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# M V M **M**obility **V**ehicle **M**echanics

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**MOBILITY & VEHICLE MECHANICS**

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# TOWARDS ZERO EMISSION: ARE E-FUELS A PROMISING OPTION?

*Ralph Pütz*[1]*

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RESEARCH ARTICLE

**ABSTRACT:** Today modern, exhaust gas treated engines exhibit almost zero emissions locally. Action is needed exclusively with regard to the conservation of fossil resources and reducing $CO_2$, both of which are closely related. For a technology-neutral approach, starting with renewable primary energies, the diverse conversion, storage, energy distribution and refueling concepts must be examined in particular with regard to their availability or investment requirements. The Power-to-Liquids approach, i.e. the use of renewable liquid fuels (so-called "e-fuels"), reveals enormous potential, which should be raised in parallel with the electro-mobility that is politically propagated as a "magic bullet".

**KEY WORDS**: zero emission, greenhouse gases, local emissions, e-fuels, electromobility



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# KA NULTOJ EMISIJI: DA LI SU E-GORIVA OPCIJA KOJA OBEĆAVA?

**REZIME**: Danas savremeni motori, sa tretiranim izduvnim gasovima, pokazuju skoro nultu emisiju lokalno. Akcije su potrebne isključivo u pogledu očuvanja fosilnih resursa i smanjenja $CO_2$, koji su usko povezani. Za tehnološki neutralni pristup, počevši od obnovljivih primarnih energija, moraju se ispitati različiti koncepti konverzije, skladištenja, distribucije energije i punjenja gorivom, posebno s obzirom na njihovu dostupnost ili zahteve za ulaganjem. Pristup napajanju tečnošću, odnosno upotreba obnovljivih tečnih goriva (tzv. „E-goriva“), otkriva ogroman potencijal, koji bi trebalo podizati paralelno sa elektromobilnošću koja se politički propagira kao „magični metak“.

**KLJUČNE REČI**: nulta emisija, gasovi staklene bašte, lokalne emisije, e-goriva, elektromobilnost

# TOWARDS ZERO EMISSION: ARE E-FUELS A PROMISING OPTION?

*Ralph Pütz*

## 1. INTRODUCTION

Both the global population and energy demand double roughly every 40 years. Fossil resources are constantly dwindling, first oil, then natural gas and, after a few centuries, even coal. Whether the so-called “peak oil” has already happened or is still to come is irrelevant – what is certain is that a gap in the supply of energy will arise, which must be filled by renewable energy sources. In addition, in the course of the climate protection conferences in Paris 2015, Marrakesh 2016, Bonn 2017 and Katowice 2018 the European Union (EU) set itself ambitious targets for reducing greenhouse gas emissions. The aim is to achieve climate neutrality within the framework of the "European Green Deal" by 2050. On 16.09.2020, the President of the European Commission announced an intermediate goal for 2030of a further tightening of the greenhouse gases (GHG) reduction from 40% to 55% in comparison to the base year1990. This requires an ambitious CO2 reduction strategy, in particular for the road traffic sector since this sector –unlike local pollutant emissions – generally fails to achieve lower CO2 levels despite ever more efficient engines due to its continuous growth (see Figure 1). Nevertheless, the entire transportation sector globally is responsible for only around 14% of GHG (see Figure 2), yet it remains a political focus. In the energy policy debate on targeted drive and fuel concepts electromobility is seen and promoted almost exclusively as a sustainable option. This ignores the fact that modern internal combustion engines of stages Euro VI (for commercial vehicles) and Euro 6d (for passenger cars) are already at a local near-zero emission level and only renewable fuels are needed to achieve a highly significant reduction in greenhouse gas emissions. In the context of the further expansion of wind power and photovoltaic systems, so-called e-fuels are gaining in importance as climate-neutral liquid fuels with high energy density since the existing vehicle technology can be maintained along with distribution and refuelling infrastructures.

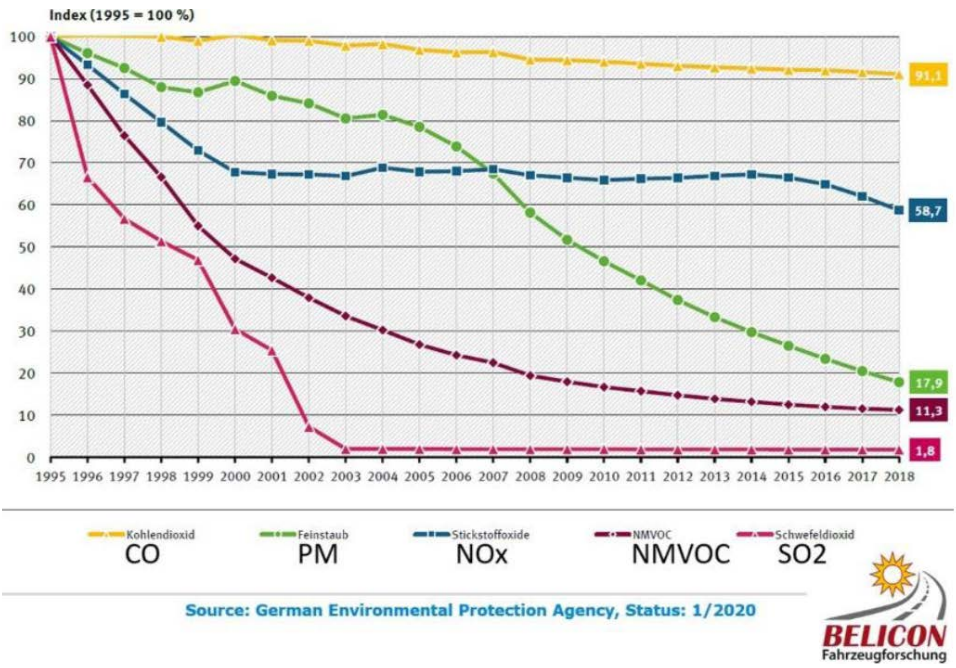


*Figure 1 Specific local and global Emissions of the German Passenger Car Fleet (1990-2018)*

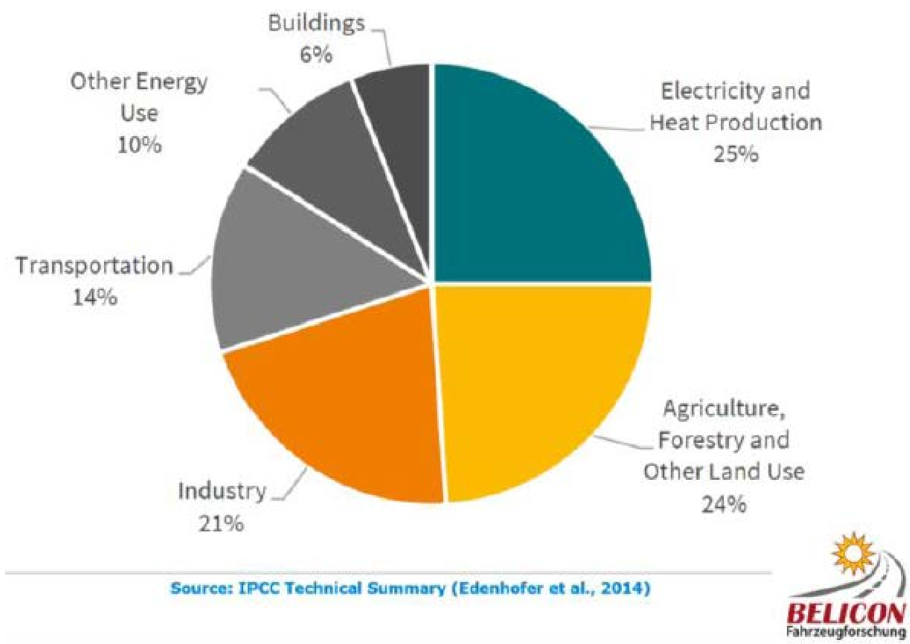


*Figure 2 Global Greenhouse Gase Emissions by Sector (2010)*

## 2. SYSTEMS APPROACH INDISPENSABLE FOR AN OBJECTIVE EVALUATION

For a comprehensive ecological and economic evaluation of vehicle fleets of different power drives and fuel types all stations of the lifecycle of transport systems must be included in the analysis, namely:

- Vehicle production (Cradle-to-Gate; CtG) and, if applicable, recovery/disposal,
- Fuel availability (Well-to-Tank; WtT),
- Driving mode (Tank-to-Wheel; TtW) and
- Maintenance.

since the isolated view of only looking at the actual driving operation – as in the relevant EU directives on road vehicles (e.g. the new "Clean Vehicles Directive" in the public transport (PT) bus sector, adopted in June 2019) –can lead to completely false conclusions. Only in this way can targeted solutions be identified for transport systems with both low local and global emissions and increased energy efficiency and reduced noise in the context of a holistic ecological integrity (see Figure 3 for example PT bus). This approach can be further developed for an entire transport company (see Figure 4). When analysing the emissions the main localised effective criteria include particle and nitrogen oxide emissions and the main global criteria primarily include $CO_2$ emissions or $CO_2$-equivalents whose effects on the determination of external costs can be summarised as an ecological profile of a drive technology. In the economic analysis the focus is on „vehicle costs“ which consist of capital services, fuel/energy costs and maintenance costs for fleet operators, supplemented by the costs of the energy supply infrastructure.

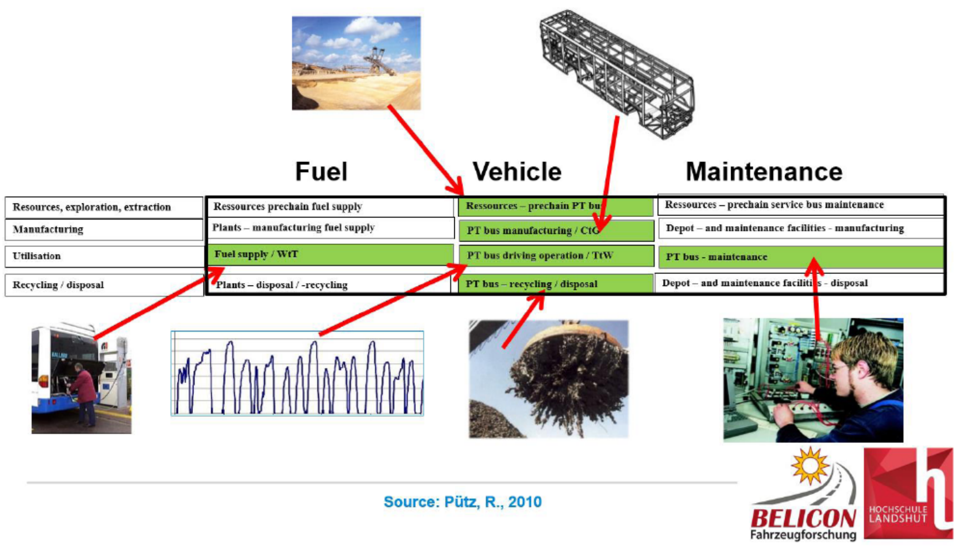


*Figure 3 Ecological Systems Approach with Subsystems (example: PT Bus)*

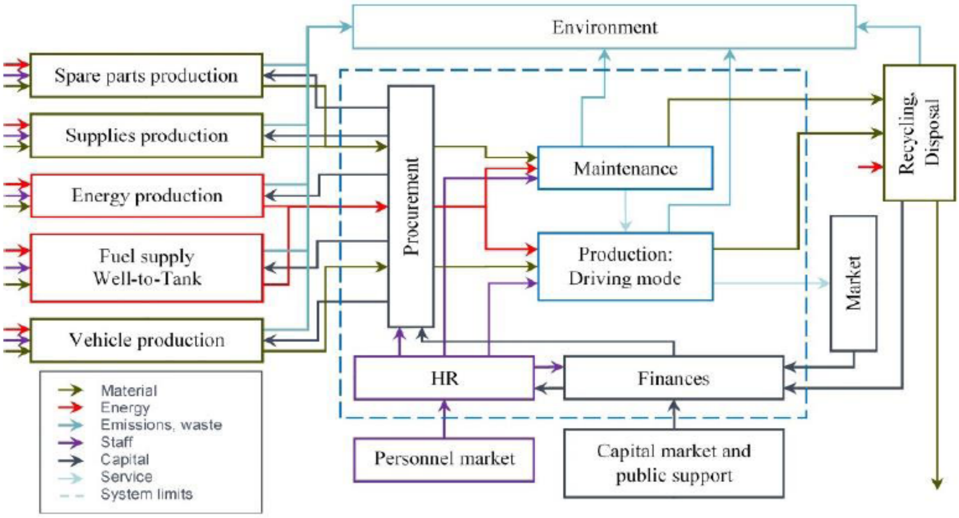


*Figure 4 Ecological-economical Model for the complex System "Transport Company" and its Subsystems*

## 3. NEAR-ZERO LOCAL EMISSION WITH EURO VI/6D COMBUSTION ENGINES

The local pollutant emissions of modern, exhaust-gas after-treated Euro VI/6d combustion engines are already accepted as uncritical. Figure 5 shows the measured values from the real operation of articulated PT buses in urban traffic with 'stop-and-go operation' for a flat line. On the left, the emission ratio of a Euro V and, on the right, a Euro VI articulated bus are shown respectively. The profiles of the exhaust gas temperatures shown in green are almost identical. The Euro V articulated bus shown on the left generates high NO emissions after the cold start, which settle down after less than 10 minutes. The Euro VI articulated bus shown on the right emits lower emissions than the operation-ready Euro V articulated bus even at cold start. With the Euro VI articulated bus shown on the right, nitrogen oxide emissions are already at ambient air level after just 10 minutes due to effective SCR exhaust gas after-treatment! Figure 6 shows in detail the particulate emissions in the ambient air and after particulate filters in a Euro-6d-passenger car, which clearly show that the intake air contains more particles than the exhaust gas and is thus actually cleaned in the process. This means that there will be no so-called "diesel crisis" if the exhaust gas after-treatment systems available as standard are used. Today the only need for action is with regard to the use of renewable fuels to significantly reduce globally effective emissions (GHG) and to conserve fossil resources.

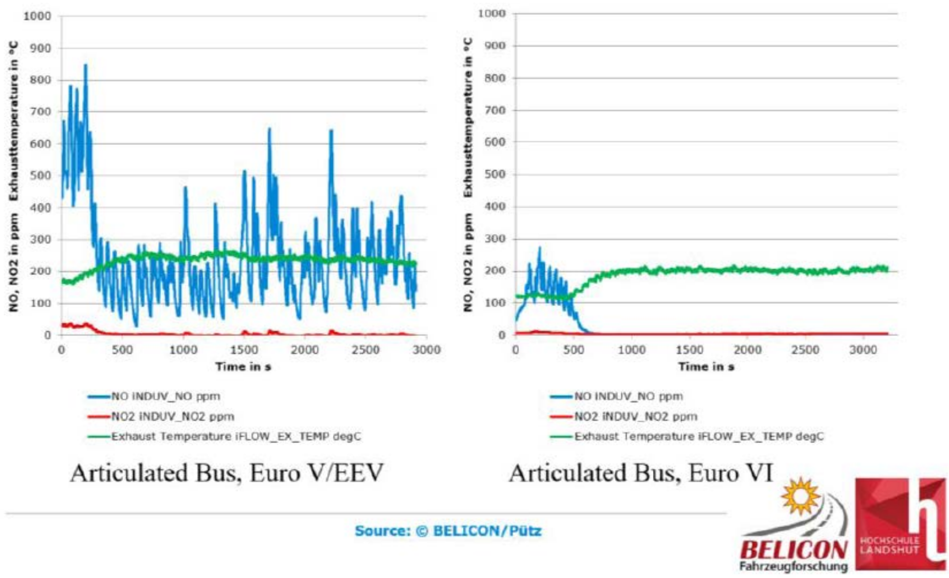


*Figure 5 Comparison of NOx Emissions in Euro V/EEV and Euro VI articulated Diesel Buses*

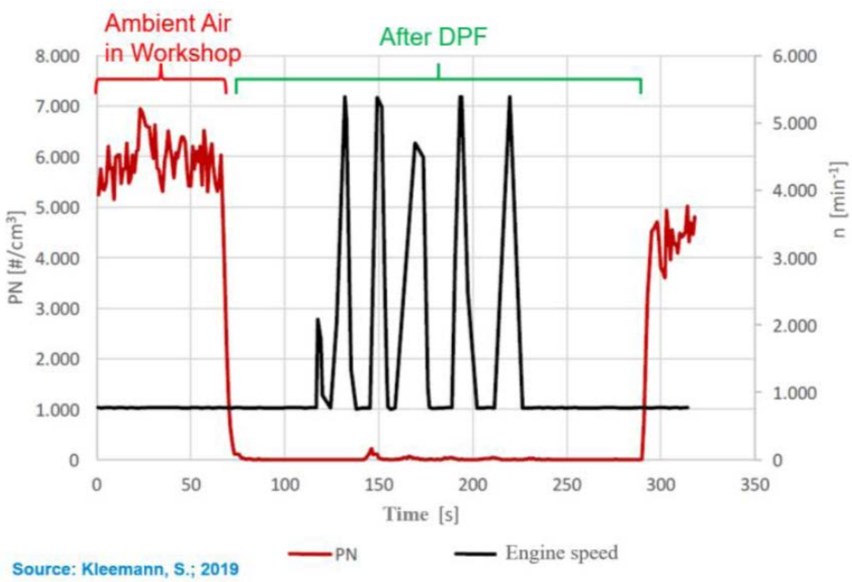


*Figure 6 Particulate Emission of a Euro 6d Diesel Car before/after Diesel Particulate Filter (DPF)*

Irrespective of the above-mentioned facts, the EU Clean Vehicles Directive defines "emission-free vehicles" as only those vehicles with no local emissions and without direct $CO_2$ emissions. A coal-powered electric bus with obvious higher $CO_2$ intensity would thus be viewed misleadingly as "emission-free" whereas a much cleaner diesel bus would be excluded by politically limited procurement quotas, despite it demonstrating integrated ecological advantages compared to an electric bus, even with an average German electricity mix (see Figures 7 and 8). Under the EU Clean Vehicles Directive, on the other hand, buses with highly sophisticated diesel engines would still be permitted as "clean" vehicles in the medium term if they are operated using sustainable biofuels or synthetic fuels (xtL fuels). Thus, in addition to the E-fuels (Power-to-Liquids) produced from renewable electricity, GtL (gas-to-liquids; from natural gas) and even CtL (coal-to-liquids; from coal) would be permissible, the latter regardless of its high $CO_2$ intensity and subsequent significant deterioration of the $CO_2$ balance compared to fossil diesel fuel. In doing so, the options for diesel powered vehicles in conjunction with GtL and natural gas power with fossil natural gas defined in the Clean Vehicles Directive as „clean" offer no ecological advantage compared to the Euro VI diesel propulsion system with conventional EN590 diesel fuel. Thus, it is clear that the EU Clean Vehicles Directive is in need of immediate amendment in order to objectively assess the actual – system-related – ecological relations. In conjunction with E-fuels (Power-to-Liquids) the ecological objectives of Euro-VI-6d vehicles with regard to both local as well as global emissions would already be achieved and would thus be definitely feasible for the entire conventional vehicle fleet where a quantum leap could be made in the reduction of GHG emissions. In addition, the use of full-hybrid diesel buses (which according to the EU Clean Vehicles Directive are only declared as "clean" in the form of plug-in hybrids)with e-fuels would provide timely ecological improvements.

