicle gets integrated like a system. From vehicle's view the body gets integrated like an add-on. This demands a new dimension of bi-directional integration. The XCU is therefore an add-on to the existing ECU's, the digital infrastructure of the vehicle. The driver can be now supported with the body's features on existing telematics user interfaces. In order to prohibit interactions or impacts on the telematic's safety, the XCU is running its own application software and supports a video interface. Since the passive video stream can be fully integrated shown on the telematic's display, and since the user's interaction is transferred via the already existing CAN communication to the body, the vehicle's secure communication will be not disturbed.

The same concept of displaying the user interface application can be also realized on an additional display, e.g. touch display. All features in the application software are based on the generic services of Appicals.

The XCU also acts as proxy for legacy devices that do not understand Appicals natively. These can be CI-bus devices, devices with a proprietary CAN protocol or other interfaces. The parametrized system configuration lifts such devices into the Appicals eco system.
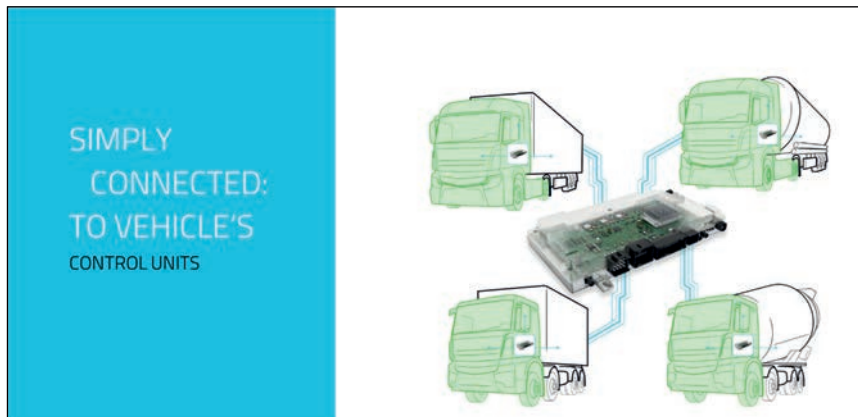
Fig. 2:   Simply connected to vehicle's control units

As already mentioned, the XCU is an add-on for the vehicle's body CAN, which allows an enormous expansion for the body's specific needs, without changing the today's digital infrastructure of the vehicle.

Simply connected to your cloud

Since the central control unit (XCU) now provides a generic model, this data stream can be now connected to the cloud. All data of one XCU and its locally connected components is represented as a single zone.

Assuming that a central data stream is the base for a digital twin of the vehicle, we've enlarged the requirements for a central control unit by an optional:

1. LTE (3G, 4G) interface, to get access to mobile communication
2. GNSS (GPS) interface, to get access to satellite communication
3. IP network, to get access to the vehicle's cloud connection
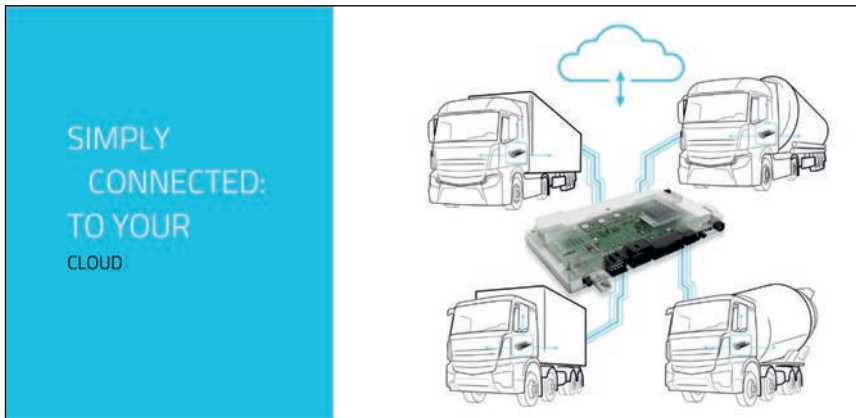
Fig. 3:   Simply connected to your cloud

XCU and cloud server communicate over a state-of-the-art web socket connection, thereby eliminating the need for polling data. Different end-points are provided for different data structures, e.g., to access usage models, to request traceability properties or to manage users and access rights. The cloud server uses the incoming data to build an exact copy of the generic model hierarchy of each XCU, thereby creating a "DigitalTwin" of the XCU. The cloud server merges all incoming zones into one large data model. Access rights are used to determine which zones a connected client is allowed to see and/or control.