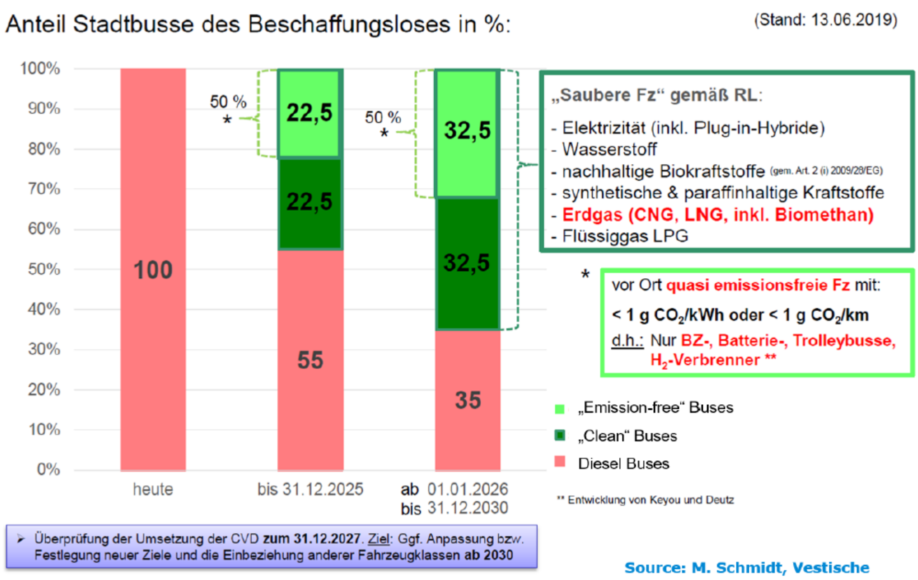


*Figure 7 Fixed Quotas for the Tendering of new PT Buses over Time acc. to EU Clean Vehicles Directive*

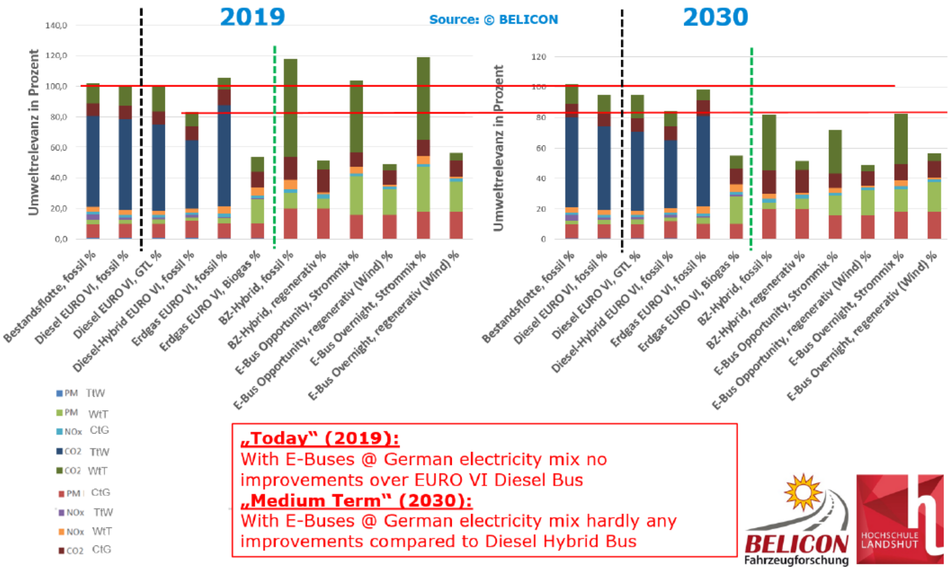


*Figure 8 System-related Environmental Relevance of an exemplary Bus Fleet 2019 and 2030*

The overall economic evaluation (including infrastructure) for PT buses is shown in Figure 9 on the time horizon of 'today' with a normal depreciation period of 9 years. Without taking into account the abundant public start-up funding for electric buses and their infrastructure, the options for electromobility are still currently way behind being economically viable. For an economic evaluation of the 'medium term' the forecast development of fuel prices is assumed, which includes investment costs for electromobility as well as the forecast, significant cost degression of the energy stores but still, however, has a replacement battery over the 12 (up to 17) years of operational use for PT buses (used from new). Today it can be assumed that the expected lifespan of the batteries with average public transport use barely lasts a 'half bus life' (ranges from 5 to 7 years). Likewise, for fuel cell technology, there is a similar significant cost depreciation assumed in the 'medium term'. It is evident that, in the 'medium term' electro buses– in particular due to ever increasing energy prices for fossil fuels (diesel and natural gas) as well as the reduction in battery and fuel cell costs and despite increasing electricity prices, will draw even closer to becoming as economics conventional drives. The economic viability of established, clean concepts with combustion engines will, however, not be achievable even in the medium term with the options for electromobility for most public transport operator circumstances. With today's dominant li-ion battery technology in the medium term, the operation of electric buses like buses with internal combustion engines – in other words, Overnight Charger – can only be possible with highly significant additional costs of over 50 percent due to the high investment costs, even without taking into account investments in the infrastructure. The Opportunity Charger will – without consideration of additional infrastructure costs – be about 20% more expensive compared to diesel technology. If the energy consumption for heating/ventilation/air conditioning (HVAC) and thus the range in winter as well as the reduced passenger capacity due to the battery mass of the overnight charger for e-buses are considered in depth, then the cost balance for e buses worsens due to the maintenance of operation of necessary additional vehicles (see Figure 10). This shows that the input of e-fuels in combustion engines also demonstrates significant economic advantages.

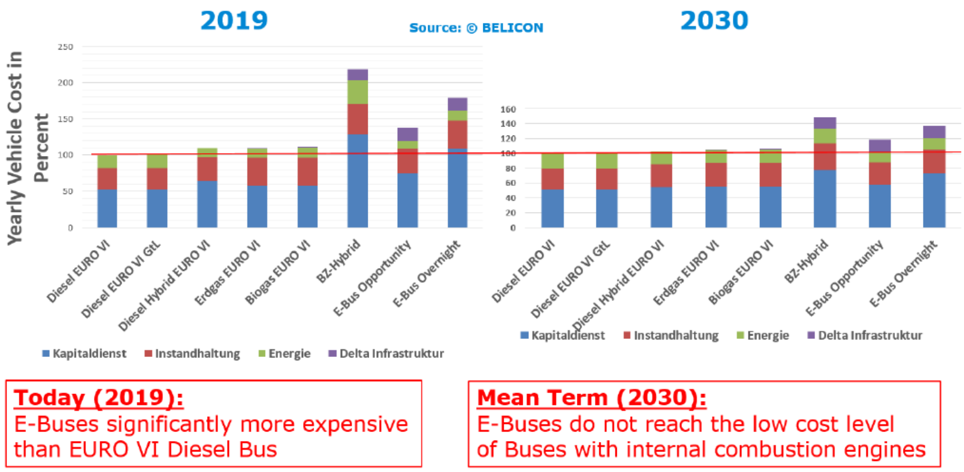


*Figure 9 Relative Vehicle Cost of an examplary PT Bus Fleet in 2019 and 2030 - without Subsidies*

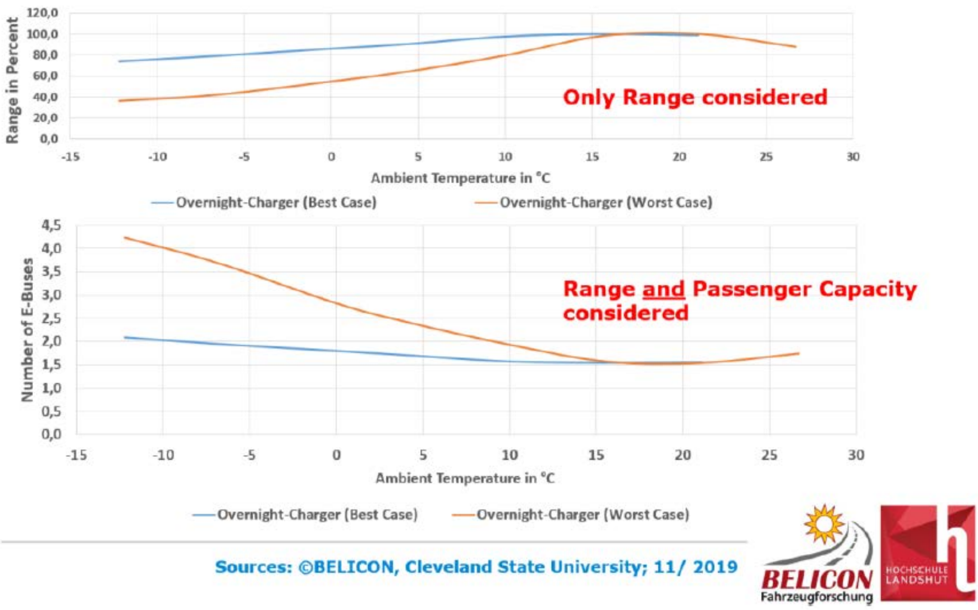


*Figure 10 Range depending on ambient Temperature and Passenger Capacity of Overnight-Charger E-Buses*

Since the further development of electromobility in the passenger car sector is also considered as a driver for the cost reduction of electric mobility in regular buses, the assessment of FEV Aachen (2017) for the period up to 2030shown in Figure 11 should be given. According to this, by 2030 in the EU only 20% of new vehicles in the passenger car and light commercial vehicle sectors will not have a combustion engine. Battery powered vehicles will make up19% and fuel cell vehicles only 1% of new vehicles. Nevertheless, 91% of new vehicles should have an electric powertrain, which demonstrates the increasing importance of (plug-in) hybridization of combustion engines. The mild hybrids account for the biggest proportion of new vehicles at 51%. This development once again demonstrates the enormous potential of e-fuels.

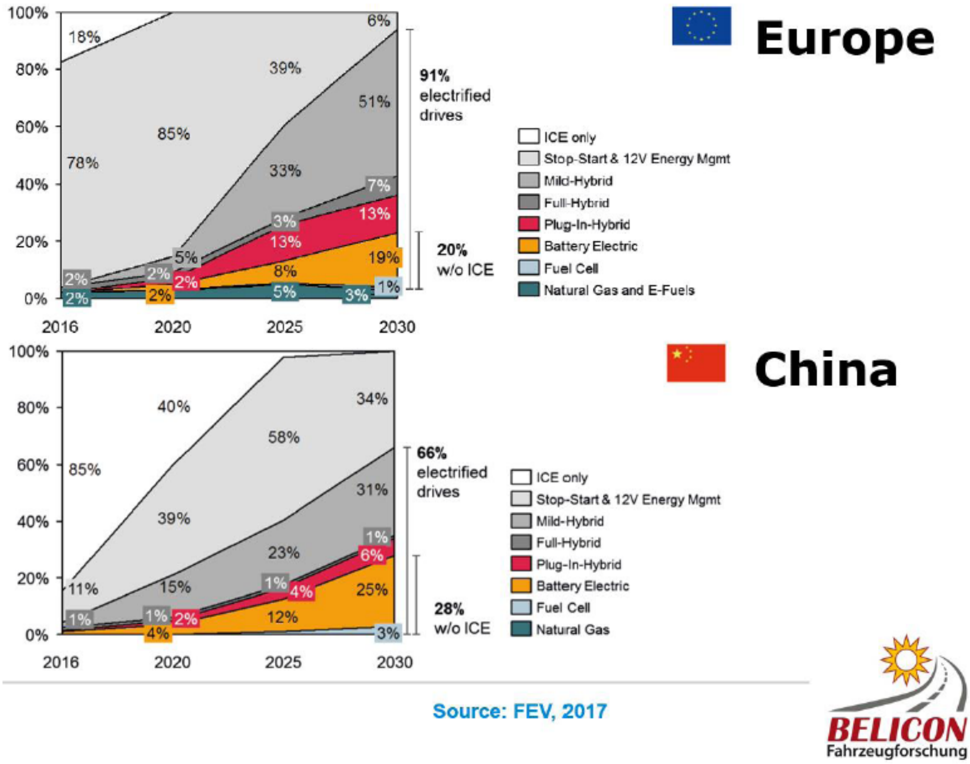


*Figure 11 New Passenger Cars till 2030: Increasing electrification of the powertrain with ICE*

## 4. E-FUELS AND THEIR POTENTIAL AGAINST E-MOBILITY

E-Fuels are climate-neutral liquid fuels that are generated by renewable electricity (solar, wind, hydropower) via hydrogen from water electrolysis and CO2 (for example from ambient air or from conventional power plants) with the help of the Fischer-Tropsch synthesis. The decisive advantages of e-fuels are their high energy density and compatibility with existing distribution and tanking infrastructure for conventional liquid fuels, but primarily also that they are produced in sun and wind-rich areas of the earth, so that the construction of wind and solar energy in areas with relatively little renewable energy (like Germany) is not required. According to the EU, for example, it would be possible to establish a strategic implementation of e-fuel production in southern Europe, which could also render obsolete the long disputed, unsustainable 'donor/recipient countries' finance systems in the long term and would strengthen the economy in southern

EU regions. In addition, the tankers which bring the new fuels to the market could likewise be powered by e-fuels. Although electromobility has advantages in terms of energy efficiency compared to the "internal combustion engine + e-fuel" approach (see Figure 12), this does not play a role in the excessive availability of renewable energy.

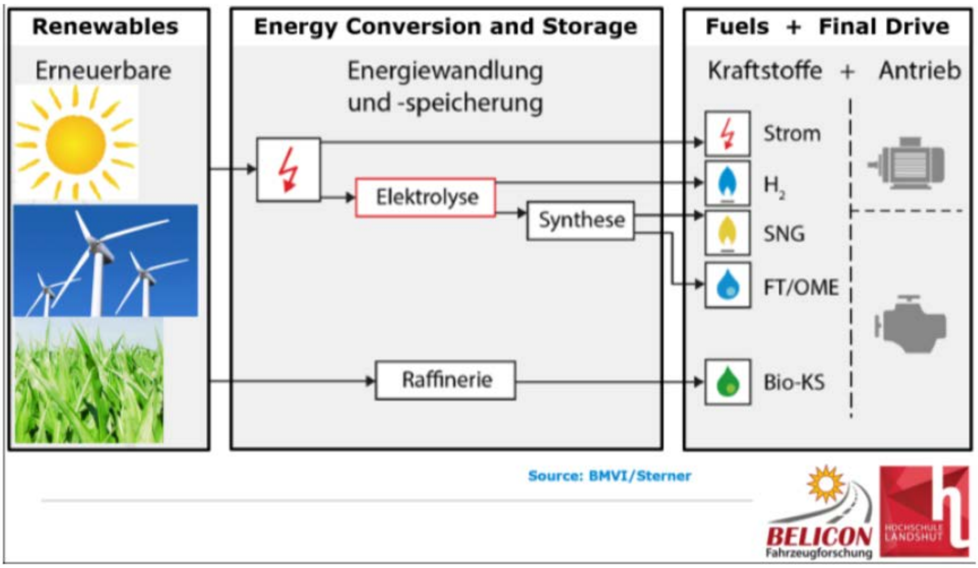


*Figure 12 Electrolysis as central Element of Power-to Liquids*

As shown above, the local pollutant emissions from modern combustion engines are already negligible so that subsequently only the influence on global emissions (GHG) should be considered. Since a complete substitution of diesel fuel by e-fuels cannot be expected in the medium term, the potential for reducing $CO_2$ should be depicted for the ‘long term’ time horizon (2040) with a 70% mixture of fossil diesel fuel compared with electric vehicles (primarily with renewable electricity) using the example of a medium sized car as shown in Figure 13. An integrated balancing of global emissions shows that, even in the long term (2040), the approach of combustion engine + e-fuels/diesel blend does not reveal any ecological disadvantages compared with electric battery vehicles primarily powered by renewable electricity; however, there are significant advantages to the vehicle costs. The e-fuel production is currently being set up on an industrial scale (for example, pilot plant in Australia) and is expected to achieve a production price of €1 per litre in the medium term, which is marketable in terms of transportation costs and profit compared to an expected diesel price of €1.70 per litre in the medium term. In the context of being technology-neutral other leading options must also be accredited in addition to electromobility. Thus, the German Energy Agency (DENA) anticipates in the long term a parallel, equal existence of electrical and non-electrical final energy applications within the framework of scenarios for combined energy and power transitions, whose proportional representation in this respect is still completely open (see Figure 14).

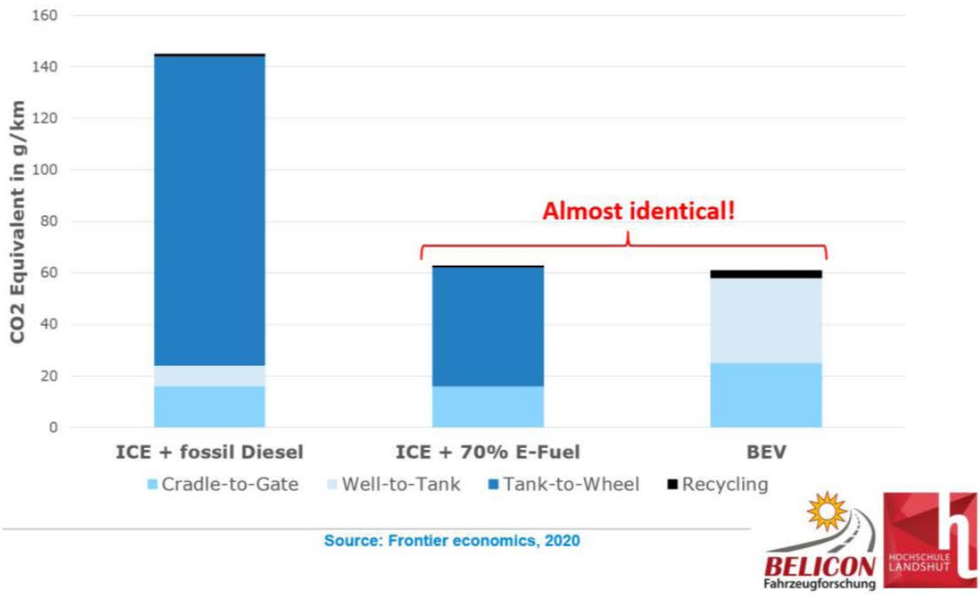


*Figure 13 $CO_2$ Reduction Potential of „ICE w. E-Fuel Blends" vs. Battery-electric Vehicles (Medium Class Car)*

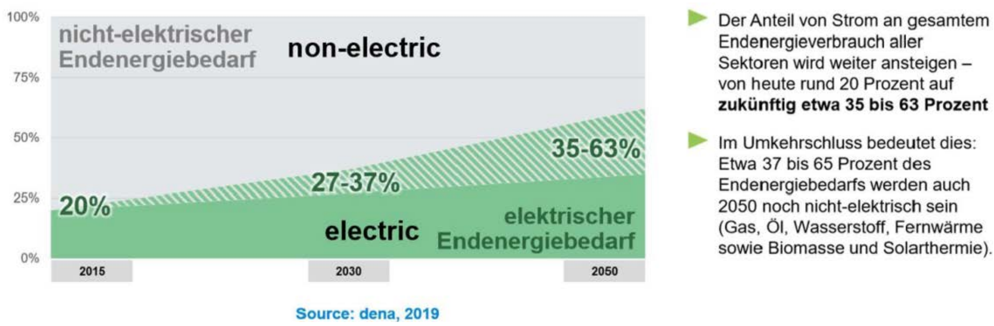


*Figure 14 Dena Study: Use of renewable Energies @ end-user over Time*

## 5. CONCLUSIONS

Today there is no need for action for local emission reduction of combustion engines (though Euro 7 is being planned). Action is needed exclusively with regard to the conservation of fossil resources and the reduction of $CO_2$, both of which are closely related. A technology-open political question should be: How does one get renewable energies (sun, wind, hydro, biomass) to the final drive stage which can not only be an electric motor, but also a highly clean internal combustion engine? For a technology-neutral approach, the diverse conversion, storage, energy distribution and refuelling concepts must be examined, starting with renewable primary energies, in particular with regard to their availability and/or necessary investments. A focus exclusively on vehicle operation (tank-to-wheel) –as in the relevant EU vehicle directives – delivers misleading results. Only a holistic accounting, taking into account all subsystems (cradle-to-gate, well-to-tank, tank-to-wheel, recycling/disposal), provides objective data on the way to a system-related zero emission. Analysis of the approach of “highly clean combustion engine with e-fuel” reveals that the politically motivated, continuous exclusion of the combustion engine with simultaneous ideological propagation of electromobility is an unsustainable strategy, which must be replaced as a matter of urgency with an open mind to technology on the basis of effective regulations in order to avoid economic development failure. The potential of e-fuels in combustion engines can be converted and dismantled nearer the time – initially by mixing with fossil fuels – for the entire existing vehicle fleet (in Germany approximately 65 million vehicles). This will be supported through the use of existing distribution and refuelling system infrastructure, whilst a comprehensive charging infrastructure must be constructed for electromobility. The imminent problem of disposal/recycling inherent in electromobility does not exist for e-fuels. From an economic viewpoint, all alternative drives in the electromobility spectrum are currently – without enormous public funding – far from economic viability. Also, in the medium term, the additional costs of the spectrum options politically defined misleadingly as “emission-free” have not yet reached the level of the highly attractive combustion engine options and, if the energy supply infrastructure is taken into account during the depreciation period, highly significant additional costs are still required. “Many roads lead to Rome” – a target-oriented policy must allow alternative options and the market mechanisms to develop the optimum, subject to effective regulations.

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# ELECTRIC AND HYBRID VEHICLES: ARE WE READY FOR THE NEW MOBILITY ERA?

*Giovanni Belingardi[1]*, Nicola Amati[2], Angelo Bonfitto[3]*

*Received in July 2020* *Revised in August 2020* *Accepted in September 2020*
RESEARCH ARTICLE

**ABSTRACT:** Hybrid (HEV) and pure electric (EV) vehicles are nowadays considered as the new frontier for the mobility. The claim is to solve a number of problems that are affecting the person and goods mobility, from the environmental point of view but also from the safety and the traffic congestion point of views. However, some concerns, in particular about the energy sources and availability are open questions. Hybrid architectures are seen as the transition toward the purely electric solutions. But probably a wide revolution of the mobility system has to take place, with new paradigm for different mobility types. For example, urban mobility is quite different and poses different targets with respect to the long-distance mobility. Goods delivery inside the town are suitable for different solutions with respect to highway trucks transportation. The paper, after a brief overview of the proposed architectural solutions for HEV, proposes a discussion of the advantages that can be obtained by using different paradigms. Then, some open questions related to hybrid and purely electric configurations are addressed. One of the key points is the availability of battery packs with enough energy capacity, affordable costs and at reasonable prices in relation with the vehicle missions. Therefore, present research activities are devoted to the development of optimal efficiency solutions both at subsystem and complete vehicle level. In detail, we will discuss some issues related to Battery Pack systems and Battery Management System (BMS) that have not yet reached an adequate level of robustness and reliability and need further investigations.



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The accurate evaluation of the state of charge (SoC) and of the state of health (SoH) becomes straightforward to properly exploit and maximize the performance of the battery pack. In addition, mechanical and thermal design issues, that include lightweight, battery pack cooling, and safety in case of impact, are additional primary points that ask for adequate viable sustainable design solutions.

**KEY WORDS**: HEV, PHEV, energy efficiency, battery systems, mobility paradigms

## ELEKTRIČNA I HIBRIDNA VOZILA: DA LI SMO SPREMNI ZA NOVU ERU MOBILNOSTI?

**REZIME**:Hibridna (HEV) i čisto električna (EV) vozila danas se smatraju novom granicom mobilnosti.Tvrdnja je da se reše brojni problemi koji utiču na mobilnost ljudi i robe, sa ekološke tačke gledišta, ali i sa stanovišta bezbednosti i zagušenja saobraćaja. Međutim, neka pitanja, posebno u vezi sa izvorima energije i dostupnošću, su otvorena pitanja. Hibridne arhitekture se vide kao prelazak ka čisto električnim rešenjima. Ali verovatno se mora dogoditi široka revolucija sistema mobilnosti, sa novom paradigmom za različite vrste mobilnosti. Na primer, gradska mobilnost je prilično različita i postavlja različite ciljeve u odnosu na mobilnost na velike udaljenosti. Dostava robe unutar grada pogodna je za različita rešenja u pogledu prevoza kamionima na autoputu. Rad, nakon kratkog pregleda predloženih arhitektonskih rešenja za HEV, predlaže raspravu o prednostima koje se mogu postići korišćenjem različitih paradigmi. Zatim se rešavaju neka otvorena pitanja vezana za hibridne i čisto električne konfiguracije. Jedna od ključnih tačaka je dostupnost baterija sa dovoljnim kapacitetom energije, pristupačni troškovi i po razumnim cenama u odnosu na misije vozila. Stoga su sadašnje istraživačke aktivnosti posvećene razvoju optimalnih rešenja efikasnosti kako na nivou podsistema tako i na nivou kompletnog vozila. Detaljno ćemo razgovarati o nekim pitanjima vezanim za sisteme baterijskih paketa i sistema za upravljanje baterijama (BMS) koji još nisu dostigli odgovarajući nivo robusnosti i pouzdanosti i potrebna su dalja istraživanja. Precizna procena stanja napunjenosti (SoC) i zdravstvenog stanja (SoH) postaje jednostavna za pravilno iskorišćavanje i maksimiziranje performansi baterije. Osim toga, mehanička i termička pitanja dizajna, koja uključuju laganost, hlađenje baterije i sigurnost u slučaju udara, dodatne su primarne tačke koje traže adekvatna održiva rešenja za dizajn.

**KLJUČNE REČI**: HEV, PHEV, energetska efikasnost, sistemi baterija, mobilnost paradigme

# ELECTRIC AND HYBRID VEHICLES: ARE WE READY FOR THE NEW MOBILITY ERA?

*Giovanni Belingardi, Nicola Amati, Angelo Bonfitto*

## INTRODUCTION

Government regulations on fuel economy and emissions introduced stringent requirements in automotive sector. Carmakers are called to reduce drastically the amount of pollutants with the goal of a more sustainable mobility, as illustrated in Figure 1. In this scenario, the strong incentive to produce alternative powertrain technologies has created a mix of different configurations and architectures for the vehicle traction. Side by side with the refinement of standard ICE-based vehicles, pure electric (EV), hybrid electric (HEV) and fuel cell hybrid electric (FCHV) powertrain gained an increasing attention in the last decade. As a matter of fact, FCHVs are still in a development phase, whilst EVs and HEVs are already common and affordable solutions that have established as reliable alternative to ICEs and gained a relevant momentum in the automotive market [1-3].

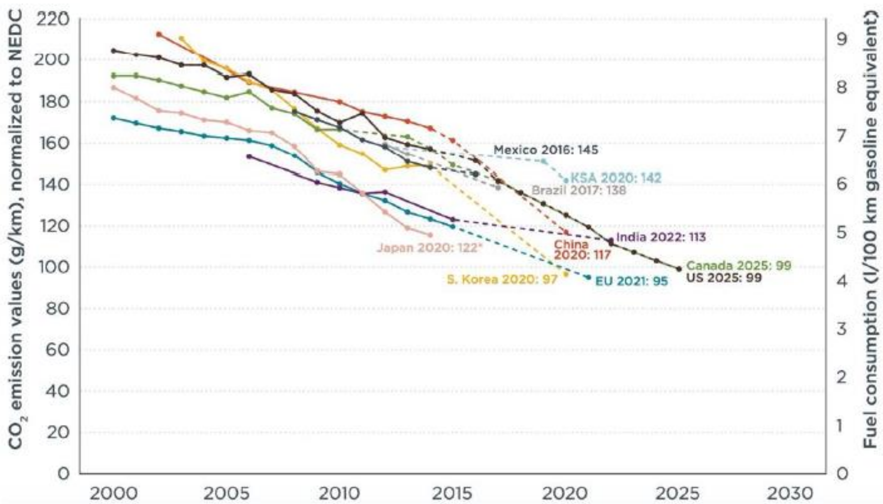



*Figure 1 Fleet CO2 emissions by country normalized to NEDC homologation driving cycle for passenger cars.Solid line: Hystorical values. Dashed lines: target values*

The technology of EVs can be considered mature and the main room for improvement have to be ascribed to the research of battery technology aimed to improve the autonomy range, that is currently settled around 400 km. In the same time, HEVs can be considered as a bridge between the ICEs and the pure electric traction. This technology is variegate, with many possible powertrain architectures and margins of development and improvement in several aspects. This paper provides an overview of the current status of the technology of EVs and HEVs and addresses the main aspects on which the research and the industrial developments are focusing their attention. Specifically, an overview of the possible hybrid powertrain architectures is provided with the analysis of the functions of each layout and a description of the sizing of the subcomponents for the different layouts. Afterwards, a discussion on the current status and on the development perspectives of the energy management controllers and battery pack is conducted. In particular, an analysis of the chemistry, cost, monitoring and sizing allows evaluating which sides of the battery technology still present margin of improvement.

However, the main objective of the paper is to highlight that the properties and advantages of powertrain electrification and hybridization may be fully exploited only when also the other components of the vehicle are designed to have the maximum efficiency. To this end, the electrification of vehicles subsystems can lead to relevant advantages in terms of fuel consumption and emission reduction. The attention in the present work is focused on three aspects: chassis electrification, specifically regeneration from shock absorbers and vehicle height adjustment, recuperation from gas exhaust, and reduction of the organic ICE losses by means of electrified accessories (i.e. e-water pump). A general trend on the development of these aspects is proposed and some specific solutions are presented along the discussion.

## 1. HYBRID ELECTRIC VEHICLE ARCHITECTURES

A first systematization of the hybrid architectures is based on the analysis of the energy flow from the sources (motor generators and ICE) to the wheels. According to this classification, the three layouts illustrated in Figure 2 are identified: parallel, series, and power-split. In parallel architectures, the power combination of the engine and electric machine/s is obtained through a mechanical connection with a gear set, a chain, or a belt. The two torque contributions are summed and transmitted to the wheels. Series architectures are designed to have electrical connection between the power generation and the wheels. The engine mechanical energy is converted in electrical and summed to the contribution coming from the batteries. The series-parallel combination allows exploiting the two layouts through the engagement and disengagement of one or two clutches to use one layout rather than the other according to the operating driving conditions. Power-split architecture combines the parallel and series layout with the adoption of a planetary gear set, the elimination of the gearbox and two electric machines [3-5].

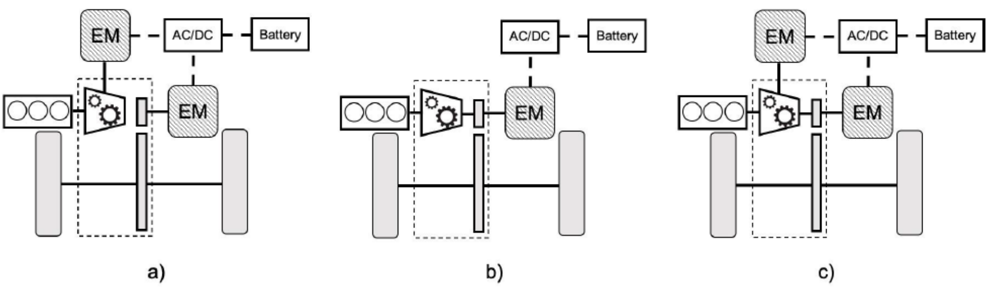



*Figure 2 Series (a), parallel (b), and power-split (c) architectures*

A further classification method is based on the degree of hybridization, i.e. on the size of the electric powertrain, and includes the following categories : 1) Micro hybrids. The nominal voltage of the electric machine is not higher than 12 V and allows for the possibility of Start&Stop implementation. 2) Mild hybrids. The nominal voltage of the motor generator in this configuration is typically 48V but solutions with 24V can be found on the market, as the solution introduced by Mazda in 2020. This layout offers regenerative braking and engine assist functions, 3) Full hybrids, in which previous functions are merged together with the additional capability of battery-only operation, and 4) Plug – in hybrids, for which the main peculiarity is the possibility to connect the electric battery to the electrical grid. The last classification approach is based on the position of the secondary energy converter and is illustrated in Figure 3.

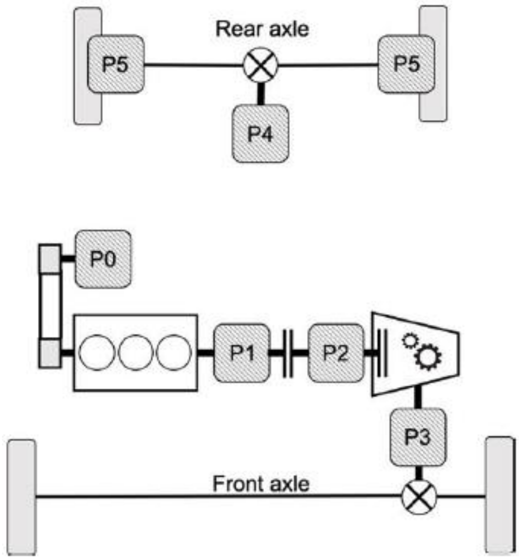


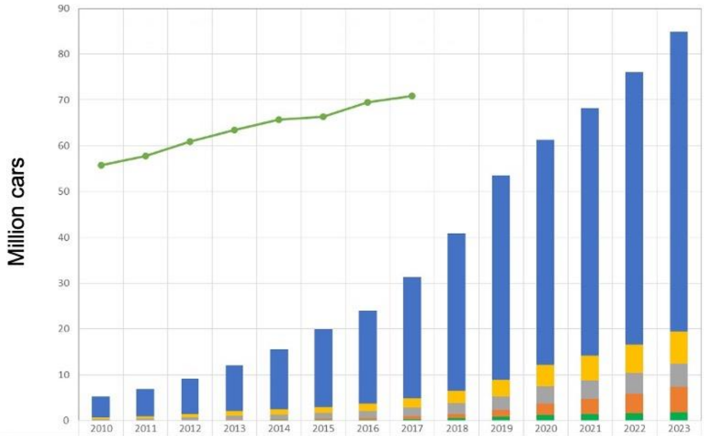

*Figure 3 Hybrid Electric Vehicle architectures based on the position of the secondary energy converter*

The categories of Hybrid vehicles based on this classification are: P0) The standard alternator mounted on the frontend accessory drive (FEAD) is substituted by a more powerful and efficient electric machine. Regenerative braking is allowed but its efficiency is low due to the number of dissipative components (differential, gearbox, ICE, belt transmission) between the wheels and the electric generator. The ICE forces the former to be designed for high speeds (15 - 18 krpm) while the limited space for the installation limits the torque and power. P1) The electric machine is located directly on the engine crankshaft (transmission side). A more efficient regenerative braking can be achieved in this case due to the absence of the FEAD. The motor can assist engine and, when integrated inside the flywheel, improve attenuation of the torque oscillations. However, due to its position it has to comply to stringent requirements about the axial size due to integration issues in the powertrain. P2) In this configuration, the electric motor is mounted downstream the mechanical clutch and the complete uncoupling between vehicle and ICE can be performed. Pure electric mode is allowed without dragging the engine inertia and its organic losses. Axial size requirements still drive the design. This layout has a strong impact on the powertrain design, since it forces the complete re-design of the transmission. P3) Moving downstream the overall driveline, the electric motor can be placed at the input or output of the secondary transmission shaft. It owns the same characteristics of P2 configuration, but regenerative braking is in this case maximized because of the presence of the differential only between front wheels and electric motor. High values of torque are requested to the electric machine since no stage of torque amplification, such as the gearbox, is present between it and the wheels. P4) Within this layout the attention is moved on the opposite axle with respectto the one in which the ICE is positioned. The electric motor is connected to the wheels by means of a differential (of whatever kind) and although a re-thinking of the electric axle should take place. This configuration offers the possibility of maximizing the recovery of the energy together with giving full potentials to the electric driving. P5) The electric machines are installed directly on the wheels. Limitations on the torque are present due to the small axial size of the machine [6]. This solution is rarely adopted by carmakers. Table 1 summarizes the main layout characteristics and function properties of hybrid electric vehicles categorized according to the aforementioned approaches.