Based on the data, which are available in the virtual XCU, the status of the vehicle can be described and via the bidirectional communication all available features can be controlled. This offers the remote access to the vehicle as a service. The user interface for the remote control can be realized as a web application software, which enables the support by an operator or service technician.

In order to be compatible to existing and established IoT standards, the cloud server also provides other endpoints, which can also be used by devices, servers or clients.
This list can be easily adjusted to individual project needs and already includes:

- Message Queuing Telemetry Transport (MQTT) synchronization
- Azure IoT Hub synchronization

- Apache Kafka synchronization
- InfluxDB storage
- HTTP REST status and control
- Grafana visualization
- NodeRED automation

Based on the aforementioned infrastructure, new high-level services become available:

- IaaS (infrastructure as a service) interfaces, run the Cloud functionality via Docker, Azure, AWS,
- PaaS (platform as a service) interfaces, standard protocols for usage, management, access control and others
- SaaS (software as a service)
    - Definition of KI pipelines which are used in real-time data processing
    - Delivery of preprocessed data, e.g. sensor fusion
    - Delivery of user interfaces
    - Delivery of predictive maintenance states

The properties and the behaviour of the XCU in the vehicle are mostly defined by the software of the device. Therefore the connection to the cloud allows over the air (OTA) updates of software. With this the features, the performance and the security of the vehicles XCU can be updated from the cloud. A fleet is most often a group of vehicles with the same purpose. The over the air services enable now the efficient and dedicated update of defined groups of vehicles without physical access to it.

The XCU is equipped with a powerful embedded PC, which allows a data logging. These data packages can be delivered to the cloud as well. This is helpful, if the connection to the mobile-network is interrupted. In addition the logged data can be pre-processed to reduce the data volume, which have to be uploaded to the cloud, or to cover dedicated analysis in the context with edge computing. This offers also the opportunity to generate predictions for body's components.

The location to generate predictions can be also the virtual XCU. Prediction Models based on machine learning (ML) or artificial intelligence (AI) can be easily implemented to the virtual XCU, so that it delivers the predictions as an output, as an additional service. State of the art

interfaces are prepared to use continuous learning models, which are running offline in the cloud to approach an incremental increase in the accuracy of predictability.

All this output data of the virtual XCU are available for all kind of software applications, so that the digital twin, the virtual vehicle's body, is getting an integrated part of your workflows and services in the customer's cloud. The cloud is the meeting point for different sources of data: a) public information in the www b) third party data in the www c) company specific data d) vehicle data e) vehicle's body data.
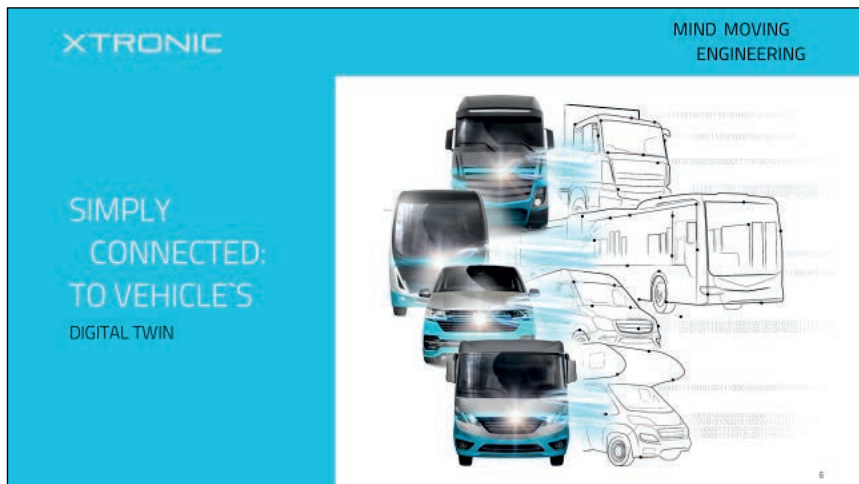
Fig. 4:   Simply connected to the virtual XCU ("digital twin")

Central configurable ECU for full interlinking across systems
The automotive industry faces product platforms in which a lot of variants have to be handled. The number of different body-setups is even bigger. This means the realization of all these body variants has to be done in highly efficient way. The automotive approach is to do it by a configuration.