***Table 1****Properties and characteristics of hybrid architectures categorized according to the size of the electric powertrain*

| | | Micro hybrid | Mild hybrid | Full hybrid | Plug-in hybrid |
|---|---|---|---|---|---|
| Properties | Battery voltage [V] | 12 | 24-48 | >200 | >200 |
| | Electric machine power [kW] | 2-5 | 10-20 | 20-50 | 30-120 |
| | Battery chemistry | Lead-acid | Li-ion, NiMH | Li-ion | Li-ion |
| | Battery capacity [kWh] | <1 | <1.5 | <10kWh | <40 kWh |
| | Estimated CO2 emission reduction | <5% | <15% | <20% | <40% |
| Functions | Start & Stop | Y | Y | Y | Y |
| | Boosting | Y | Y | Y | Y |
| | Regeneration from braking (engine off) | N | Y (no P0, P1) | Y | Y |
| | Pure electric mode | N | N | Y | Y |
| | Regeneration from ICE | Y | Y | Y | Y |
| | Cold Engine cranking | N | Y (no P0) | Y | Y |
| | Sailing/Coasting | N | Y (no P0) | Y | Y |
| | Creeping | N | Y (no P0) | Y | Y |

In some of the described architectures, the impact on the overall vehicle structure is marginal, i.e. in the case of micro-hybrid and mild P0, whilst in some others, the powertrain should be consistently modified. Therefore, in order to reduce the time to market and gain short terms benefits, manufacturers tend to avoid the complete powertrain and car body re-design in order to find a place for electric battery, power electronics and electric motors. The statistics of market penetration of hybrid and electric vehicles in the market are illustrated in Figure 4.




| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STOP/START | 4.57 | 5.93 | 7.72 | 10.03 | 13.04 | 16.95 | 20.34 | 26.44 | 34.38 | 44.69 | 49.16 | 54.07 | 59.48 | 65.43 |
| Mild HEV | 0.32 | 0.47 | 0.72 | 0.94 | 1.13 | 1.35 | 1.62 | 2.11 | 2.75 | 3.57 | 4.64 | 5.34 | 6.14 | 7.06 |
| Full HEV | 0.3 | 0.42 | 0.63 | 0.88 | 1.06 | 1.27 | 1.52 | 1.9 | 2.38 | 2.97 | 3.71 | 4.08 | 4.49 | 4.94 |
| PHEV | | 0.01 | 0.05 | 0.09 | 0.14 | 0.2 | 0.3 | 0.52 | 0.88 | 1.49 | 2.54 | 3.3 | 4.29 | 5.57 |
| BEV | 0.02 | 0.04 | 0.06 | 0.11 | 0.14 | 0.19 | 0.24 | 0.36 | 0.54 | 0.82 | 1.22 | 1.41 | 1.62 | 1.86 |
| Total produced cars | 55.8 | 57.8 | 60.9 | 63.42 | 65.7 | 66.33 | 69.51 | 70.85 | | | | | | |

*Figure 4 Statistics of penetration of hybrid electric vehicles in the market*

## 2. BATTERY AND CONTROL STRATEGY ANALYSIS

The electrification and hybridization of a vehicle include a multidisciplinary and transversal integration of many aspects, ranging from the mechanical to the electrical, passing through control logic and electrochemical behaviour of the batteries. In this paper, the attention is focused on some aspects that are of relevant importance in the design of the vehicle: the battery pack, control strategies and electrification of the accessories.

### *2.1 Battery pack*

Batteries have a huge impact in the design of a hybrid or pure electric vehicle. The technology and management of this pivotal component witnessed a steady improvement in the last decade, driven by the always growing figures of electrical powertrains in automotive industry. Extensive studies regarding the battery are present in the literature. Here, an analysis is conducted considering the following aspects: chemistry, sizing, specific energy and power, performance, lifespan, charging time, monitoring, safety, and cost.

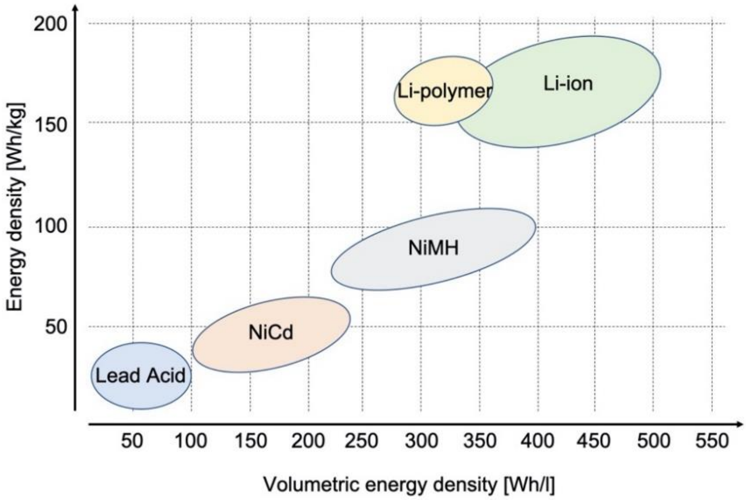



*Figure 5 Energy density of the main battery technologies adopted in automotive industry*

Nowadays, almost all pure and hybrid electric vehicles are equipped with Lithium-ion (Li-ion) batteries. However, some carmakers (e.g. Toyota) are still using Nichel Metal-Hydrade (NiMH) for some of their vehicles. As a matter of fact, NiMH features less energy density with respect to Lithium-ion, as illustrated in Figure 5, it has 25% more weight and occupation, and cannot perform long charge cycles, which limits the adoption for plug-in vehicles. On the other hand, it does not require a Battery Management System and has higher performance in case of low temperature. The on-going research on the battery chemistry is focused on Sodium-ion and Lithium-Sulfur with a targeted energy density of 400 Wh/kg. Lithium-ion batteries are based on a set of different chemistries. The most common chemistries of Li-ion in automotive industry are: Lithium-Nichel-Cobalt-Aluminum (NCA), Lithium-Nichel-Manganese-Cobalt, Lithium-Manganese-Spinel (LMO), Lithium-Titanate (LTO), and Lithium-Iron-Phosphate (LFP). Lithium-Cobalt oxide (LCO), that is very common in consumer devices, is not used in automotive for safety issues. Safety is the most important criterion for the selection of the chemistry. The most dangerous threat of a battery is the occurring of the thermal runaway, that consists of unexpected chemical reactions which obstruct the heat release and can result in a fire. The causes of this misbehavior overcharging, high discharging rates, or possible short circuits. Chemistries that are most exposed to this phenomenon are NCA, NMC, and LMO, which at the same time offer higher energy density. They must be used in combination with a robust battery box, efficient cooling system, and reliable battery pack monitoring to avoid overcharging and deep discharging [7][8]. A precise state of charge (SOC) and State of Health (SOH) monitoring is also very useful to avoid psychological collateral effects, such as the range anxiety of the driver, extend the lifespan of the battery and improve hybridization performance [9][10]. Current common solutions for the SOC and SOH monitoring are based on the adoption of Look-Up Tables (LUTs) filled with preliminary experimental characterization conducted in laboratory environment, that are extremely time-consuming and require high computational cost and extremely large memory for the maps. Alternative approaches are the model-based techniques, such as Extended Kalman Filter (EKF) or Smooth Variable Structure Filter (SVSF). These techniques might suffer inaccuracies due to the difficulty in reproducing all the operating conditions on the embedded reference model. An approach that is gaining growing attention is the adoption of Artificial Intelligence, such as neural networks. This technique is model-less, do not require high computational cost and has good accuracy performance, provided that the training dataset is sufficiently complete and well reproducing a wide set of operating conditions of the batteries in different charging/discharging cycles and at different levels of degradation of the battery. The possibility of enlarging the lifespan of a battery through the adoption of proper monitoring techniques is indeed very important for the carmakers. In automotive industry, a battery is considered exhausted when 20% of capacity or power fading is reached. As a matter of fact, some carmakers select the battery size planning eight to ten years of life for the batteries. Others prefer to downsize the battery capacity planning warranty programs. The sizing of the battery is strongly depending on the architecture and on the planned use of the vehicle. Currently, the attention of the carmakers is focused on enlarging the specific energy (capacity per unit of weight) rather than specific power (power per unit of weight). This is motivated by the necessity of improving the autonomy range of the vehicle more than the power that is already equal or even higher than the ICEs'. The technical considerations have to be conducted in conjunction with the cost analysis of a battery pack. Current cost of the batteries is settled at around 250$/kWh. This number was four to six times higher only ten years ago. The cost is obviously depending on the volumes and on the price of raw materials, assembly and equipment. Further descending is expected in the next future, even with a less steep trend. The large scale, the research of new chemistries and the optimization of the production processes will help this progress along with the reduction of the recharging time and the increasing of the charging stations, which will improve the customer perception of electric vehicles.

### *2.2 Energy flow management strategies*

As above mentioned, a correct estimation of the available energy in the batteries (SOC) is crucial for the effectiveness of the energy flow supervisor of the hybrid electric vehicle. This controller decides which is the amount of power that the energy sources of the vehicle have to provide at each instant. Its role is of utmost importance since it allows optimizing performance, minimizing fuel consumption and emissions and keeping the battery working in safe conditions. Moreover, a correct flow management gives the possibility of exploiting the maximum potential of the hybridization and of the vehicle functions. Once defined the architecture and the size of the subsystems of a hybrid vehicle, the controller is on charge of providing the correct logic to make the vehicle compliant with the regulations [11][12][13][14]. Specifically, when it comes to fulfill the requirements imposed by the regulations, such as the Worldwide Harmonized Light-vehicle Test Procedure (WLTP) and on the road with the Real Driving Emissions (RDE), the controller must guarantee the correct charge sustaining and charge depleting behavior of micro, mild, full and plug-in hybrid vehicles. The energy management strategies for a HEV are categorized in two classes: model-based and rule-based techniques. Model-based solutions can be furtherly divided in numerical (dynamic programming and genetic algorithms) and analytical (Pontryagin's minimum principle and Equivalent Consumption Minimization Strategy (ECMS)). These techniques aim to define the optimal solution giving a known driving cycle. Due to this characteristic, these solutions are non-causal and cannot be adopted on real vehicles since the future driving cycle is never known a-priori. ECMS is the only model-based strategy that can be used in real time since it provides a local optimization solution and does not require the a priori knowledge of the operating conditions. On the contrary, rule-based solutions, such as Fuzzy Logic and Charge and Deplete, are based on a set of conditions that are defined by the designer on the basis of his expertise and are completely causal approaches.Typically, the design of the supervisor is driven by the necessity of minimizing the CO2 emissions with respect to the stringent regulations, enlarging the battery lifespan, and reducing consequently the fuel consumption to satisfy the customer expectations. Future developments of the energy management strategies will be linked to the integration of information coming from sensors (camera, lidar, etc.) and connectivity features to improve the control performance and adapt it to the driving cycle and environment conditions.

## 3. EFFICIENCY IMPROVEMENT OF VEHICLE SUBSYSTEMS

Improvement of battery system performance and their proper utilization as well as the improvement of the hybrid system control strategies remain two relevant aspects on which carmakers are spending large efforts. The main objective is to reduce the fuel consumption and the CO2 emission. To maximise this task, an improvement of the efficiency at vehicle level has to be taken into account in order to avoid that the efforts on battery systems and control strategy improvements are drastically mitigated. To fill this gap, it will be shown the effectiveness of the electrification of some parts both at the powertrain and chassis level.

### *3.2 Improvement of ICE efficiency*

The increment of the thermodynamic efficiency remains a permanent demand of the automotive industry. This motivates a huge effort in the research of novel fuels, improved ignition laws, new cycles. In the last decade, a relevant effort has been dedicated to the reduction of the internal combustion engine organic losses. This by the introduction of new low friction materials and lower viscosity fluids for lubrications. Additionally is has been improved the efficiency of the front accessory drives and of the valve drives (belts, bearings, tensioning devices). The last results show that margins for improvements are already possible but that they are becoming always more limited. The electrification of some components opens to the opportunity of increasing not only the efficiency of the component itself but also that of the engine. In the present section are presented the benefits coming from the electrification of the water pump, the front accessory drive tensioning device, the electrification of the A/C compressor, the turbo compound.

#### 3.1.1 Electrified water pump

Standard cooling systems exploit a direct mechanical connection between the centrifugal pump and the belt drive system. In this condition, the pump is always connected and the coolant circulates in the engine in all the operating conditions, even when cooling is not desired. Being the device not controllable, the design of the pump is referred to the worst case (low speed at high ambient temperature). Therefore, in many operating conditions the amount of cooling flow driven by the pump is much higher with respect to the needed flow. Also the engine warm-up is therefore penalized. Consequently, not only the cooling efficiency is limited but also the engine efficiency is reduced [15][16][17][18]. Two different solutions are proposed to overcome this limitation. They are illustrated in Figure 6. Solution (a), reported in the left side of the picture, is referred to the activation of the water pump with a discrete on/off logic to operate the pump only when needed. This task is accomplished by introducing an electromagnetic clutch able to uncouple the impeller from the pulley driven by the belt or by introducing a moving friction wheel that can engage or disengage the water pump pulley. A fuel saving up to 1.2% (WLTP driving cycle) can be achieved by such a function. Solution (b) is represented in the right side of Figure 6. In this case the pump is driven by an electric motor. The pump is thereforetotally uncoupled from the crankshaft and can be powered following the exact needs of the internal combustion engine thermal level by controlling the motor speed. A fuel saving of 3 % (WLTP driving cycle) has been obtained in that case.

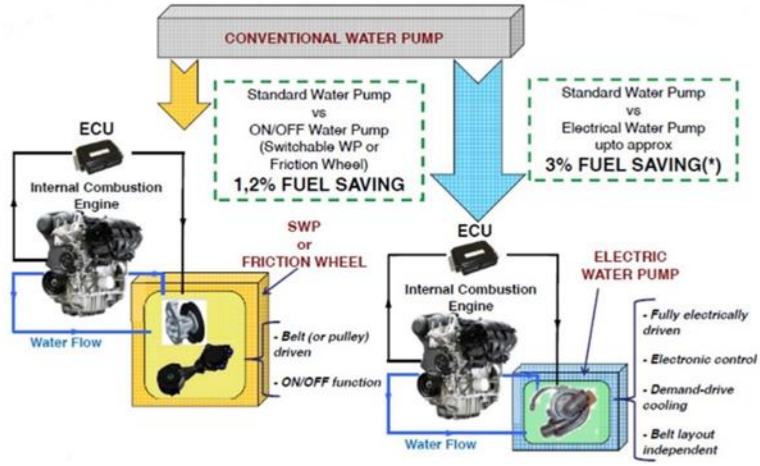



*Figure 6 Solutions for more efficient operation of the cooling water pump*

3.1.2 Active tensioning device for accessory drives

Accessory belt drives are affected by power losses linked to the dissipations in the bearings, tensioning systems, belt. The main contribution is ascribed to the belt and the belt power loss is affected by the preload which should be high enough in order to allow the correct power trainsmission in all the range of transmitted torque. In a conventional system the installation preload should cover the worst case. An additional preload should be considered in order to take into account the elongation of the belt and therefore the reduction of the preload during the belt life. It is evident that in many operating condition the belt preload is much higher with respect to the requested one. Some numerical values can help to understand the term of the problem. In a high performing belt drive for Micro Hybrid P0 system, the power loss of the belt drive at the idling speed of 800 rpm at the belt preload of 180 N is equal to 380 W and the global transmission system efficiency is equal to 96 %. At the same idling speed a preload of 600 N leads to a power loss of 750 W and decrement of the efficient up to 90 %. An active device able to regulate the belt preload according to the actual needs can help to improve the system efficiency. In Figure 7 is reported an example of active tensioning device able to modify the belt tension from about 300 N up to more than 600 N. The arm in this case is driven by a geared electric motor. The internal mechanism is conceived so that the tensioner at low tension works as a conventional automatic tensioner while to achieve high tension, the tensioner arm is controlled rigidly by the driving unit. The active tensioning system, able to reach a belt tension up to about 600 N is functional to the operation of the electric machine connected to the belt as a motor to fulfill tasks as engine start and e-traction in which the torque direction is opposite with respect to the generation or recuperation. Take into account that the change of direction of the torque in the e-machine inverts the tension level in the tension span and therefore the law of power transmission.

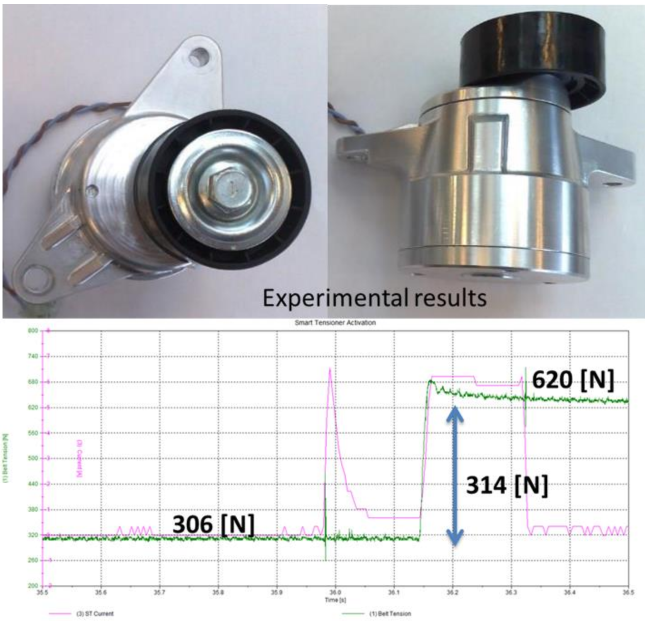



*Figure 7 Example of active tensioning device and its performace*

3.1.3 Electrification of the A/C compressor

The A/C compressor is powered by the ICE throughout the accessory belt drive system in conventional layouts. The compressor can be switched on or off by means of an electromagnetic clutch located in between pulley connected to the belt and the compressor unit. A proper duty cycle controls the operation of the compressor. The electrification of the compressor is intended in the sense that it is powered by an e-motor. This is conceived in hybrid powertrains in which the kinetic energy recovered by the electric machine is reused to power the A/C compressor driving the e-motor. The chain of the efficiency in this case results to be higher with respect to driving the A/C compressor passing thought the ICE that has low efficiency. This concept is valid for all the auxiliaries or accessories that are powered by the ICE. The electrification of the A/C compressor has a benefit also in terms of comfort of the vehicle occupants because the vehicle compartment temperature and humidity can be controlled also with the ICE off. In P0 hybrid systems, an alternative to drive the A/C compressor by an e-motor is to introduce a clutch between the crankshaft nose and the accessory belt drive system crankshaft pulley. In this case the ICE crankshaft can be decoupled by all the accessories connected to the belt. They can be powered by the BSG motor. Simulation analysis confirm a fuel saving of 2 % if a WLTP driving cycle is followed.