Assuming that an entire configuration concept will be the solution for this, we've elaborated requirements for a configurable central control unit, which allows to:

- Define the generic models which represents the intended function of the ECU
    - o e.g. define a climate control model
- Link each model to a specific low-level module that implements functionality
    - o Link the climate control model to the Airtronic driver module,
- Link the low-level module to external inputs and outputs
    - o Link the Airtronic to analog inputs and PWMs on external ECU connectors that represent the measured temperature or control the actual heater
- Link the model to communication frameworks
    - o Define Appicals devices and services to access the climate control model with nearfield devices
- Add automation
    - o Define conditions and rules to react on critical states
    - o Use scheduling to activate the climate control model at certain times
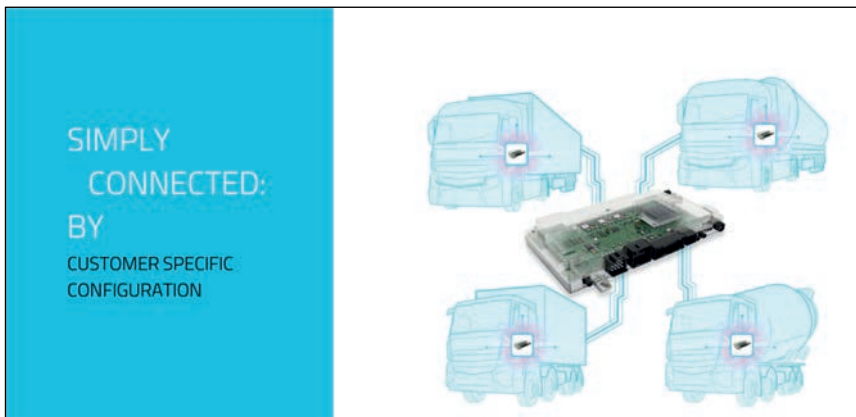
Fig. 5:   Simply connected by customer specific configuration

- Use a limited set of generic models to represent the complete behaviour of the ECU
- Differentiate models with semantic properties
- Add manufacturer specific functionality with complex function modules
- Use a standardized set of Appicals services to minimize UI efforts
- Linkage between models, modules and Appicals is automatically tested for consistency

- Complete system configuration is stored as human-readable JSON
  - Includes revision information
- System configuration is automatically translated into a binary message
  - Transferrable to the ECU with standard protocols and tooling, e.g., UDS
- Binary configuration is loaded by the ECU at runtime
- Minimal RAM and flash overhead, no dynamic memory management needed
- Implemented in C, compatible with a wide range of compilers

Conclusion

The central control unit [2] for the vehicle's body is a contribution to the evolution of commercial vehicles. The consequent and complete approach to digitalize and connect bodies' components allows now the optimized and efficient usage by the user and the creation of a digital twin, which enables new services, business models and cost savings.
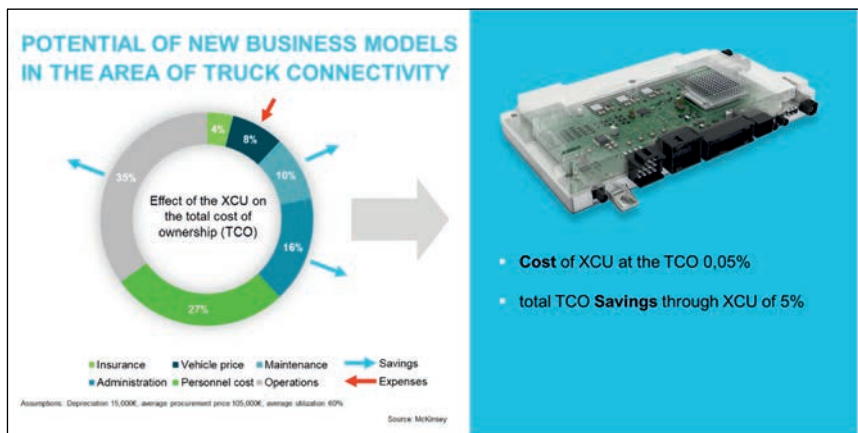
Fig. 6:   Simply connected to save costs

[1]   https://www.Appicals.com/developer_services_overview_en

[2]   https://www.xtronic.de/en/connectivity

Standardized body builder network with cloud connection

Holger Zeltwanger, CAN in Automation e. V., Nuremberg

Abstract

Commercial vehicle body builders are using increasingly electronics. To satisfy the customer demand on pre-emptive maintenance options a standardized interface between the body application unit and the telematics gateway has been developed by DIN. This standard also comprises a gateway to the in-vehicle networks. The standardized network is based on Classical CAN using J1939 or CANopen as application layer.

Body application

Many commercial road vehicles are equipped with aftermarket body applications. Providers of such body applications use increasingly electronic control systems. Such body applications include tail lifts, truck-mounted cranes, refuse collecting equipment, or fire-fighting devices. The kind of body applications is very divers and very specific. The market of body builders is highly fragmented.

All these different body applications need a gateway to the in-vehicle networks to get information from the truck or trailer on which they are mounted. Additionally, the body application sends request to the commercial road vehicle via such an in-vehicle gateway provided by the OEM (original equipment manufacturer). Unfortunately, these gateways are OEM-specific. Most of them provide a CAN interface option running a SAE J1939 application layer with more or less proprietary messages. There is one OEM supporting CANopen (standardized in EN 50325-4) as application layer.

With the increasing usage of electronic controllers in the body application, the customers need pre-emptive maintenance options. This is to get information about the status of the body application. Additionally such a link to cloud services could be used to transmit for example temperature values of the refrigerated load or the opening and closing of tail-lifts.

In order to enable body builders to implement their systems and sub-systems on road vehicles from different brands, a standardization of interfaces is needed.

DIN started such a standardization project. The DIN 4630 standard proposal has been voted positively and will be published soon. Another DIN standard is going to reference DIN 4630: DIN 14704 standardizes the in-vehicle network gateway for fire fighting trucks specifying additional parameters and J1939 messages (parameter groups).

DIN 4630 basics

In the beginning of the standardization project, there was a long discussion about the application layer. First idea was to use CANopen as the application layer, which is especially implemented in complex body applications with sub-layered networks. Typical examples include refuse collecting vehicles as well as fire fighting trucks. But there is only one OEM providing a CANopen-based gateway to the in-vehicle networks. All other OEMs prefer a J1939-based gateway. CANopen gateways are highly configurable, which meets the body application vendors perfectly.

Considering the fragmented market of body builders, the responsible DIN working group experts decided to support both application layers. This is, why the DIN 4630 document specifies logical units such as the Body Application Unit (BAU), the Telematics Gateway Unit (TGU), the In-vehicle Gateway Unit (IGU), and the Fleet Management Unit (FMU). These logical devices can be implemented in any electronic control unit (ECU). This means, an ECU can feature IGU and FMU functionality. You can also integrate multiple BAU functions in one ECU controlling the truck-mounted crane and a tipper function.

This approach is also very suitable for body applications with a sub-layered deeply embedded communication system, which could be also CAN-based. DIN 4630 allows to route status data from the devices connected to these deeply embedded networks into the cloud via the TGU. It is also possible that such a deeply embedded device or sub-system can request functions from the truck or trailer.

Figure 1 and Figure 2 show some examples of possible implementations.