3.1.4 Electrification of the turbocompoud

The management of the energy and the potential energy recuperation at the level of the exhaust gases merits a dedicated discussion. It is well known that approximately one third of the energy produced by the combustion is lost in the exhaust gases. The remaining energy is splitted in mechanical (about one third) and thermal (about another third). In engines equipped with turbocompressors part the energy lost in the exhaust gases is recuperated by the turbine to power the compressor that compresses the inlet air in the cylinders. Nevertheless, a large amount of power is lost as the power needed by the compressor is less with respect to the power that the turbine can theoretically recuperate in most of the working point. Figure 8 reports the turbine and compressor working points in a 2.5 liter diesel engine. The amount of energy that can potentially be recuperated is evident. The electrification of the turbocompound means that an e-machine is installed in the system to recuperate part the wasted energy. Among the several configurations that have been proposed in the literature, one of the most promising considers and e-machined installed on the mechanical connection between the turbine and the compressor impeller as shown in Figure 9. Such a configuration leads to minimize the turbolag effect being the e-machine able to supply torque to the compressor at low engine speed when the power provided by the turbine is not enough to drive the compressor. In Figure 10 are reported two examples of e-turbocompounds having the e-machine installed in between the compressor and the turbine ad able to manage a power ranging from 2 to 5 kW. A lot of effort has been dedicated to the development of the technology that is now mature for the industrialization process. Simulations carried out at power unit system level highlight that improvements are potentially possible but a proper turbo matching is requested. Figure 11 shows the increment of the global efficiency expressed as

$$\eta_{gl} = \frac{P_{mechanical} + P_{electric}}{\dot{m}_{fuel} \cdot H_i} \tag{1}$$

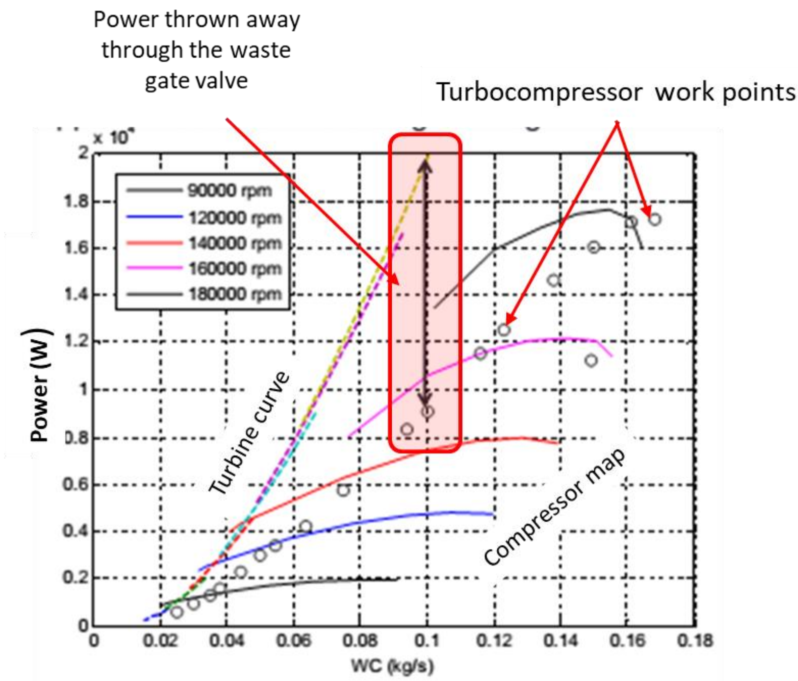



*Figure 1 Compressor and turbine map*

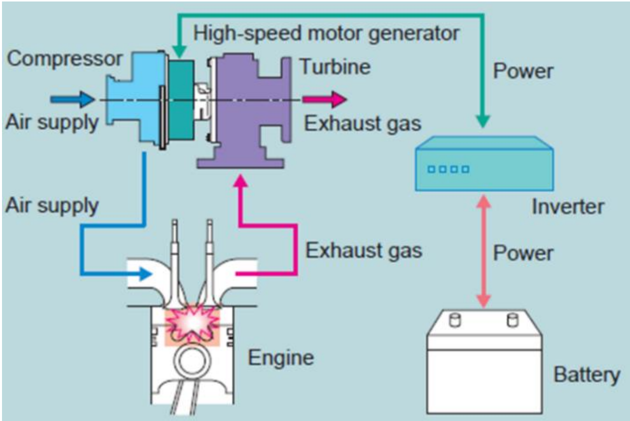



*Figure 9 Scheme of e-tubocompound installed on the turbine-compressor shaft*


*Figure 10 Examples of e-turbocompounds (e-machine installed in between the turbine and compressor)*

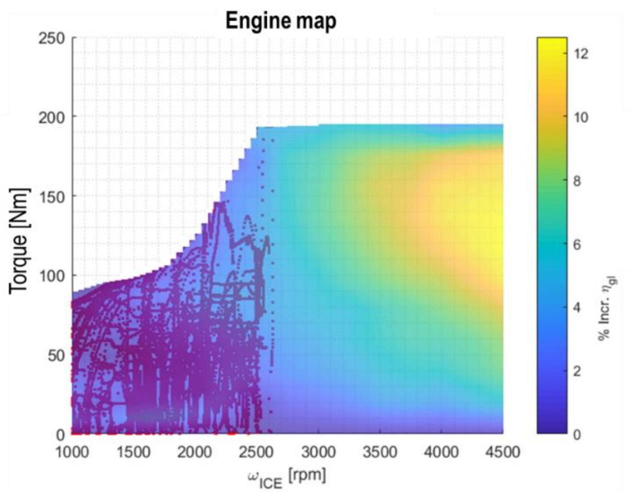



*Figure 11 Engine map with possible improvments*

In the different working region of a 1.2 liters ICE equipped with a 8 kW e-turbocompound. It is evident that improvements up the 10-12 % of the global power unit efficiency are possible at high speed and high torque of the ICE. The dark blue points refer to the working points that are covered by the ICE during a WLTP driving cycle. The benefits in this case are marginal. The conclusion is that there are benefits with significant improvement of the global efficiency in case of a proper matching between the ICE working points and characteristics of the e-turbocompound. The performance obtained in F1 race car power units confirm the above mentioned considerations.

### *3.2 Chassis electrification*

In the common belief the electrification in the modern vehicles is a process that is typically devoted to improving the efficiency of the powertrain system as described in the previous section. The objective of improving the vehicle efficiency leads to consider potential improvements also at chassis level. The adoption of electromechanicalsolutions can be considered of great importance. In this context, two applications are gaining increasing attention and are object of academic and industrial development: vibrational energy recuperation from the suspension shock absorbers and improvement of the aerodynamic efficiency by adapting the vehicle attitude according to the load and driving condition.

#### 3.2.1 Regenerative shock absorbers

Vehicles equipped with regenerative shock absorbers can transfer the vibrational energy coming through the road irregularities into electricity. To realize the regeneration target, the developed device should be able to vary their damping behaviors while converting part of the dissipated power into electricity. Therefore, an electric machine together with a suitable transmission system needs to be integrated to the vehicle suspension. Several typologies of have been investigated during the last years. Here are described two solutions: regenerative shock absorber employed with electro-hydrostatic and electro-mechanical actuation principle. The former uses a hydraulic actuator directly interfaced with a motor-pump group by means of hydraulic circuit to convert the linear motion of the piston into rotation. To maximize the energy regeneration as well as to guarantee the damping features, the hydraulic, mechanical and electric subsystems must be integrated and optimized as an entire system. On the other hand, the electromechanical approach allows obtaining good performance by using an electric machine working in generation mode that has to be properly driven to optimize the energy recovering by guaranteeing the right trade-off between the handling of the vehicle and the comfort of the passengers. Figure 12 shows an example of electrohydrostatic solution developed for a segment B passenger car while Figure 13 is referred to an electromechanical configuration conceived for the same vehicle. In addition to comfort benefits related to the control of the damping to improve the vertical acceleration of the passenger compartment, benefits in terms of 2.5 $gCO_2/km$ (4 corners) have been proved experimentally in the case of an ISO class C ground condition [20][21][22][23].

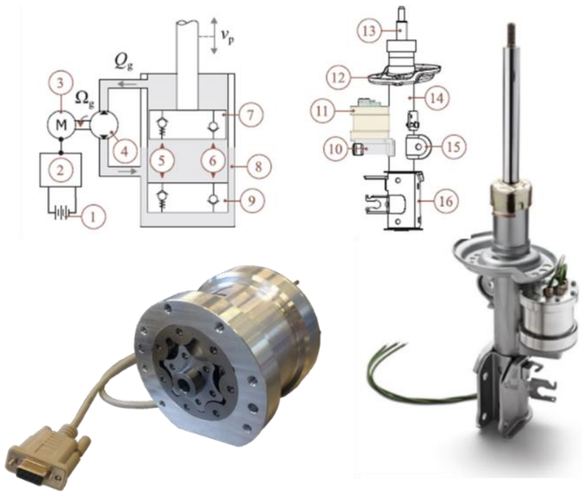


*Figure 12 Electrohydrostatic technology and application*

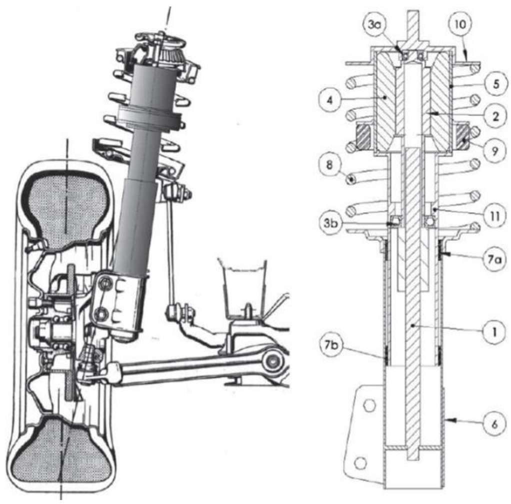


*Figure 13 Example of electomechanical regenerative shock abosorvers*

3.2.2 Height adjustment

Height adjustment systems are conceived to modify the attitude of the vehicle body in terms of static pitch angle and height from the ground according to the driving path and load condition in order to achieve a minimum aerodynamic drag coefficient in all the vehicle driving condition. The concept was implemented by Citroen in the '970 by using an hydropneumatic solution that recently was abandoned for cost reasons. Nevertheless, the interest for the improvements of the vehicle aerodynamics remains a current need. To this end, Figure 14 shows the effect of the aerodynamic drag coefficient on the fuel consumption with reference to a segment B passenger car. The reduction of Cx from 0.35 to 0.31, as depicted in the figure, is achieved by reducing the height of the vehicle body from the ground of 50 mm. The industrial interest is nowadays mainly devoted to the implementation of electromechanical non - reversible solutions that control the position of the lower spring holder with respect to the vehicle body. In Figure 15 is reported a schematic representation and a vehicle implementation.

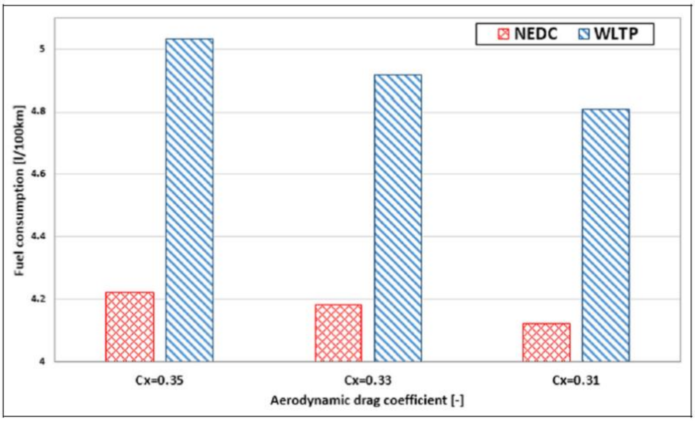



*Figure 14 Fuel consumption reduction as a function of the aerodynamic drag coefficinet for a segment B passenger car*

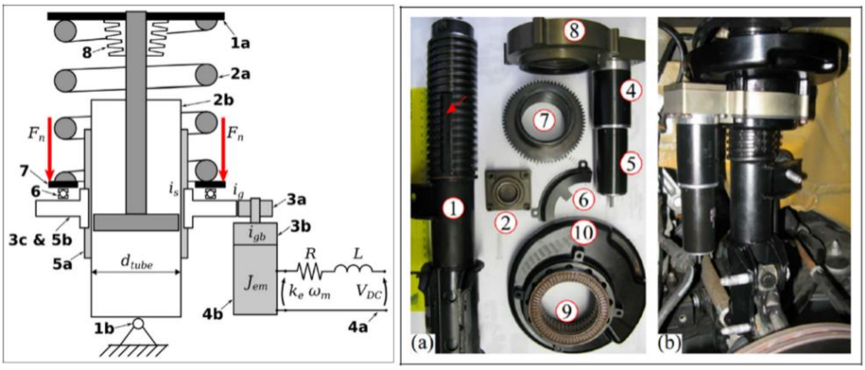



*Figure 15 Schematics and an implementation of an irreversible electromechanical system*

## 4. CONCLUSIONS

The paper presents a general description of the trend in powertrain hybridization and electrification, highlighting the main features in terms of architectures, functions and advantages as fuel consumption and emission reductions. The proposed analysis focuses also on the current technology status and development trends of two relevant aspects for hybrid and electric vehicles: the battery pack and the energy flow supervisor. A final discussion focuses on the utility of optimizing the global vehicle efficiency. This has been done in the past also in conventional vehicles. The implementation of an electric power unit having as one of the main task the recuperation of the kinetic energy during braking, opens a new scenario. The recuperated kinetic energy that has been stored in a battery systems, needs to be reused in a quick time and in an efficient way. It is not mandatory that the task should be accomplished by the electric power unit. The energy can be reused also to power electrified accessories leading to improve other vehicle subsystems (active tensioner, electric ICE accessories, active height adjustment systems). In parallel the presence of at least a 48 V electric systems motivated the implementation of electrified accessories devoted to recuperate wasted energy (e-turbocompound, regenerative dampers). The vehicle electrification is therefore conceived as vehicle efficiency improvement. Additionally comfort features can also be accomplished.

## ACKNOWLEDGMENTS

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# THE APPLICATION OF INDUSTRY 4.0 IN PRODUCTION PROCESSES OF THE AUTOMOTIVE INDUSTRY

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RESEARCH ARTICLE

**ABSTRACT:** The use of new technologies to connect people, equipment and machines, i.e. Industry 4.0 is a key player in the manufacturing processes of all industries, as well as in the automotive industry. The Industry 4.0 application in the automotive industrial environment brings smart automation in the automotive element manufacturing process, as well as the car assembly process. The automotive industry is ranked first in the Insuatria 4.0 application in manufacturing processes, and the reason is the global market where every automotive company wants to be a leader. So far, the automotive manufacturing processes have been automated for decades and have been quite automated, but rigid automation has been required. To establish full connectivity to the manufacturing process, there was a lack of wireless connectivity and communication, or production networks where information carriers communicate with each other and exchange data and data. Real-time information, making automation more flexible, improving productivity as well as quality itself. Manufacturers are given the opportunity to quickly adapt the production of other products, which has not been the case so far. The paper presents trends in the use of second-generation service and industrial robots, as well as the use of smart sensors to increase the quality of production and assembly. Industry 4.0's application in the automotive industry has been growing day by day until production processes become completely intelligent.

**KEY WORDS**: Industry 4.0, automotive, manufacturing, assembly, smart sensor



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## PRIMENA INDUSTRIJE 4.0 U PROIZVODNIM PROCESIMA AUTOMOBILSKE INDUSTRIJE

**REZIME**: Korišćenje novih tehnologija za povezivanje ljudi, opreme i mašina, odnosno industrije 4.0, ključni je igrač u proizvodnim procesima svih industrija, kao i u automobilskoj industriji. Primena Industrije 4.0 u automobilskom industrijskom okruženju donosi pametnu automatizaciju u procesu proizvodnje automobilskih elemenata, kao i u procesu sklapanja automobila. Automobilska industrija je na prvom mjestu u aplikaciji Insuatria 4.0 u proizvodnim procesima, a razlog je globalno tržište na kojem svaka automobilska kompanija želi da bude lider. Do sada su procesi proizvodnje automobila automatizovani decenijama i bili su prilično automatizovani, ali je bila potrebna stroga automatizacija. Da bi se uspostavila potpuna povezanost sa proizvodnim procesom, nedostajalo je bežično povezivanje i komunikacija, ili proizvodnih mreža u kojima nosioci informacija međusobno komuniciraju i razmenjuju podatke i podatke. Informacije u realnom vremenu, čineći automatizaciju fleksibilnijom, poboljšavaju produktivnost kao i sam kvalitet. Proizvođačima se daje mogućnost da brzo prilagode proizvodnju drugih proizvoda, što do sada nije bio slučaj. U radu su prikazani trendovi u korišćenju servisnih i industrijskih robota druge generacije, kao i upotreba pametnih senzora za povećanje kvaliteta proizvodnje i montaže. Primena Industrije 4.0 u automobilskoj industriji raste iz dana u dan sve dok proizvodni procesi ne postanu potpuno inteligentni.