LEGEND
BAU = body application unit
ECU = electronic control unit
FMU = fleet management unit
IGU = in-vehicle network gateway unit
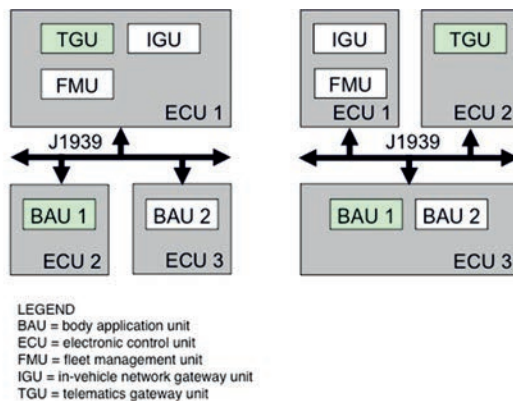TGU = telematics gateway unit

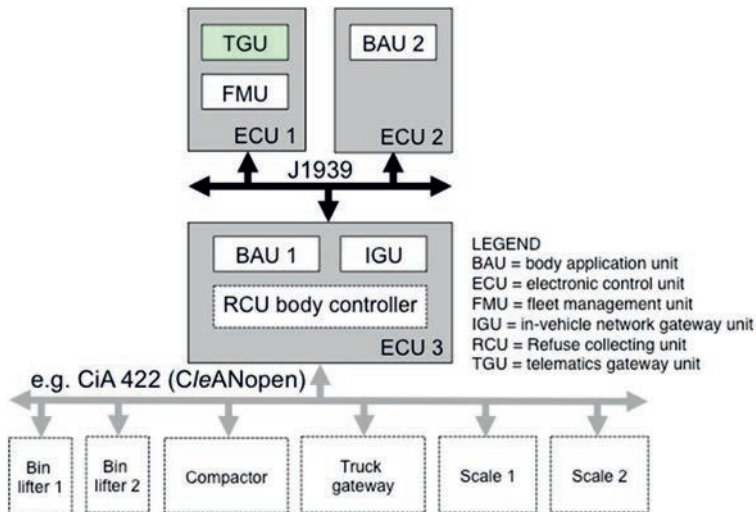Fig. 1: DIN 4630 logical device implementation on ECUs

Fig. 2: Body application with a sub-layered embedded CAN network

There are body applications with multiple sub-layered embedded control networks. The CANopen-based embedded control network for refuse collecting vehicles is standardized in EN 16815:2019. There is also a standardized embedded control network for fire fighting equipment (DIN 14700), which is currently under revision. It also uses CANopen functionalities.

Body Application Units

The number of body applications is countless. In DIN 4630 just a view have been standardized in the first version. The following BAU types have been standardized:

- Lifting unit (LU)
    - o Vehicle-mounted crane unit (VMCU) compliant with EN 12999
    - o Tail-lift unit (TLU)
- Heating and refrigerating unit (HRU)
    - o Generic HRU
    - o Cargo space/container single/multi-temperature HRUs
- Refuse collecting unit (RCU)
    - o RCU compliant to EN 16815
    - o RCU not compliant to EN 16815

- Container unit (CU)
    - Removable/non-removable tank for liquids
    - Tiltable/removable silo for bulk materials
- Tipper unit (TU)
    - Different styles of dump units
    - Roll-off container unit