**KLJUČNE REČI**: Industrija 4.0, automobilska industrija, proizvodnja, montaža, pametni senzor

# THE APPLICATION OF INDUSTRY 4.0 IN PRODUCTION PROCESSES OF THE AUTOMOTIVE INDUSTRY

*Isak Karabegović, Edina Karabegović, Mehmed Mahmić, Ermin Husak*

## INTRODUCTION

Although well known, the automation and modernization of production processes in the industry began in the 60s of the last century, when industrial robots were included in automation and modernization. Automation was well accepted at the time, but from today's point of view we have to admit that automation was rigid and not enough flexible. The reason for the inflexibility lies in the fact that in order to manufacture another product, especially in the automotive industry where rapid changes are required, the same production process required reprogramming of every industrial robot with its grips, change tools, etc., thus causing long production delay and an additional production costs [1-5]. In the last 20 years there has been a rapid development of new technologies such as robotic technology, digital technology, sensor technology, information technology, etc., which are being implemented in the production processes. We are currently at the beginning of the fourth industrial revolution because many of the industrial development strategies of the technologically advanced countries advocate the transformation of industrial production through the implementation of advanced technologies. Industry 4.0 creates radical new approaches in the production process itself, through the communication between the devices in the production process and the implementation of a large number of sensors that provide data based on which decision-making process is made, thus giving great benefits to the automotive industry. The Industry 4.0 platform has one common objective to balancesupply and demand in a very affordable way by providing a wide range of products to the customer, with both parties interacting. The integration of digital technologies with other advanced technologies will transform manufacturing processes in industrial production because the price of these technologies is continuously declining in the market and they are becoming more widespread in production processes. The second reason is that ICT technologies are implemented with other technologies and enable digital transformation of production process [6-10]. When it comes to transforming production processes in the automotive industry, it is impossible to imagine the process without the inclusion of robotics, and networked digital, sensor and information technology. The second-generation of industrial robots has been developed, which must be intelligent and autonomous, thus increasing the reliability of the production process, reducing the time of the finished product, and providing precision and adaptability that exceeds human capabilities. Their implementation will increase the assembly process itself.

## 1. INDUSTRY 4.0 – DIGITAL PRODUCTION IS IN THE PRODUCTION PROCESSES

In the last 20 years there has been wide development and implementation of digital technology in companies, from the supply of materials to the delivery of finished products. Most innovative applications are implemented in the automotive industry production processes. We are currently at the beginning of the fourth industrial revolution because many of the industrial development strategies of the technologically advanced countries advocate the transformation of industrial production through the implementation of advanced technologies, especially digital technologies (Figure 1).

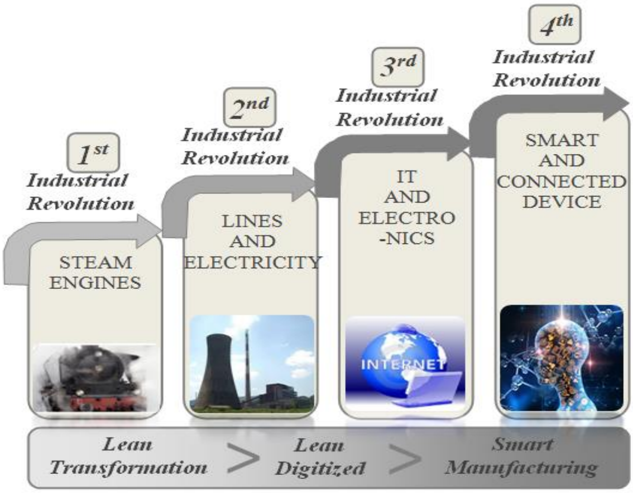


*Figure 1 The evolution of industrial revolutions in the world*

Germany first announced its ‘’High-Tech Strategy 2020’’ program in 2011 in Hannover under the name Industry 4.0. In 2012, the USA Advanced Manufacturing Partnership Steering Board specified recommendations for positioning USA for the long-term leadership in advanced technology. Similarly, in 2013, the UK Government Office for Science highlighted the strategy ‘’The Future of Manufacturing - A new era of opportunity and challenge for the UK", while China’s objective is to become technologically most advanced country with a strategy called ‘’Made in China 2025’’. The Swedish Government's strategy for new industrialization is to strengthen companies' capacity for change and competitiveness through automation and digitalization. The market is driven by the global economy, and competition is the highest in the automotive industry. Automotive companies are competing how to reduce labor costs and remain competitive in the market. In order to be the leader they need to increase productivity, and provide top quality, i.e. to produce vehicle with less cost. The competitive advantage over others can be achieved through the application of new Industry 4.0 innovations that offer the solution. Digital technology has made a large contribution within Industry 4.0 as shown in Figure 2.The contribution of digital technology within Industry 4.0 is reflected in the large amount of data and analytics we can use to make the right decisions when it comes to the production process. We are able to digitize and integrate vertical and horizontal value chains in companies, which will give the automotive industry a new chance to transform the current linear production method into a network with full connectivity and available information at all times in all segments of the production process, from the input of raw material to the information on each finished product in use.

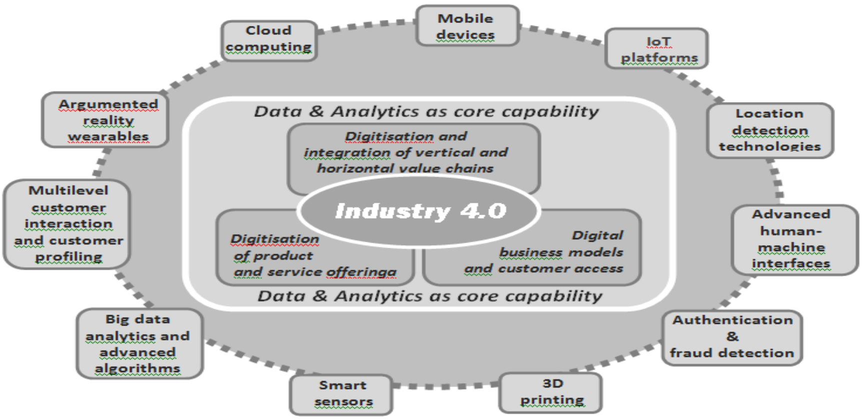


*Figure 2 The contribution of digital technology within Industry 4.0*

We have the ability to use digital business models as well as customer access, all of which enabled by: smart sensors, 3D printing, IoT platforms, Mobile devices, Location detection technologies, Advanced human-machine interfaces, Authentication & fraud detection, Multilevel customer interaction and customer profiling, Augmented reality wearables, Cloud Computing, Big Data analytics and advanced algorithms, as shown in Figure 2. Through the Industry 4.0 application in production processes, the technologies shown in Figure 2 lead to connectivity and smart communication between machines and workers in the production process. They enable us to increase productivity and quality, as well as adjust to the new levels [11].

## 2. THE APPLICATION OF THE INDUSTRY 4.0 IN THE AUTOMOTIVE INDUSTRY

Ever since their invention, the industrial robots have found the greatest application in the production processes of the automotive industry. To this day, industrial robots have been continuously installed in the automation of automotive production processes, and the trend is increasing each year. Figure 3 shows the trend of industrial robot application in the world and the application in the automotive industry in the past ten years [9, 13-18]. The statistical data are taken from the International Federation of Robotics (IFR), the UN Economic Commission for Europe (UNECE) and the Organization for Economic Cooperation and Development (OECD). The trend of industrial robot application in the production process is growing worldwide. In the last ten years the situation has changed from 60.000 robot units used in 2009 to the value of about 448.000 robot units applied in 2019. We can conclude that this is a linearly increasing trend, as shown in Figure 3a. The growing trend is predicted to continue in the coming period, so that about 630.000 robot units are expected in 2021. The highest percentage of industrial robots are applied in the automotive industry, as shown in the Figure 3b.

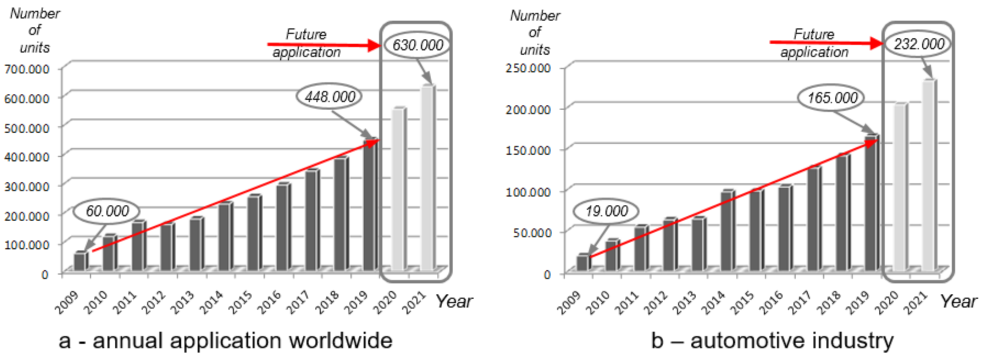


*Figure 3 Annual application of industrial robots in production processes in the world and in the automotive industry for the period 2009-2019 and estimated application for 2020 and 2021*

In 2009, about 19.000 robot units were used in the automotive industry. The trend of application in the automotive industry continued to increase each year, so that in 2019 the application in this industry amounted to about 165.000 robot units. It is estimated that automotive industry will implement about 232.000 robot units in 2021. The trend of robot applications will continue to increase in the future owing to the application of Industry 4.0 in production processes, which would be impossible without the participation of both industrial and service robots. The development of new technologies such as digital technologies, sensor technologies, information and communicationtechnologies contribute to the development of robotic technology. The collaborative robots in the robotic industry are currently a main research topic in the world, with the aim of creating environment in which workers can safely work together with robots that would assist humans in performing their daily routines without risk. It should be noted that collaborative robots are not intended to completely replace workers, but rather to work together with the workers and to remove the enclosures that currently encircle first-generation industrial robots in the production processes. Worker can perform various complex operations and analytical tasks, whereas the collaborative robot is easy to operate, performs monotonous repetitive operations, can handle dangerous substances, as well as lift heavy objects. The differences between workers and robots are shown in Figure 4 [19, 20].

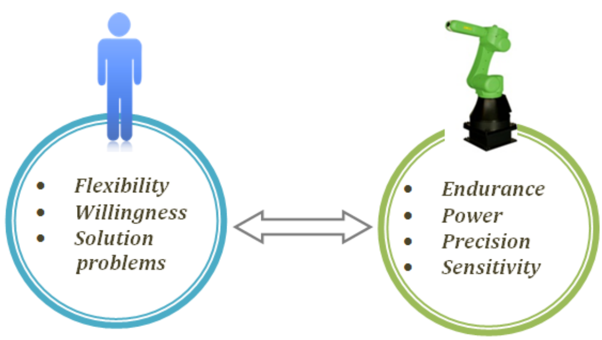


*Figure 4 Advantages that should be considered for worker and industrial robot when deciding to install a robot Vehicles Directive*

The advantages of collaborative robots over workers and first-generation industrial robots are the following: lifting loads greater than 20 kg, handling hazardous materials (hazardous chemicals that affect workers' health, high temperature items, etc.) and reducing occupational injuries. The flexibility of deploying collaborative robots is that they reduce the working area to perform tasks and do not need enclosures. The collaborative robot has great sensitivity because it has advanced sensors such as integral force and torque sensors, as well as visual sensors that provide safe workspace and protection zones, secure collision detection, secure tool detection, safe force monitoring, etc. The collaborative robot can be easily programmed to perform various tasks which gives it more flexibility. The collaborative robot automatic working cycle is flexible so that it can easily adapt the robot's characteristics to individual tasks. Collaborative robots guarantee the safety of the workers in workplaces where functional safety must be ensured, i.e. there must be a safety zone. A safety zone can be ensured by monitoring the speed of the robot, depending on the distance of the worker from the robot itself, as shown in Figure 5 [20]. The collaborative robot with sensors is designed to directly interact with workers within a common defined workspace. One such DSC (DualCheck Safety) system was developed by the company FANUC, as shown in Figure 5 [21-23].

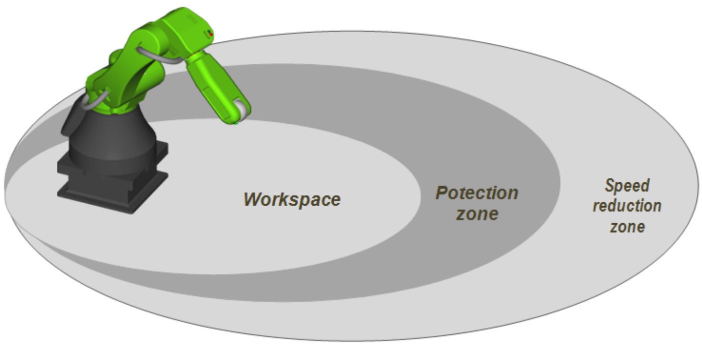


*Figure 5 Collaborative robot security system DSC (DSC - Dual Security System) by company FANUC*

The laser sensor-based DSC system monitors additional security and controls the robot accordingly as follows. When the worker is not in the three zones indicated, the robot is operating at the full design speed of its work task. When a worker enters a speed reduction zone, the sensor gives information to the PLC, which gives the command to reduce the speed of performing operations. If the worker resumes movement and enters the protection zone, speed of operation continues to decrease and ’’Contact stop’’ is activated. If the worker enters the workspace, the robot switches to collaborative mode, the operating speed is reduced, and the ‘’Contact stop’’ is still enabled. When a worker touches a robot, gripper, or work piece, the robot stops performing tasks (stops working). When the worker moves away, the robot resumes operation at a rate that is dependent on the zone in which the worker is located. Besides the increase in the application of Industry 4.0 and robots in the automotive industry production processes, in addition to welding and body painting processes of vehicles where robots are most used, the use of robots will also increase in the assembly processes alongside with workers, as shown in Figure 6 [12].The application of Industry 4.0 and industrial and service robots in the automotive industry is vital to the quality of the finished product - the vehicle. In the near future, many solutions are predicted to provide: a guaranteed assembly process with increased quality, the processes will become adaptable to the assembly input positions which will increase the safety and quality of individual operators, the results of assembly stations will be guaranteed, as well as horizontal and vertical integration between research, development, production, services with feedback and closed loop.


*Figure 6 The application of Industry 4.0 and collaborative robots in theautomotive industry assembly process*

With the application of Industry 4.0 to the automotive production processes, the classic linear production process will be replaced by an online production process [19-24]. Likewise, new services are based on a real-time data and data analytics, leading to improved production process performance and machine optimization in the production process, as well as predictive maintenance. The application of Industry 4.0 in the production processes of the automotive industry will continue to grow, mainly in the assembly process, assuming that the assembly process must be performed by a combination of humans and collaborative robots.

## 3. CONCLUSIONS

The convergence of new technologies, including robotics, 3D printing, artificial intelligence, and the Internet of Things, which drive the Cloud Computing and Big Date concept, i.e. Industry 4.0 is transforming the way companies do business. The best example is automotive companies where these technologies are mostly applied. Industry 4.0 has the potential to improve products, adapt experiences, increase productivity, improve safety and reduce costs in many industries, most notably in the automotive industry. Instead of replacing people, which many fear, Industry 4.0 will focus on improving human capability, by creating efficiency that could not be achieved before. One of the strongest examples of application of Industry 4.0 can be seen in the production processes of the automotive industry, from the vehicle manufacturing process to the assembly process, as the paper states. By installing a large number of smart sensors in the automotive production process, we are able to send information to the Cloud where we have the ability to analyze them and act accordingly. For example, one application is defect identification and preventive maintenance, which is possible by analyzing a large amount of Big Data that goes beyond human abilities. Of all Industry 4.0 technologies, it is expected that robotics and related artificial intelligence will have a profound impact on the production process in the automotive industry, as demonstrated by industrial robot applications in the world and in the automotive industry that is presented in the paper. Many applications of Industry 4.0 are being implemented gradually, with full effect expected in 15 to 20 years. The implementation of Industry 4.0 in the automotive industry results in increased productivity, reduced costs, increased product quality, reduced product life cycle, increased product diversity and flexible manufacturing, whereas companies are becoming recognizable in the global market.

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# ANALYSIS OF INFLUENCING FACTORS ON BRAKE WEAR AND NON-EXHAUST EMISSION WITH REFERENCE TO APPLIED MATERIALS IN BRAKE PADS

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RESEARCH ARTICLE

**ABSTRACT:** Wear of the elements of the brake friction pair and particle emission caused by the operation of the brakes (non-exhaust emissions) is one of the biggest polluters of the environment from traffic and a problem that needs to be solved in the coming period. The brake pads are made of a mixture of different materials that ensure the longevity and efficiency of the brake system. The applied materials have different wear intensities in certain operating conditions, but wear is influenced by different factors that have been analyzed by other authors in their research. An overview of materials in brake pads, as well as their influence on wear and non-exhaust emission based on modern research is performed in this paper.

**KEY WORDS**: brakes, influencing factors, materials, wear, particles



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## ANALIZA UTICAJNIH FAKTORA NA HABANJE KOČNICA I NON-EXHAUST EMISIJU SA OSVRTOM NA PRIMENJENE MATERIJALE U KOČNIM PLOČICAMA

**REZIME**: Habanje elemenata frikcionog para kočnice i emisija čestica koje nastaje radom kočnica (non-exhaust emisija) predstavlja jedan od najvećih zagađivača okruženja od saobraćaja i problem koji je potrebno rešiti u narednom periodu. Kočne pločice su sačinjene od mešavine različitih materijala koji obezbeđuju dugotrajnost i efikasnost kočnog sistema. Primenjeni materijali imaju različit intenzitet habanja u određenim radnim uslovima, ali na habanje utiču različiti faktori koji su u analizirani od strane drugih autora u njihovim istraživanjima. U ovom radu izvršen je pregled materijala u kočnim pločicama, kao i njihov uticaj na habanje i non-exhaust emisiju na osnovu savremenih istraživanja.