Each of these BAUs support dedicated parameters, which are mapped to J1939 parameter groups (PGs) or can be manufacturer-specifically mapped into CANopen process data objects (PDO). The mapping to PGs is static and each PG has a data field length of 8 byte. The mapping to PDOs is configurable. A PDO can have a data field length of 1 to 8 byte. The J1939 mapping of BAU parameters is specified in Annex A. Annex B specifies the mapping to CANopen.
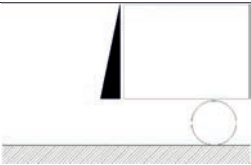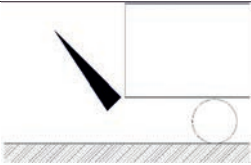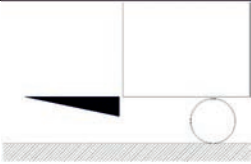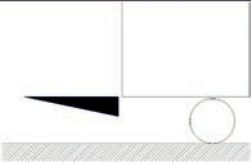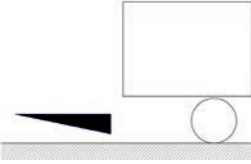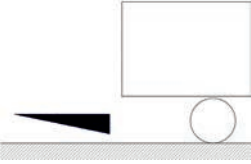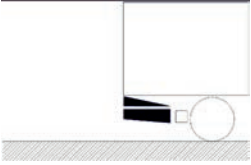
There are some general BAU parameters as well as those, which are BAU specific. The generic ones comprises, for example the remaining operating hours before the next maintenance. This is mapped into a PG or a PDO with the additional information, if the remaining operating hour value is related to the complete BAU or to one of the sub-devices connected to an embedded network.
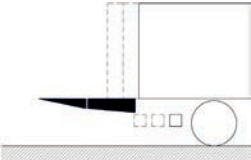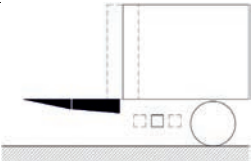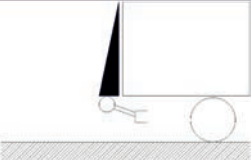
For tail lifts there are for example the position, the movement, and the user on/off parameters specified. They are mapped into the TLU1 parameter group, when implementing the J1939 higher-layer protocols. In case of CANopen communication, the ECU controlling the tail-lift transmits these parameters by means of the PDO service. Additionally, these parameters can be read individually by means of the SDO (Service Data Object) services.

All parameters have a minimum length of one byte. The assigned data types comply with J1939 and CANopen definitions. The tail-lift position status parameter is given as enumeration. Table a shows the defined position values.

Table 1: Possible positions of a tail-lift

Value	Definition	Normal position	Retractable position
00_{16}	Unknown position	N/A	N/A
01_{16}	Driving position		

Value	Definition	Normal position	Retractable position
02_{16}	Working position	Unequal driving position	Unequal driving position
03_{16}	Platform closed		N/A
04_{16}	Platform open		N/A
05_{16}	Floor bed height (vertical)		
06_{16}	Ground (vertical)		
07_{16}	Between floor bed height and ground (vertical)		
08_{16}	Stowed position (horizontal)	N/A	
09_{16}	Working position (horizontal)	N/A	Unequal stowed position (horizontal)

Value	Definition	Normal position	Retractable position
$0A_{16}$	Horizontal position 1	N/A	
$0B_{16}$	Horizontal position 2	N/A	
$0C_{16}$	Horizontal position 3	N/A	
$0D_{16}$	Moveable RUPD driving position (only for trucks)	N/A	
$0E_{16}$	Moveable RUPD driving position (for truck and trailer)	N/A	
$0F_{16}$ to FD_{16}	Reserved		
FE_{16}	Error		
FF_{16}	Not available		

The tail-lift unit can be combined optionally with an RFID unit running on the same ECU, if desired. This can be used, when the loading and unloading of items should be recorded automatically. Another combination with a weighing unit is also possible.

Further body application will be introduced in the next versions of DIN 4630 on demand of body builders. This could even include nomadic devices such as fork-lifts, which communicate wirelessly via a gateway. The pre-emptive maintenance data is forwarded via the DIN 4630 network to the TGU and than to the cloud.

Telematics Gateway Unit

The first use-case of the CAN-based DIN 4630 network was the transmission of parameters for pre-emptive maintenance purposes. This includes information about the remaining operation hours, the next maintenance date, etc. The TGU can be implemented in a separate ECU providing just this functionality. But it can be also implemented in the ECU featuring the IGU (In-vehicle Gateway Unit) functionality.

The IGU collects status parameters of the ECUs (e.g. device and MCU temperature), of the implemented BAU or its sub-parts (e.g. operating status, maintenance information), and of the other installed virtual devices (e.g. IGU). There also BAU parameters specified indicating failures and warnings. Besides collecting data, the IGU can control remotely the BAUs by means of enabling and disabling them. This includes functions such as geofencing and time fencing, which are not secured.

It is also intended that the DIN 4630 connected virtual devices are software-updated via the TGU. This is supported by the specified higher-layers: SAE J1939-21 and CANopen. Both approaches provide a transport protocol to do so. The CANopen SDO (service data object) transport protocol has no restriction of data download size.

The TGU interface to the cloud is not yet standardized. This could be done in a second step, if desired. Such a standardization would be helpful to use cloud services from different parties including those by fleet owners in combination with those provided by the truck or trailer OEMs.

Fleet Management Unit

The DIN 4630 standard tries to use existing specifications and standards, wherever it is possible. The Fleet Management System (FMS) specification is completely referenced (latest version). It can be implemented in the ECU with IGU functionality. Alternatively, it can be part of the ECU with the TGU function. Of course, it also can be implemented as stand-alone ECU.

J1939 application layer

Annex A of DIN 4630 specifies the mapping of parameters to J1939 higher-layer protocols. The J1939-21 application and transport layer protocols are mapped to CAN lower layers as standardized in ISO 11898-1 and ISO 11898-2. DIN 4630 specifies a connector: 7-pin socket connectors from TE Connectivity (1-1718230-1) or from ITT Cannon (APD/ISO 15170) or equal socket connectors from other manufacturers using the coding A. Table 2 shows the pin-assignment.

Table 2: Pin-assignment of the DIN 4630 connector used for J1939

No.	Pin name	Function
1	VCC	Battery voltage (clamp 30) fused with 10 A
2	GND	Battery ground max. 10 A (unfused)
3	Reserved	None
4	CAN_H	CAN high, one of the differential network lines
5	CAN_GRD	CAN ground
6	CAN_L	CAN low, one of the differential network lines
7	Reserved	None

As far as possible, existing parameter groups are referenced. There are already some needed PGs specified in the SAE J1939 Digital Annex. Additional PGs are standardized in ISO 11992-2 and ISO 11992-3. These ISO standards are originally intended for the communication of commercial trucks and trailers – in other words towing respectively towed vehicles. Especially, those parameters requesting services from the truck are needed as well as status information of the towing vehicle.

PGs are normally transmitted periodically; nevertheless some PGs are requested by means of the PG RQST. PGs larger than eight bytes need a transport protocol as specified in SAE J1939/21; it is also necessary for the mandatory address claiming specified in SAE J1939/81 and the mandatory diagnostic messages specified in SAE J1939/73. Each hardware entity (ECU) and each logical entity (BAU, FMU, IGU, and TGU) need an own SA (source address).

CANopen application layer

Annex B of DIN 4630 specifies the mapping of parameter to CANopen higher-layer protocols. CANopen was developed originally in a European research project as in maintained by the non-profit CAN in Automation (CiA) users' and manufacturers' group headquartered in Nuremberg, Germany. It is internationally standardized in EN 50325-4 and add-on CiA specifications. This includes the CiA 305 layer-setting services (LSS) supporting a node-ID assignment via the CAN network. The node-IDs for ECUs and functional units are specified as shown in Table 3.

Table 3: Node-ID assignment

Unit	Node-ID
ECU 1 to ECU 11	01_{16} to $0B_{16}$
BAU 1 to BAU 8	21_{16} to 28_{16}
TGU	30_{16}
FMU	31_{16}
IGU	32_{16}

CANopen features configurable PDO communication. This allows optimizing communication on the DIN 4630 network, in order to reduce busload. CANopen features the SDO transport layer services allowing the transmission of data of any size. This means you can download software updates. Appropriate parameters are specified in the add-on CiA specifications.

All communication and DIN 4630 application parameters are accessible by means of SDO services in the CANopen object dictionary. Each parameter has a unique 16-bit index and 8-bit subindex.

The embedded sub-networks for refuse collecting vehicles and for fire-fighting trucks are based on CANopen. They are standardized in EN respectively DIN 14700 (currently under revision). For those body applications, it would be an advantage, if OEMs provide a CANopen IGU. Otherwise the body builder needs an additional J1939-to-CANopen gateway.

Summary and outlook

In the communication between BAUs, FMU as well as IGU and cloud server(s) via TGU, the following value-added services are considered, but are not limited to these use cases:

— state/status information;

— diagnostic and maintenance information;

— error information to the driver;

— geofencing;
— charging systems;
— data logging;
— software/configuration updates .