**KLJUČNE REČI**: kočnice, uticajni faktori, materijali, habanje, čestice

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## INTRODUCTION

Wear of the friction elements of the braking system leads to environmental pollution, creating the so-called non-exhaust emission of particles, which occurs due to the wear of two surfaces that are in contact with each other. The harmfulness of the particles formed by the wear of brake materials is reflected in the fact that the friction elements of the brakes are often composed of substances that are harmful to human health [1,2]. The problem and the reason for the harmfulness is that the particles are released into the environment, and they also contain harmful substances that a person inhales through the air [3, 4]. Some of the materials are so harmful that their use is slowly declining in brake pads or is completely banned such as asbestos. Asbestos is very harmful to human health, so it is no longer used in most countries, but it also has very good tribological properties [5, 6]. It is important to note that today we are moving towards finding alternative materials that would replace harmful substances, and in addition to maintaining the efficiency and durability of the brake elements. Non-exhaust particle pollutants are sources that emit particles by their wear, i.e. wear of the contact surfaces of the elements, but do not emit particles by some combustion process as emitted by the engine. Brakes are one of the sources of non-exhaust emission. In addition to the wear of the brakes, non-exhaust particles are also created by the wear of other parts and elements of the vehicle, e.g. tires, various metal assemblies such as joints, gears, couplings, … Today, with strict legal restrictions on exhaust emissions and the increasing use of electric vehicles, these sources are becoming the dominant source of particles, especially when it comes to brakes. The problem in the case of application of friction materials, i.e. materials used for the production of brake pads, is that there may be changes in the braking coefficient (brake efficiency), but also the intensity of brake wear [7]. So it is very important to take care of the applied materials, but in addition, extensive tests are necessary. The reason for this is that the brake pads as well as the disc must meet two key requirements, and that is a high value of the coefficient of friction, but a low wear rate of friction materials [8]. The applied materials, i.e. the composition of the brake pads and the material from which the disc is made, have a great influence on these two key requirements. The conclusion is that when analyzing brake wear and particle formation, materials have a significant impact, but it is important to note that wear is also affected by operating conditions, i.e. different parameters and quantities that can be analyzed when it comes to the braking process. In order to identify the influence of various parameters or factors on brake wear, this paper reviews some of the factors that affect brake wear. In addition, this paper presents an analysis of the most commonly used materials used in brake pads, but also those researchers have found to be the most present in particles.

## 1. CHARACTERISTIC AND MOST COMMONLY APPLIED MATERIALS IN THE COMPOSITION OF BRAKE FRICTION PAIRS

The brake pads contain different materials, each with its own specific role, so they can be classified in several ways. With this in mind, the materials used in brake pads are divided into several groups:

- Friction additives - which determine the friction properties of brake pads and contain a mixture of abrasives.
- Fillers - which reduce costs and improve the workability of brake pads.
- Binder - which holds the brake pad components together.
- Reinforced fibers that provide mechanical strength [9].

When it comes to materials, today, more and more research is being done on alternative materials that could be used in brake pads, which is present in the works of several authors. Thus, in [10], examples of some of the materials that could be used in exchange for a longer material that is more harmful are presented. One of the goals is that such materials have as little harmfulness as possible, i.e. that their wear creates particles that do not have a harmful effect on humans [11]. The properties of brake pads that are pursued in the process of product development and achieving a quality product are: a high coefficient of friction, favorable thermal conductivity, high thermal resistance, low mass, high resistance to wear, low noise level, low cost, not making the damage to the brake surface of the metal element of a friction pair, and corrosion resistance, [12]. Table 1 shows some of the natural materials tested that could be applied in brake pads.

***Table 1*** *Investigated alternative materials that could be used in brake pad*

| Reference | Alternative material |
|---|---|
| Olupona et al.[13] | Cocoa bean shells |
| Singaravelu et al. [14] | Crab shell powder |
| Ademoh and Adeyemi [15] | Maize Husks |
| Idris et al. [16] | Banana peels |
| Olabisi et al. [17] | Palm kernel shells cocoa beans shells, maize husks |
| Primaningtyas et al. [18] | Rice husk |

| | |
|---|---|
| Lagel et al. [19] | Tannins furanic resin |
| Bretotean et al. [20] | Coconut fiber |

Today, there are a number of materials used in friction pads. According to the source [21], the composition of sixty-five commercial brake pads and fifteen brake discs used on motor vehicles was analyzed. Using XRF method (X-ray fluorescence) for material analysis, the composition of these pads was performed and Table 2 shows the elements that are part of the brake pad material.

***Table 2*** *Results of composition analysis of 65 brake pads and 15 discs [21]*

| Element | Unit | Maximum | Minimum | Average | Number of samples |
|---|---|---|---|---|---|
| Materials used in brake pads | | | | | |
| Fe | %m/m | 44.7 | 8.4 | 22.7 | 65 |
| Cu | %m/m | 17.8 | 0.11 | 11.2 | 65 |
| Zn | %m/m | 18.0 | 0.09 | 4.7 | 65 |
| Sn | %m/m | 8.9 | 0.01 | 3.3 | 65 |
| Al | %m/m | 5.2 | 0.42 | 1.7 | 65 |
| Si | %m/m | 5.2 | 0.05 | 1.8 | 65 |
| Zr | %m/m | 7.1 | 0.00 | 1.2 | 57 |
| Ti | %m/m | 12.1 | 0.02 | 0.9 | 65 |
| Sb | %m/m | 8.3 | 0.01 | 2.7 | 29 |
| Cr | %m/m | 2.1 | 0.04 | 0.8 | 65 |
| Mo | %m/m | 4.0 | 0.00 | 0.8 | 50 |
| Mn | %m/m | 2.4 | 0.10 | 0.3 | 65 |
| V | %m/m | 1.7 | 0.01 | 0.3 | 62 |

| | | | | | |
|---|---|---|---|---|---|
| Ni | %m/m | 0.4 | 0.05 | 0.1 | 38 |
| Bi | mg/kg | 10,949 | 0.00 | 2060 | 65 |
| W | mg/kg | 9863 | 0.00 | 1825 | 65 |
| P | mg/kg | 8750 | 0.00 | 1225 | 65 |
| Pb | mg/kg | 53,681 | 0.16 | 1305 | 65 |
| Co | mg/kg | 4564 | 0.00 | 196 | 65 |
| Materials used in brake disc | | | | | |
| Fe | %m/m | 93.7 | 92.0 | 92.9 | 15 |
| Al | %m/m | 0.9 | 0.5 | 0.6 | 15 |
| Si | %m/m | 2.4 | 1.7 | 2.0 | 15 |
| Zr | %m/m | 0.01 | 0.003 | 0.004 | 3 |
| Cr | %m/m | 0.3 | 0.1 | 0.2 | 15 |
| Mo | %m/m | 0.2 | 0.005 | 0.031 | 15 |
| Mn | %m/m | 0.8 | 0.5 | 0.6 | 15 |
| Ni | %m/m | 0.1 | 0.1 | 0.1 | 4 |
| Bi | mg/kg | 9.6 | 0.1 | 5.2 | 15 |
| W | mg/kg | 9.2 | 0.1 | 4.4 | 15 |
| P | mg/kg | 578.5 | 0.2 | 73.7 | 15 |
| Pb | mg/kg | 9.6 | 0.0 | 4.8 | 15 |
| Co | mg/kg | 8.3 | 0.9 | 4.7 | 15 |

When it comes to specific materials that can be found in particles, a number of authors have tried to find and analyze, which are the dominant elements that indicate that the particles of non-exhaust emissions originated precisely from the braking system. Thus, Table 3 shows the materials that are characteristic of the wear of the braking system, and that can be found in the fractions of the particles, and according to the results obtained by different authors.

***Table 3*** *Characteristic materials in non-exhaust source monitoring as dominant elements in brake pairs*

| Reference | Material |
|---|---|
| Hulskotte et al.[21] | Fe, Cu, Zn и Sn |
| Lawrence et al. [22] | Ba, Cu, Fe, Mn, Ni, Pb, Sb |
| Mosleh et al.[23] | Al, Mg, Sb, Si, S и Cu |
| Bukowiecki et al. [24] | Cu, Fe, Mo, Sb, Sn, Zn, Zr |
| Adamiec et al.[25] | Ti, Cr and Cu |
| Duong and Lee [26] | Cu, Ni |
| Alves et al. [27] | Ba, Cu |
| Adachi and Tainosho [28] | Ba, Ce, Cu, Fe, La, Sb, Ti, Y, Zr |
| Valotto et al. [29] | Fe, Cr, Sb and Mo |

Having in mind the existence of different elements in the brake pads, they can be divided into several categories according to their composition in different ways. It is important to note that one of the divisions that can be found most often, according to the content of metals, i.e. metallic materials. Thus, according to the composition of the brake pads can be divided into:

- metallic brake pads,
- semi-metallic brake pads,
- low-metallic brake pads,
- asbestos brake pads, asbestos-free brake pads (NOA- Non-Asbestos Organic),
- carbon brake pads,
- ceramic brake pads [30].

Metal brake pads usually contain only elemental metals and graphite as a lubricant [31]. Semi-metal friction linings are one of the most wear-resistant brake pads and therefore, the most durable. Such brake pads contain metals that are combined with graphite and other fillers in order to maintain their resistance to wear but also to have as little impact on the disc as possible [32]. According to the source [33] they contain 35 to 65% of metals while according to the source [32] they contain 30 to 70% of metallic materials while according to [14] from 30 to 60% of metals. Low metal brake pads according to the source [35] contain 10-30% of metallic materials. According to the source [33], organic friction linings consist of materials obtained from organic origin, such as glass, Kevlar, resin or rubber. Organic friction linings or NAO (Non-Asbestos Organic) have replaced asbestos substances due to health risks. These friction linings contain less than 10% metal [36], but the rest of the friction material comes from plant-derived fibers, high-temperature resins and other materials. These friction linings are intended for light vehicles and normal driving conditions and modes [37]. Ceramic friction plates are primarily made of ceramic material with copper reinforcing fibers [33]. Fine copper fibers used in ceramic friction coatings are applied, in order to increase their friction and thermal conductivity [32]. Ceramic brake calipers have a longer service life and good temperature stability [35], but have the lowest wear rate, have a favorable effect on disc wear and produce the least noise [34]. A more detailed and clear overview of the composition of some of the brake pads is given in Table 4, where, based on data of various authors, a presentation of the composition of the brake pads is formed.

***Table 4*** *Division of brake pads according to the percentage of metals they contain in their composition*

| Type of brake pad | Reference | Percentage of metal materilas |
|---|---|---|
| Metallic brake pads | Banait et al. [31] | Graphite and metals |
| Semi-metalic brake pads | Brigestone [32] | 30 – 70% |
| | Grigoratos and Martini [38] | Up to 65% |
| | Bonfanti[36] | >50% |
| Low metal brake pads | Grigoratos and Martini [38] | 10-30% |
| | Bonfanti [36] | 10-50% |
| Non-asbestos organic brake pads (NAO) | Bonfanti [36] | <10% |
| | Ma et al. [39] | Dont contain very low percentage of metals |

## 2. FACTORS AFFECTING BRAKE WEAR AND PARTICULATE FORMATION

When it comes to the factors that affect the brake wear, Ausburg et al. [40] illustrated the factors that lead to wear and thus the formation of particles. A graphic representation according to this author is shown in Figure 1. Rudnytskyj [41] came to similar results of influential factors, where it is stated that contact area, running-in, transfer-film, load, sliding velocity and temperatures affects the brake wear. According to the authors [12], the friction between friction pair elements and their wear are influenced by the complex combination of the speed changes, temperature increase, load and braking energy.

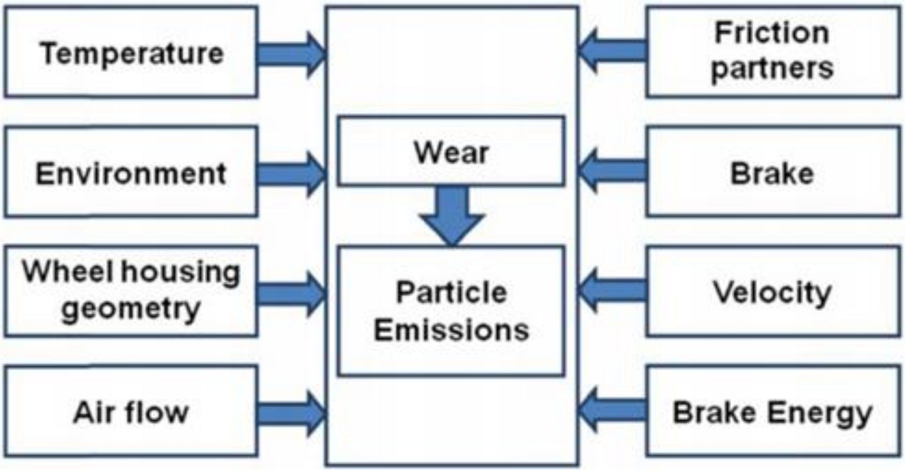


*Figure 1 Factors influencing particle formation [40]*

Based on the research [42], it was found that the wear rate of brake pads made from different materials, but also the friction between the elements of friction pairs is mostly influenced by the following characteristics or factors:

- Braking conditions: brake pressure, initial braking speed, braking time, increase in braking temperature, etc.,
- Material characteristics: physical, chemical and mechanical friction properties, etc.,
- Characteristics of friction surfaces: surface roughness, contact properties, etc.,
- Operating conditions: ambient temperature, humidity, air flow and so on,
- Structural parameters: shape, size and contact mode of a brake pair, etc.

The temperature at the contact surface has a significant effect on brake wear. With an increase in temperature, there is also an increase in the wear rate of the brakes, but also an increase in the concentration of the formed particles, as evidenced by the results of research [43, 44]. Based on research and results [31], it was found that asbestos pads have the lowest thermal conductivity and with the increase in the percentage of metal in the brake pads, the thermal conductivity, so the temperature itself increases. Thus, Figure 2 shows the different brake pads and their conductivity, where it can be seen that metal brake pads have the highest thermal conductivity.

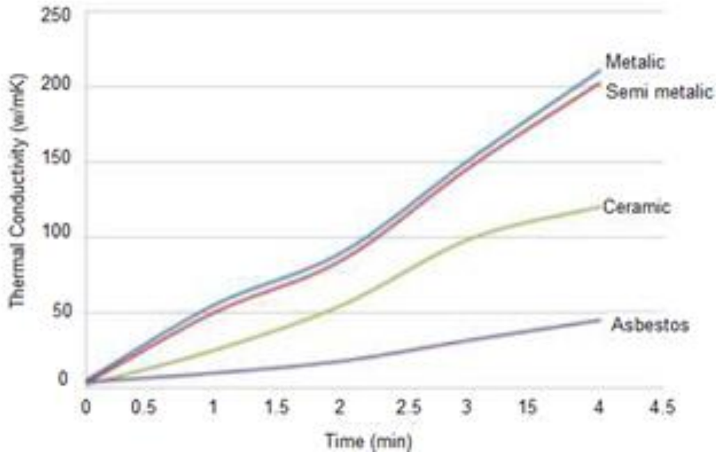


*Figure 2 Thermal conductivity of different brake pad types [31]*

Relying on research [31], it was also found that the load or pressure in the contact surface between the elements of brake pair has a significant impact on the wear rate, but also the wear rate varies depending on the type of brake pad. The results are shown in Figure 3, where it is clearly noticeable that the metal brake pads have the highest wear rate and this increases with increasing load.

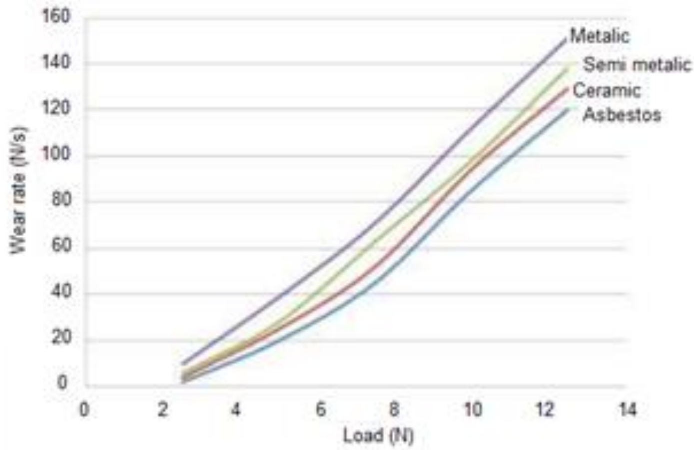


*Figure 3 Wear rate versus load for different brake pad types [31]*

Similar results on the influence of load on the rate of brake wear were obtained in [45, 46] for organic and metallic brake pads. In both cases, there was an increase in the wear rate with an increase in brake pressure. However, according to the source [47], the wear rate of organic brake pads is higher than in the case of wear of metallic friction pads. By road tests according to the reference [48], three types of brake pads (organic, semi-metallic and ceramic tiles) were studied in three test modes, and it was concluded that organic friction pads wear the most and lose weight, while semi-metal brake pads have lost the least weight. The characteristics of the materials themselves and the method of production of brake pads also have a significant impact on the wear of brake pads. Thus, the porosity of the material and the hardness of the brake pads have a significant effect on the wear of the brake pads and the formation of particles. When it comes to the porosity of brake pads, the more porous the brake pads, the higher is the wear rate. This examination of the brake pads showed that brake pads with higher hardness have a higher degree of brake wear [47]. The wear rate of brakes is also significantly influenced by the sliding length of the brake pads on the contact surface of the brake disc [49]. Studies [50, 51], in which organic and metallic friction pads were used, have shown that the wear rate is influenced by the disc rotation speed, i.e. the initial speed at which the braking process begins. In the study [52], the phenomena that occur in the contact surface between the disc, and the friction pads were analyzed. Thus, it was found that changing the sliding speed between the contact surfaces of the brake pairs, and the pressure in the contact surface leads to a change in the concentrations of the formed particles. Furthermore, the increase in pressure and sliding speed leads to an increase in the concentration of the formed particles. Similar results were obtained in the study [53]. But, according to the results of tests [47], it was found that an increase in the sliding speed between the friction materials leads to a decrease in the wear rate of the material. Particle formation also depends on the deceleration, as well as the initial velocity or rotation speed of the disc [54]. By increasing the initial velocity and deceleration, the particle concentration of both $PM_{10}$ and $PM_{2.5}$ also increases. Also, in the source [54], it was proved that many more particles are released after braking and re-accelerating the disc, bearing in mind that then the particles are released from the friction surfaces of the brake. It has even been found that drum brakes are more environmentally friendly, bearing in mind that the particles are retained inside the drum, while with disc brakes, they are released directly into the environment. Similar results were obtained in [55], where it was determined that the amount of particles formed and the wear of the friction elements of the brake depend on the speed and deceleration. Braking and complete stopping at a speed of 50 km/h creates 40-100% more particles than when braking at a speed of 30 km/h. Humidity is also one of the factors that can affect the wear rate of brake pads and discs, which was found in a study [56], where it was concluded that with increasing humidity, the wear rate of semi-metallic and organic brake pads decreases. However, in research [57], it was concluded that the increase in humidity also increases the wear rate of brake pairs. It is certainly always necessary to take into account the applied brake pads and the materials used, but still this parameter is very important considering that it varies in operation of vehicles or brakes.