The TGU can pre-process the BAU, FMU, or IGU data and forwards them to cloud service providers. Users of such services are owners of commercial vehicles, providers of BAUs, and other interested parties such as vehicle OEMs (truck, trailer and semi-trailer manufacturers). Each ECU hosting one or more logical entities (BAU, FMU, IGU, and TGU) provides a set of general parameters. Each logical entity compliant to DIN 4630 provides a dedicated set of parameters depending on its functions.

The DIN 4630 standard will be published soon. The submitted comments need to be observed, resolved, and implemented. This body builder network approach is very flexible regarding the implementation. Figure 3 shows an example of a truck/trailer combination. Both vehicles feature body applications and separate TGUs, because the trailer needs to communicate to cloud services, when it is not connected to the truck. A typical application would be a trailer with refrigerating function. The shown example there are two ISO 11992 networks, one for braking and running gear and another one for other functions.
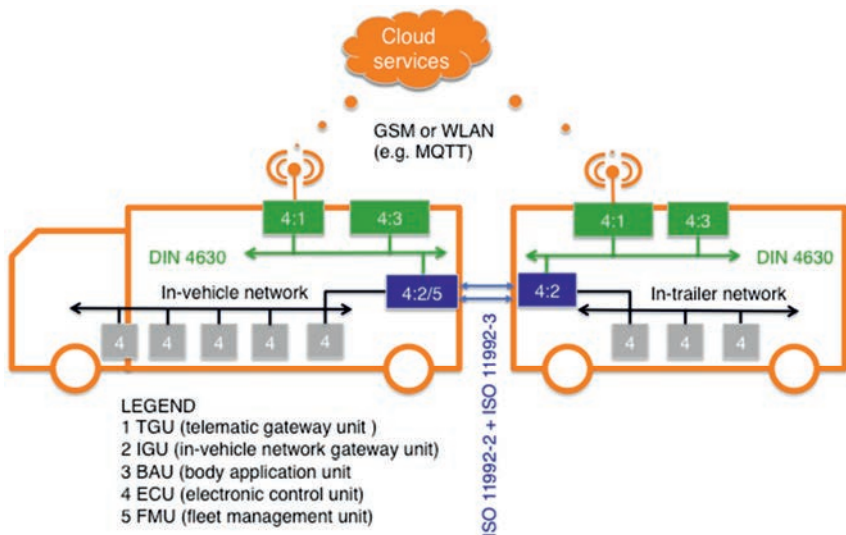

Fig. 3: Implementation example of DIN 4630 networks in road vehicles

The DIN 14700 and DIN 14704 standards for firefighting vehicles are still in development. The EN 16815 standard for refuse collecting vehicles is published since 2019. CiA is currently updating this standard in the CiA 422 series.

The open question is the standardized IGU implementation. Because all IGU functions are optional, interoperability between different implementations is not guaranteed at all. Even not for a minimum functionality.

References

[1]   CiA 301, CANopen application layer and communication profile

[2]   DIN 4630, Road vehicles – Data parameter specification for body application units in commercial vehicles

[3]   DIN 14700, Firefighting and fire protection – CAN interface for devices in emergency vehicles (under revision, integrating all parts of the legacy DIN 14700 series into one document)

[4]   DIN 14704, Firefighting and fire protection – Firefighting-specific parameters for in-vehicle gateway units (under development, not yet published)

[5]   EN 16815, C*le*ANopen – Application profile for municipal vehicles

[6]   EN 50325-4, Industrial communications subsystem based on ISO 11898 (CAN) for controller-device interfaces – Part 4: CANopen

[7]   ISO 11898-1, Road vehicles – Controller area network – Part 1: Data link layer and physical signaling

[8]   ISO 11898-2, Road vehicles – Controller area network – Part 2: High-speed medium access unit

[9]   ISO 11992-2, Road vehicles – Interchange of digital information on electrical connections between towing and towed vehicles – Part 2: Application layer for brakes and running gear

[10] ISO 11992-3, Road vehicles – Interchange of digital information on electrical connections between towing and towed vehicles – Part 3: Application layer for equipment other than brakes and running gear

[11] SAE J1939 series, Recommended Practice for a Serial Control and Communications Vehicle Network

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