## 3. CONCLUSIONS

The brakes are the emitter of particles that is considered to be one of the most influential participants in the non-exhaust emission of vehicles. The formation of particles in this case is caused by the wear of elements of friction pair, i.e. brake disc and brake pads. The problem is much more serious due to the fact that brake pairs often contain metals or other materials that wear out and become part of the particles, i.e. they are in particle fractions. In that case, with the heavy-metal content, the particles become very harmful to human health and the environment. Brake pads often contain different elements such as Fe, Cu, Zn, Al, Mg, Sb, Si, Ti, Cr. Such elements in brake pads are characterized as the most commonly used materials. Bearing in mind that brake pads often contain metals, which otherwise have a harmful effect on humans, brake pads are divided into several categories according to the percentage of metal material in the mass of one brake pad. In order to reduce the harmfulness of particles and brake pads, alternative natural materials that would replace metals or some other harmful substances are increasingly being tested. Brake wear is affected by a number of factors and quantities that occur during the braking process. The problem is that all parameters are as complex as the braking process. A large number of authors have examined the influence of different parameters on brake wear rate and particle formation. Some of these factors are the temperature in the contact surface of the friction pairs, the pressure between the friction pairs, the humidity, the sliding speed, the sliding length … It is important to note that with the change of all parameters, there is also a change in the wear rate of the brakes and the concentration of the formed particles. The applied materials in the brake pads certainly have an important influence, so all parameters can have a different influence depending on the composition of the brake pads.

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# APPLICATION OF PLAIN BEARINGS WITH CONTROLLED WEAR ON AUTOMOTIVE VEHICLES

*Alexander Novikov[1]*, Alexey Rodichev[2]*

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RESEARCH ARTICLE

**ABSTRACT:** The article describes the principle of operation and operating conditions of the balancing suspension of automotive vehicles. An analysis of the wear of the bushings of the balancing suspension was made, on the basis of which an integral normal distribution curve was constructed and the number of plain bearings suitable for operation was determined. The consequences arising from the critical wear of the balancer suspension bushings and their effect on road safety are considered. The article proposes a promising solution for replacing a conventional plain bearing with a plain bearing with controlled wear, made using active parameter control technology. In this design, the emphasis is on controlling the wear of the bearing surface of the sleeve (plain bearing) of the balancing device of the rear suspension of trucks. Special attention is paid to the technological difficulties of applying an antifriction coating in the manufacture of a plain bearing with controlled wear.

**KEY WORDS**: plain bearing, active control, wear, anti-friction coating, safety



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# PRIMENA KLIZNIH LEŽAJEVA SA KONTROLISANJIM HABANJEM NA AUTOMOBILIMA

**REZIME**: U radu je opisan princip rada i uslovi rada balansiranog sistema oslanjanja vozila. Urađena je analiza habanja čaura za uravnotežavanje oslanjanja na osnovu koje je konstruisana integralna kriva normalne raspodele i određen potreban broj kliznih ležajeva za rad. Razmatrane su posledice nastale na osnovu kritičnog habanja balansiranog oslanjanja ležaja i njihov uticaj na bezbednost na putevima. U radu je predloženo rešenje za zamenu konvencionalnog kliznog ležaja sa kliznim ležajem sa kontrolisanim habanjem, izvedeno primenom aktivne tehnologije upravljanja parametrima. U ovom dizajnu naglasak je na kontroli habanja nosive površine čaure (klizni ležaj) balansirnog sistema zadnjeg oslanjanja kamiona. Posebna pažnja posvećena je tehnološkim poteškoćama nanošenja antifrikcionog premaza u proizvodnji kliznog ležaja sa kontrolisanim habanjem.

**KLJUČNE REČI**: klizni ležaj, aktivna kontrola, habanje, premaz protiv trenja, sigurnost

# APPLICATION OF PLAIN BEARINGS WITH CONTROLLED WEAR ON AUTOMOTIVE VEHICLES

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## INTRODUCTION

Most goods for various purposes are transported by road transport. This is primarily affected by the mobility of road transport, the possibility of its use on roads with different surfaces, and in some cases even with complete impassability. Despite all this, the cost of transported goods will remain quite low compared to other types of transport. One of the most common vehicles for transporting goods are KamAZ, KrAZ, MAZ family vehicles. Representatives of these brands of automobile transport work in quarries, on construction sites, in agricultural production, as well as in many industries of our country. They have sufficient carrying capacity, increased cross-country ability and highly maneuverable.

## 1. PROBLEM FORMULATION

The performance of vehicles on roads with different types of pavement at different speeds during one day of operation is determined by the reliability of the car, that is, the property consisting of reliability, maintainability, durability and persistence. One of the important systems of the car, ensuring the reliability of movement and reliability of the car - is the suspension. According to leading experts in the field of transport operation, working with a faulty suspension reduces the durability of the car by more than 1.5 times. A faulty suspension also causes an increase in vertical and angular accelerations, sharp jolts and bumps on the body of the suspension. Working with malfunctioning suspensions affects the controllability, stability of the car and reduces the safety of its movement. Due to the vibration of the frame, the alignment of the engine and the gearbox of the car is violated, and the mounting of the body parts is also weakened [1]. Failures in the suspension of a vehicle involved in road traffic can lead to road traffic accidents (RTA), the consequences of which are characterized by the death and injury of people, material damage from damage to vehicles, goods, road or other structures, the payment of disability and temporary disability benefits, and etc. From all of the above it follows that the diagnosis of the suspension have great importance in improving the reliability of cars and especially large payloads of the KamAZ, KrAZ, MAZ type [2].

## 2. THEORETICAL PART

The rear suspension of the KamAZ car (Figure 1) is equipped with a balancing device consisting of two axles pressed into brackets and shoes, into which bushings (sliding bearings) made of antifriction material are pressed [9].

*Figure 1 Balance suspension of the KamAZ car*

Bushings work under abrasive conditions [1]. These bushings (Figure 2) limit the resource of the rear suspension of vehicles and require restoration or replacement with new of the repair size. One of the most common failures of the balancer suspension is the wear of the balancer bushings. Between the bushings and the axis of the balancer, a clearance of 0.5 ... 0.8 mm is allowed. With such a gap, in fact, large loads act on the bushing, especially during turns. There are four types of bushings from various materials:

- bronze,
- aluminium,
- aluminum with zinc,
- fluoroplastic.

To determine the reliability of the balancing suspension of a KamAZ car, an analysis was made of the wear of the bushings [4] (plain bearings) of the balancing suspension of automotive vehicles. Measurements were carried out on 60 bushings. The car mileage ranged from 46 ... .62 thousand km, the operating life from 8 to 12 months.

*Figure 2 Shoe bushings for balancing device of KamAZ car*

Worn surfaces of the shoe sleeve were measured in two planes and two mutually perpendicular sections. The location of the planes: A – A - 15 mm from the end face of the sleeve B – B -. 10 mm from the flange of the sleeve. The measurement scheme is shown in Figure 3.

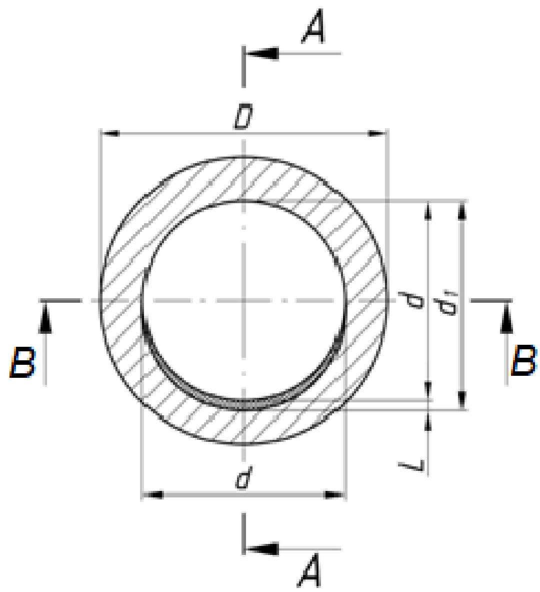


*Figure 3 Measurement scheme for worn surfaces*

*D* – bushing outer diameter; *d* – bushing inner diameter; $d_1$ – diameter of inner worn surface; *L* – amount of wear

The measurement of the inner diameter is carried out using the indicator caliper IC 10 GOST 868 - 82 with a division value of 0.01 mm (Figure 4).

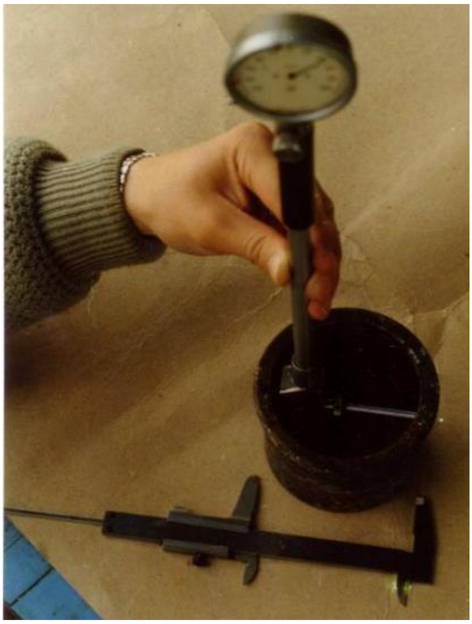

*Figure 4 4 Methodology for measuring the shoe sleeve*

## 3. EXPERIMENTAL STUDIES

Wear information was processed using a computer. The results of experimental studies are presented below. As a result of the studies, an integral normal distribution curve was constructed and the number of serviceable bushings without repair was determined (Figures 5 and 6).

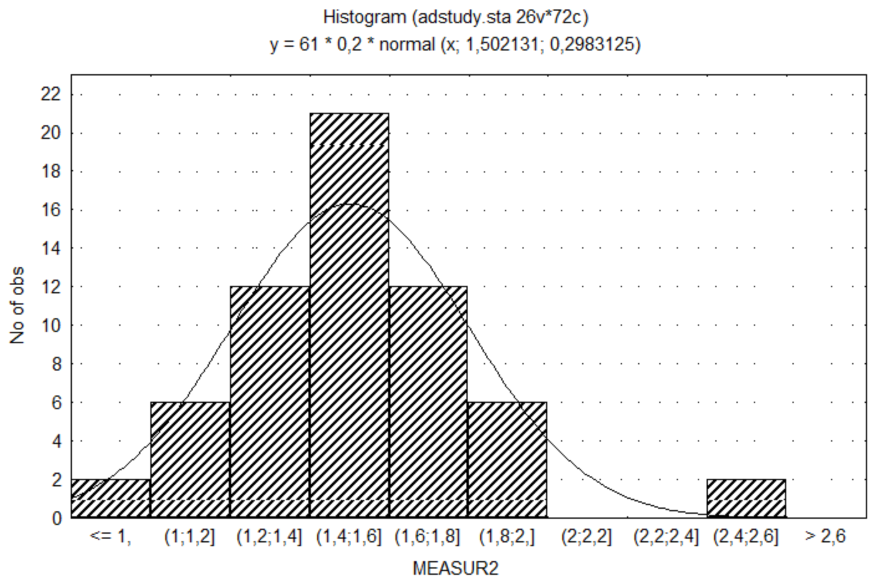


*Figure 5 Plane A-A*

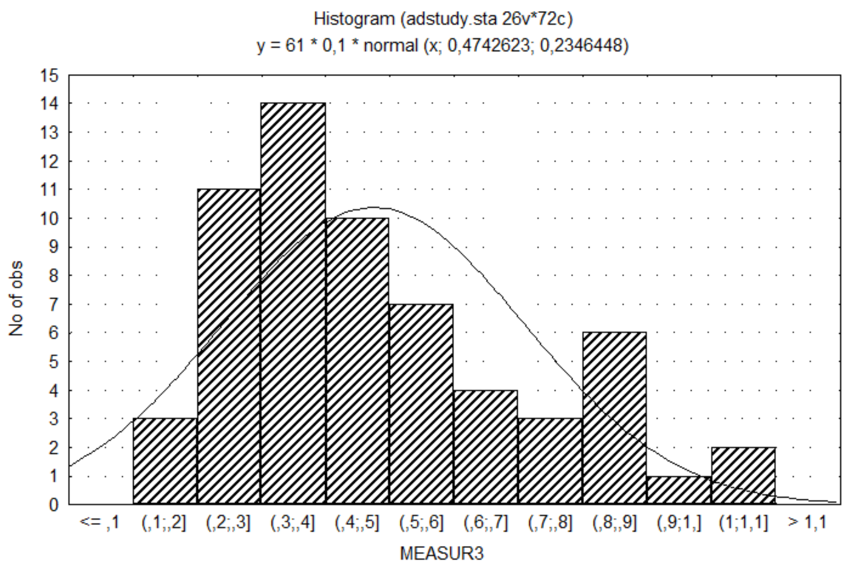


*Figure 6 Plane B-B*

Analysis of the wear state of plain bearings showed that the inner cylindrical surface of the bronze bushings is outside the range of acceptable operation sizes. Wear of the balancer sleeve by 0.1 mm increases the wear rate by several times, while the sleeve is completely destroyed (Figure 7) [5]. As a result, the load on many nodes of the suspension (springs, spring supports, axle balancer and other elements of the suspension) increases in many times. In case of deterioration, or breakdown, of which (Figure 8), an emergency may occur with a subsequent traffic accident.

*Figure 7 Worn balancer bushings*

*Figure 8 Battery damage*

Reliable operation of the rear balancer suspension of the KamAZ car is impossible without quality control of spare parts, timely maintenance and high-quality repairs. In this case, it is advisable to propose the use of a plain bearing with controlled wear instead of a conventional antifriction sleeve. The analysis of such devices made it possible to choose the invention [6], the essence of which is as follows: a sliding bearing contains a housing and a sleeve made of bimetallic material placed in it (Figure 9). An insulated wire is located in the layer of antifriction material, and the housing is equipped with an electric power element connected to the insulated wire and a signal device, the insulated part of the wire protruding in the layer of antifriction material of the sleeve by an amount equal to the maximum wear, which allows controlling the occurrence of the limiting state of the sliding bearing and, thereby, increase the reliability of the entire bearing assembly.

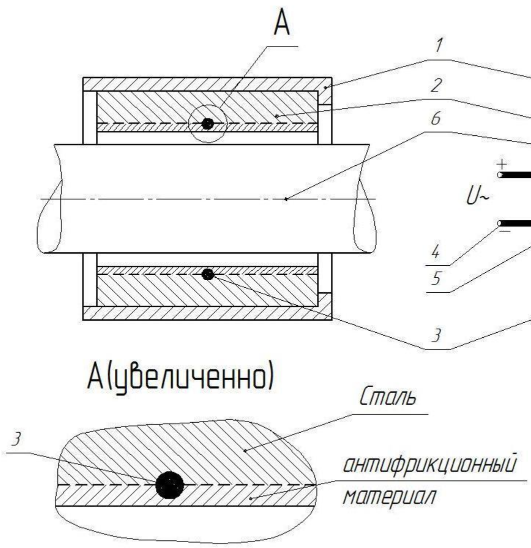


*Figure 9 Mechatronic plain bearing (RF patent No. 2398112)*
*1 – body; 2 – bimetal plain bearing sleeve; 3 – insulated wire; 4 – power supply; 5 – signal device; 6 – shaft*

Very often, design decisions are very difficult, and sometimes impossible, to implement due to the lack of technological capabilities to obtain the desired result. The main factor that complicates the manufacture of this sliding bearing is the temperature of applying an antifriction coating to the surface of the steel base of the bimetallic sliding bearing. All processes of thermal spraying are based on one principle - heating of the material (powder or wire) and its acceleration towards the sprayed surface to form a coating. In a collision, the particles are deformed and bonded to the surface, while a huge number of particles stick to one another, a coating is formed, while the particles are bonded to the material through mechanical or metallurgical bonds. Our team solved this problem with the use of film antifriction coatings instead of thermal spraying and a plain bearing with controlled wear was made (Figure109). The technological process includes several operations:

1) The first stage, we take a standard bronze plain bearing.

2) The second step in the manufacturing process of a plain bearing with controlled wear is surface activation.

This is achieved by cleaning and shot blasting (sandblasting). At the same time, grooves for laying wires are grinded on the inner surface.

3) At the third stage, the wire is insulated and laid in special grooves.
4) At the fourth stage, a film of antifriction coating is applied (in the form of a solution) by introducing it into the grooves.
5) In the fifth stage, the applied coating dries.
6) At the sixth stage, the coating is tested for quality by evaluating the mechanical properties and microstructure.
7) At the final stage, the wire is checked for possible damage after applying an antifriction coating.

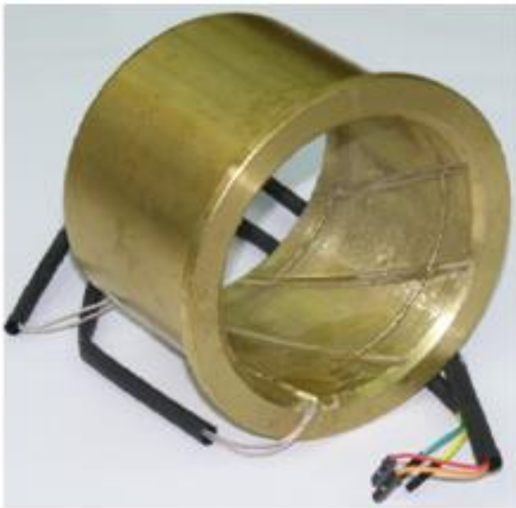

*Figure 10 Wear-controlled plain bearing*

## 4. CONCLUSIONS

Monitoring the wear of the bearing surface of the bearings of the most loaded and critical bearing units allows you to prevent the occurrence of a sudden failure of the "shaft-bearing" system, as well as significantly increase the life of the entire machine. A high degree of integration and the absence of additional mechanisms and devices allows, without constructive changes, to upgrade already proven designs by introducing the function of monitoring and preventing emergency situations into them. Overcoming the difficulties of applying an antifriction coating to the surface of a sliding bearing, as well as testing all the nuances of the design at real facilities, is the logical conclusion to the development of a promising sliding bearing with controlled wear before it is directly introduced into production.

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Nazivi slika, tabela: Figure __ (Table _): Times New Roman, italic 10 pt

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